Symmetries at ISAC

April 30, 2008

Contents

1 Ongoing program

The ongoing program at ISAC in fundamental symmetries concerns the charge-changing part of the weak interaction in the first generation of particles, as measured in nuclear beta decay. Details of these programs are contained in other sections, and only a rough sketch of the ongoing program is made here.

1.1 Standard Model tests with β-decay

High-energy particle physics frontier experiments will still find constraints from semileptonic experiments in the first generation to be useful, if they can be done to sufficient accuracy. One benchmark for accuracy is set by a recent SUSY calculation implying that 0.001 sensitivity to scalar-vector or tensor-axial vector Fierz interference terms in beta decay would provide useful and unique constraints on first generation left-right sfermion mixing [1]. Reaching such sensitivity is the goal for several planned β-decay experiments at TRIUMF.

1.1.1 Angular and spin correlations in beta decay with the TRIUMF neutral atom trap

The atom trap will be used for upgraded beta-neutrino correlation and spin-correlation experiments with a goal of reaching the sensitivity needed to see new 4-fermi contact effective scalar and tensor interations. The new technique using coincidences of nuclear recoils with atomic shakeoff electrons can gather the statistics at 0.001 level in a week of counting, either in the 'Fierz' scalar-vector interference term in the β-ν distribution of the pure Fermi decay ^{38m}K, or in the recoil spin asymmetry term in polarized ^{37}K decay. The challenge in these measurements will then be minimizing systematic errors.

Time-reversal violating measurements utilizing time-odd spin-momentum correlations would also reach such sensitivity.

Collinear laser beamline for polarized β-decay correlations "2nd-class" currents are weak isospin-violating terms induced by QCD into semileptonic interactions. Their presence would be a fundamental standard model violation. First-generation β-decay experiments remain the best probe of these, complementary to hadronic τ decays. A group primarily from Osaka U. with TRIUMF scientist technical support pursues these with the laser-polarized collinear beamline. Polarizations an order of magnitude better than those generated using spin-orbit coupling in nuclear reactions have let this group do a very accurate measurement of the alignment-dependent anisotropy in ^{20}Na. They need the isobaric mirror decay of ^{20}F to complete this experiment. Stable ^{19}F has been polarized and a ^{20}F beam will be available soon.

1.1.2 Super-allowed β decay strengths

Worldwide efforts in super-allowed Fermi β decay in experiment and theory

Super-allowed Fermi decay provides the most stringent test of the Conserved-Vector-Current (CVC) hypothesis, the most precise value for the CKM matrix element Vud, and the most stringent limit on the presence of scalar interactions that couple to standard-model left-handed neutrinos. Using the data from the 13 most precisely measured cases, CVC has been confirmed to a relative precision of 1.3×10^{-4}. With the confirmation of CVC, the up-down CKM matrix element has been found to be Vud = 0.97416(13)(14)(18), where the latter uncertainties arise due to nucleus-dependent isospin-symmetry breaking (for which a new full calculation has appeared which requires testing [2]) and radiative corrections. The upper limit on the size of a possible scalar contribution, relative to the well-known V-A interaction, is currently 2.6×10^{-3}, approximately twice the error needed to constrain the SUSY model mentioned above.

Studies at TRIUMF are designed to test the theoretical calculations of isospin-symmetry breaking and to provide data vital for the refinement of scalar interaction limits. To date, measurements have been performed on ^{18}Ne, ^{26m}Al, ^{38m}K, ^{62}Ga, and ^{74}Rb, all of which have led to significant improvements. Future measurements will include ^{10}C, ^{14}O, ^{34}Ar, ^{46}V, ^{50}Mn, ^{66}As, and ^{70}Br, where high-precision measurements of the lifetimes, branching ratios, and masses will be performed by the fast-tape-transport system at GPS1, the 8pi spectrometer, and TITAN.

1.2 Nuclear structure contributions to quantitative understanding of $0\nu\beta\beta$ decay

This decay can occur only if the neutrino is its own antiparticle, i.e. the neutrino is "Majorana" instead of "Dirac". A positive signal means that the concept of lepton number is no longer valid, independent of any nuclear structure information or knowledge of the weak matrix element.

However, interpretation of either a positive or a null signal in terms of a finite neutrino mass needs supporting experimental information. There could even be a definitive declaration that the neutrino were Dirac, if the electron neutrino mass were independently determined to be much larger than the observed $0\nu\beta\beta$ rate would imply [3]. Here ISAC experiments can contribute to the worldwide effort to test the difficult nuclear structure calculations (which require a sum over all possible vitual states in the intermediate nucleus) needed to draw such conclusions.

A modification of the TITAN EBIS ion trap apparatus will measure the ratio of electron capture (EC) to β^- branches of the intermediate nuclei in 7 candidate systems. The 6 Tesla magnetic field of the EBIT will guide β^- particles away to a silicon detector on-axis. The Helmholtz coil configuration of the magnet allows for large solid angle for X-ray detectors to measure the very small ($<10^{-3}$) EC branch free of the β^- background. This method will systematically resolve experimental discrepancies in the electron capture branches. It will then provide helpful tests of specific predictions of QRPA calculations in several of the cases [4].

Inspired by recent stable beam reactions tests of QRPA predictions of single-particle occupancy [5], studies of the nuclear structure of the parent nuclei ^{76}Ge and ^{150}Nd by the decays of clean beams of fission products ^{76}Ga and ^{150}Pr can be done.

Measurements of the nuclear anapole moment will test the understanding of the effective field theory of weak hadronic interaction in the nuclear medium, which is important for corrections to double beta decay from the exchange of heavy particles (described in further detail below).

The effective mass measured in $0\nu\beta\beta$ decay is $\langle m_{\nu e}\rangle = |\sum_i U_{ei}^2 m_i|$, a sum over all possible admixtures of massive neutrinos. 'Sterile' neutrinos of 100 keV mass and 10^{-4} admixture could account for the entire $0\nu\beta\beta$ effect at the present limit of sensitivity, while direct experiments stand at 10^{-2} sensitivity. Using precision recoil momentum measurements described elsewhere in this document, the atom trap could achieve 10^{-5} sensitivity to such sterile neutrinos by searching for lower-energy monoenergetic recoils from electron capture decay.

2 The proposed program studying time reversal symmetry and neutral currents

We present here two ambitious and compelling programs for precision measurements using radon and francium isotopes. These experiments will push state-of-the-art atomic and nuclear experimental techniques to extend TRIUMF's local physics reach into the time-reversal-violating and weak neutral current sectors for the first time.

We begin with the broad science motivation, then we sketch the planned experiments, then we give a more detailed physics motivation and a description of the experiments.

2.1 The science: In search of time reversal violation: Electric Dipole Moments

One of the greatest challenges remaining in science is to account for the amount of matter we see around us. Evidence for some kind of Big Bang is overwhelming, but any cosmological model using the physics that we know now produces much more equal amounts of matter and antimatter than we see. It is true that there is only one baryon per billion photons, but even that amount is orders of magnitude larger than our physical models can produce.

Most of the physics in the standard model respects time-reversal symmetry ('T'). This is deeply related to matter-antimatter asymmetry ('CP') through the CPT theorem, which is obeyed by any locally Lorentz invariant quantum field theory, like the standard model. Small violations of CP were discovered in the 1960's in the K meson system, and similar violations have been found more recently in the B meson factories. This level of CP violation is beautifully described in one piece of the standard model, but it is not large enough to account for the baryon asymmetry.

So the matter we see around us every day is a direct indication that there is physics beyond the standard model. This physics could take the form of an additional source of CP and/or time-reversal violation. This particular cosmological puzzle can be tested by experiment.

It was realized in the 1950's by Landau and others that the existence of a permanent electric dipole moment (EDM) in a physical system would be a model-independent violation of time reversal symmetry. Below we will describe a search for an EDM in radon isotopes that would improve our sensitivity to most models of new CP violating processes by one to three orders of magnitude.

2.2 The science: Precision measurements of weak neutral currents

When new states are discovered at the LHC, it will be important to know their couplings to the first generation of particles. Electrons and muons can be distinguished in the detectors, but up/down quark jets cannot be distinguished from jets of other generations. Atomic parity violation and other low-energy experiments are in a unique position to assist with this question. The challenge is to make them sensitive enough, which generally means part per thousand accuracy. We will describe below experiments in atomic parity violation in francium that are designed to achieve this accuracy.

The study of weak interactions between nucleons gives unique information about very short-ranged correlations between them. We will use francium atoms to study a parity-violating electromagnetic moment that could provide conclusive information that these correlations change in nuclear matter.

2.3 The TRIUMF experiments: Why high-Z atoms?

The TRIUMF experiments will be done with atoms with high atomic number Z. In broadest terms, these higher-Z atoms are more sensitive to possible new short-ranged interactions between leptons and quarks because the electron wavefunction overlap with the nucleus is larger. For atomic parity violation the effects scale like Z^2N with additional relativistic enhancement, anapole moments scale like $Z^{8/3}A^{2/3}$, and there is similar scaling for EDM's.

To utilize these effects, precision atomic techniques will be combined with the availability of relatively copious amounts of the necessary isotopes from ISAC. For the radon experiments, the decays are used to probe the nuclear spin direction. For the francium experiments, laser trapping and cooling allows the exploitation of modern spectroscopic techniques on the relatively small number of radioactive atoms.

We describe below some details of three approved experiments

• S929, an electric dipole moment search in octupole-deformed radon isotopes

• S1065, a measurement of the parity-violating 'anapole moment' in francium isotopes, a measure of the modification of the weak interaction between nucleons by extremely short-ranged effects from the nuclear medium

• S1010, a measurement of neutron distributions in francium via the hyperfine anomaly in precise atomic spectroscopy.

We will also show other planned and possible francium experiments:

• a measurement of the rate of the 'forbidden' M1 transition between the 7S ground state and 8S excited state, which is sensitive to relativistic corrections to many-body perturbation theory

• a measurement of atomic parity violation in the 7S to 8S transition, sensitive to the strength of the weak neutral current

• a search for the electron electric dipole moment with a francium atomic fountain.

2.4 Detailed physics motivation for EDM's

Studies of CP violating interactions have impact on the nature of elementary particle interactions and the origin of the predominance of matter over antimatter in the universe. Electric dipole moment measurements provide a unique and important probe of CP violation. The signal is unambiguous (i.e. there are no confounding final state effects), techniques of atomic and nuclear physics provide continually improving precision, and CP violation in the K and B meson systems is dominated by the single phase in the Standard Model CKM matrix (Fig. 2). An example of the impact of EDMs is the tight constraints on supersymmetry set by the combination of recent results from the neutron, the electron, atoms and molecules (see Fig. 1, Table 1, and the UCN section of this plan). The anticipated discovery of an EDM in one of these systems would be the first step in using CP violation to probe new physics, and measurements in several systems would, over time, fully clarify the new physics.

CP violation is also a crucial component of the Sakharov mechanism of baryogenesis, which could explain the dominance of matter over antimatter in the Universe. In the Sakharov mecha-

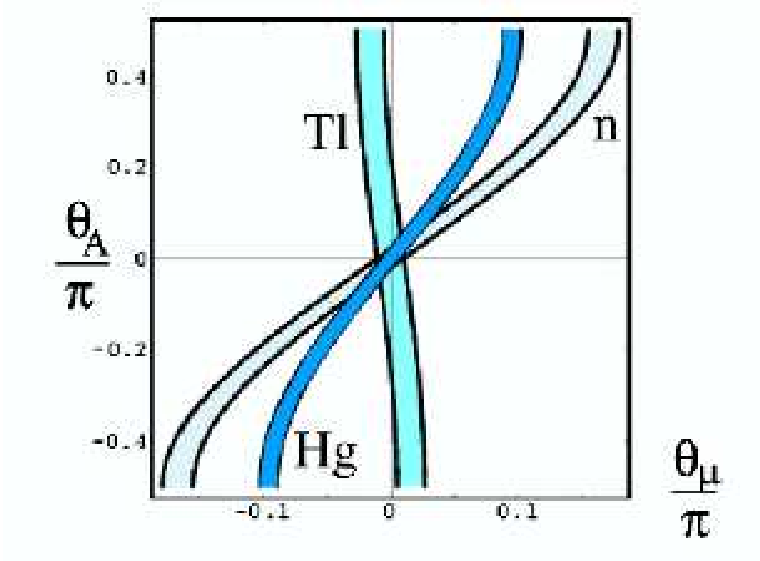


Figure 1: One explicit example of the complementarity of EDM experiments. Constraints are shown from the three types of EDM experiments: Tl (electron), Hg (J=0 atom), and neutron, on two CP-violating parameters in SUSY (Figure 8 of Ref. [14], for common superpartner mass 500 GeV and tanβ=3). The three types of EDM experiments taken together set much more powerful constraints.

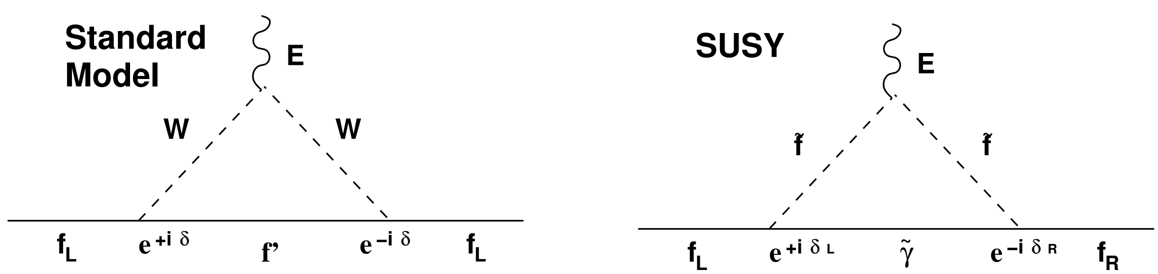


Figure 2: An example (taken from Fig. 2 of Ref. [6]) of how electric dipole moments vanish in the standard model in 1-loop order. There is only one CP-violating phase, so emission and reabsorption of a virtual W boson by a fermion (f) are time-reversals of each other, the complex number phases of the 2 processes cancel, and there is no EDM at this order. Many standard model extensions add additional phases that need not cancel. The example shown is a SUSY model where the fermion changes handedness, so EDMs are produced at this lower order.

nism, the matter-antimatter asymmetry is generated in a non-equilibrium first order phase transition by CP and baryon number violating interactions; however the phase in the CKM matrix is not sufficient to generate the observed baryon asymmetry, thus new forms of CP violation are expected [7]. Most significant extensions of the Standard Model introduce additional phases that could produce the baryon asymmetry and lead to EDMs many orders of magnitude larger than the CKM values. An electron EDM much smaller than the current limits could rule out electroweak baryogenesis in any SUSY model [8], and extending the sensitivity to neutron and heavy atom EDMs would also provide strict constraints.

Table 1: Limits (90% C.L.) on phenomenological parameters of CP violation, including the most recent neutron EDM result[15] and evaluation of atomic sensitivities from reference [16]. In addition to what is shown here, the strong interaction effects are typically parameterized with additional effective meson couplings– for isoscalar and isovector parts as well as range– for which the J=0 atom and neutron experiments can be seen to be complementary.

Parameter	^{199}Hg limit[17]	Neutron limit[15]	Electron limit	Theory Ref.
$\bar{\theta}_{QCD}$	1.5×10^{-10}	4.1×10^{-10}	-	[18]
down quark EDM	-	5×10^{-26} e-cm	-	[19]
color EDM	3×10^{-26} e-cm	-	-	[18]
$\epsilon_q^{\mathrm{SUSY}}$	2×10^{-3}	5×10^{-3}	-	[21]
$\epsilon_q^{\mathrm{Higgs}}$	$0.4/\tan\beta^*$	-	$0.3/\tan\beta$ (Tl)[20]	[21]
x^{LR}	1×10^{-3}	5×10^{-3}	-	[21]
C_T	1×10^{-8}	-	5×10^{-7} (TlF)[23]	[22]
C_S	3×10^{-7}	-	2×10^{-7} (Tl) [20]	[22]

*The ratio of masses of the two Higgs bosons in this theory is $\tan\beta$.

Other EDM experiments Nucleon/nuclear EDM searches using J=0 atoms like Hg and Rn include ^{225}Ra atoms in an optical trap at Argonne National Lab and an experiment in liquid xenon at Princeton. A storage ring experiment on the deuteron is being planned by people at KVI. Neutron EDM experiments are being pursued at the SNS at Oak Ridge and at PSI, and this plan contains a possible UCN experiment at TRIUMF.

Electron EDM searches include molecular beam experiments in YbF at Imperical college, PbO at Yale, and PbF at Oklahoma, a molecular ion experiment at JILA, experiments in solids using gadolinium iron garnet at Amherst, and an optical lattice experiment with cesium atoms at Penn St.

Any of these experiments will quote a time in which they can gather relevant statistics with the promise of improving present sensitivity by one to four orders of magnitude. The goal is always to reduce systematic errors to reach the statistical level, and the sources of error are very different in each experiment. One strength of the radon EDM search is the ability to extrapolate experience from the work of the Michigan group in stable isotope xenon experiments to anticipate and eliminate potential systematic errors in the design stage.

Multiple successes would be complementary, as was emphasized above. ^{225}Ra and our radon isotopes share enhancement by octupole deformation (see below); even here there would be different sensitivity to three possible time-reversal violating strong interaction couplings that would make our experiments complementary.

2.4.1 Radon and EDM's

Radon isotopes have many attractive features for advancing sensitivity to CP violation. Radon provides the experimental advantages of noble gas atoms, the possibilities for multiple-species experiments that directly measure the most important systematic effects, and the promise of new techniques for precision measurement with radioactive species. The most important feature is enhanced sensitivity to CP violation in isotopes with octupole deformed nuclei [9, 10].

Octupole enhancement For ^{223}Rn, octupole deformation leads to an enhancement of the observable atomic EDM by a factor estimated to be greater than 500 relative to ^{199}Hg [9].

Recent theoretical advances have strengthened the case for these measurements. The work of Jon Engel and collaborators continues to clarify how octupole deformation and octupole vibrations enhance sensitivity to CP violation in the nucleus. Victor Flambaum and coworkers have reevaluated the sensitivity of the atomic EDM to CP violation in the nucleus and show that earlier calculations underestimated the sensitivity of noble gas atoms relative to ^{199}Hg. Engel and collaborators are currently calculating the enhancements in ^{223}Rn as well as several spherical isotopes (including xenon) relevant to our program.

Finding the best radon isotope The theoretical enhancement found in Ref. [9] in ^{223}Rn needs basic experimental support, because nothing is known about its excited states. There is a great deal of indirect experimental evidence suggesting octupole deformation in radon isotopes. Global finite-range droplet models suggest a finite β_3 in this region [58]. The known ground-state charge radii show a pattern of odd-even staggering that favours a finite β_3 in ^{219,221}Rn, though the information in ^{223,225}Rn is ambiguous [57]. (Note that the charge radii of radium isotopes near ^{225}Ra support its known octupole deformation.) Even-even isotopes of radon have been populated in multiparticle transfer reactions, and γ-ray spectroscopy implies that ^{224}Rn has octupole deformation with a first 3^- state at 290 keV while ^{222}Rn is octupole vibrational with a first 3^- state at 635 keV [59]; these studies suggest that ^{223}Rn might not be the best case. There is a proposal being submitted to ISOLDE to use Coulomb excitation to excite the radon isotopes and determine the B(E1)'s and B(E3)'s of low excited states to the ground state.

The excited states of the radon isotopes in question are unknown, so the first measurements of S929 would populate ^{221,223}Rn from decays of ^{221,223}At to measure excited state energies, spins and parities, and E1 and E3 transition strengths complementary to the measurements at ISOLDE.

2.4.2 RadonEDM: experimental overview

Here we give a basic sketch of the experiment. Progress of the collaboration in polarizing and manipulating radon can also be found in Ref. [12].

The RadonEDM experiment builds on existing experimental techniques with known small systematic errors. The radon nucleus is polarized by spin-exchange optical pumping with rubidium.

The polarization is measured by the anisotropy of the gamma radiation, using a high-efficiency germanium array (TIGRESS or GRIFFIN) with data acquisition electronics optimized for very high count rates. See Fig. 3.

Consider an atom with angular momentum $\vec{J}$ and electric and magnetic dipole moments d and μ. The Hamiltonian is

$$H = -(\mu\vec{B} + d\vec{E}) \cdot \vec{J}.$$

The term $\vec{E} \cdot \vec{J}$ is odd under parity and time reversal. If $\vec{E}$ is parallel/antiparallel to $\vec{B}$, precession frequency of the atom is

$$\hbar\omega = 2(\mu B \pm dE),$$

An EDM is revealed by measuring the change in precession frequency when $\vec{E}$ is reversed with respect to $\vec{B}$. In the radon EDM experiment, the frequency will be measured by free induction decay, defined below.

Radon will be collected from the ISAC-1 low energy beam transport and transferred to a measurement cell using the cryogenic/gas transfer technique developed at TRIUMF and described in reference [11]. The measurement cell will contain alkali metal, preloaded and N_2 gas. The isotope ^{223}Rn has a 23.2 m half-life and will be stored in the cell for about 1 hour. An EDM measurement cycle consists of polarization by laser optical pumping of the alkali-metal vapor, a $\pi/2$ pulse and free precession of the ^{223}Rn in the electric (5 -10 kV/cm) and magnetic fields (1 mG). In the first EDM experiment, the free precession will be monitored by counting gamma-rays from several resolved transitions in the daughter nucleus ^{223}Fr which will have an angular distribution relative to the radon $\vec{J}$. As $\vec{J}$ rotates, the gamma ray detection rate in each of the eight detectors (Fig. 3) will modulate at 2ω.

The precision of the frequency measurement depends on the free-precession decay time (T_2), the size of the gamma-ray anisotropy (A), the number of decays counted (N), the background (B), and the electric field(E), thus

$$\sigma_d = \frac{1}{4E}\frac{1}{T_2}\frac{1}{\sqrt{A^2(1-B)^2N}}.$$

We assume T_2= 30 seconds, as achieved for radon in our experiments at Stony Brook. The count rate detectable by the TIGRESS detectors will be limited to 120 kHz for the entire array, and thus we expect $\sigma_d \approx 10^{-25}$ e-cm in one day and $\sigma_d \approx 10^{-26}$ e-cm for a 100 day run of the count-rate limited experiment. With the enhanced sensitivity compared to ^{199}Hg, this would reach up to 10 times further in probing CP violation.

This technique allows for a true co-magnetometer occupying the same volume that would determine systematic effects that could mimic an EDM. Isotopes of other noble gas elements, where the EDM effect is orders of magnitude smaller, can be simultaneously polarized by the spin-exchange optical pumping methods in the same cell. Their γ-ray decays can then be nicely separated from those of the radon (along with background gammas from subsequent decays) using the energy resolution of the germanium detectors. Wall sticking and polarization loss for different co-magnetometers will be different, so different noble gasses with different spins will be tested to determine the best case.

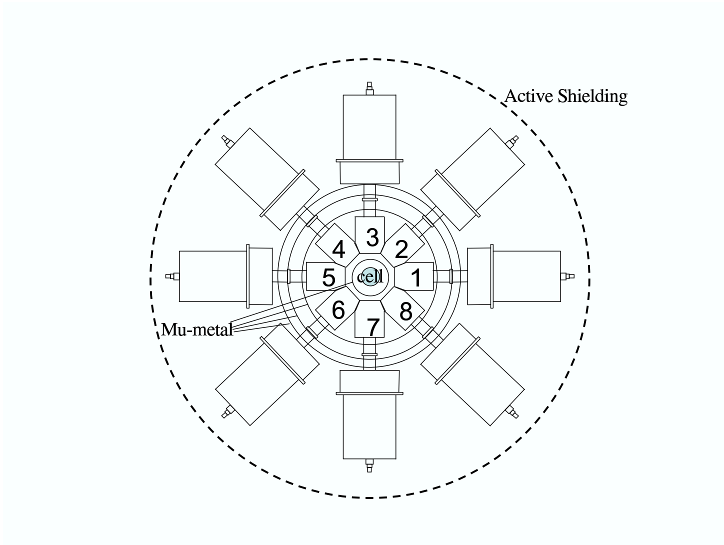


Figure 3: Schematic of the layout of eight TIGRESS or GRIFFIN detectors combined with magnetic shielding etc. for the Radon EDM experiment. Gas will be transferred to the cell.

2.4.3 Radon EDM using β asymmetry

A possibility that could take advantage of larger yields would be current-mode beta detection.

We expect production rates of ^{223}Rn to be 5-10 times greater than the count-rate limited collection rate in germanium detectors. We have designed the Radon-EDM experiment with an upgrade path that will make use of any amount of ^{223}Rn produced.

The most promising upgrade would use the beta-asymmetry technique that will count β's from ^{223}Rn decay in current-mode detectors. Thin silicon detectors would minimize sensitivity to gamma rays, the dominant background source for this technique.

New EDM cells would be constructed with tapered glass side walls of thickness 100 μm (the attenuation length for 400 keV betas) or less. Polarized electron scattering experiments E142 and E154 at SLAC[56] used curved glass windows 80 μm thick with a differential pressure of 10 atmospheres.

To estimate the statistical error, we assume an analyzing power of $A = 0.2$, about half the estimated beta asymmetry for ^{223}Rn from its known Gamow-Teller decays (which would need to be measured with β-γ coincidences), assuming a factor of two dilution of the asymmetry from multiple scattering. The statistical sensitivity for the beta-asymmetry technique is 1×10^{-27} e-cm for 100 days of running at ISAC. This would extend sensitivity to CP violation by a factor of more than 100 compared to the current ^{199}Hg result. If a 20 times higher production rate could be achieved on an actinide target, we would expect a sensitivity of 5×10^{-28} e-cm, a sensitivity to CP violation a factor of more than 400 greater than the current neutron and ^{199}Hg results.

RadonEDM projected sensitivity :

The projected sensitivity for the presently planned γ-ray technique is shown in Table 2, pro-

Table 2: Count rates and statistical sensitivity for gamma-anisotropy and beta-asymmetry measurements at 10μA and 200μA of beam current for a 100 day measurement. with $T_2 = 30$ s and E=5 kV/cm. ^{223}Rn yields (from earlier TRIUMF and ISOLDE measurements) are expected to be 2×10^7 s^{-1} for 10μA.

	Gamma Anisotropy	beta asymmetry	
		10μA	200μA
Count Rate (s^{-1})	1.2×10^5	5×10^6	4×10^7
A	0.2	0.2	0.2
Background	0.01	0.3	0.3
Total N (100 Days)	1×10^{12}	4×10^{13}	8×10^{14}
σ_{d_A} (e-cm)	1×10^{-26}	4×10^{-27}	5×10^{-28}

ducing a sensitivity approximately 10 times better than ^{199}Hg experiments when octupole enhancement is included. Projected sensitivity from the β asymmetry technique is also tabulated.

The duty cycle would take the radon beam for about 1/5 the time, so the 200 shifts mentioned in the table can be shared with other experiments.

The team (senior investigators): Tim Chupp's U. Michigan group achieved excellent sensitivity to EDM's in the less-inherently sensitive xenon system, and that experience directly translates into much of the experimental design. Nuclear detection and structure expertise is provided by a large fraction of the TIGRESS/8pi collaboration, including Carl Svensson, Paul Garrett at Guelph, Corina Andreoiu at SFU, Roby Austin at St. Mary's, and Greg Hackman and Gordon Ball at TRIUMF. Mike Hayden at SFU is expert in low-field NMR, precision magnetic shielding and coils, and cryogenic techniques. Matt Pearson and John Behr at TRIUMF provide experience in lasers and manipulating isotopes.

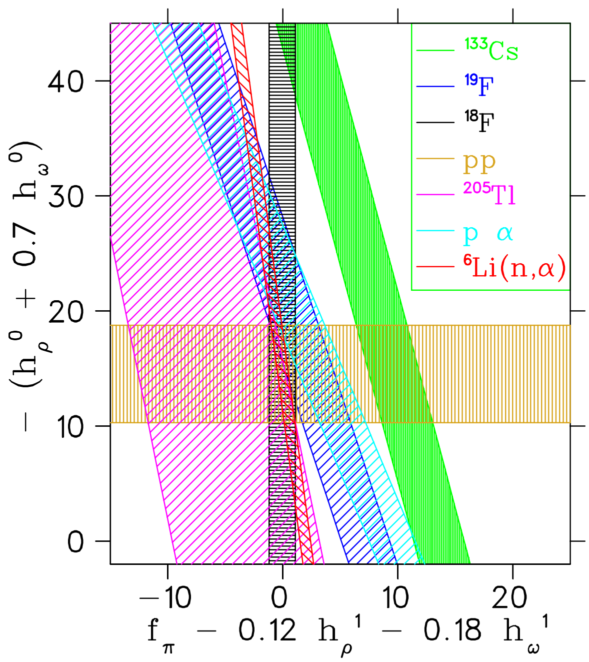
2.5 Anapole moments in francium: physics motivation

The strength of the weak neutral current in nuclear systems remains a puzzle. Historically, if the isovector weak meson-nucleon coupling f_π had been larger, weak neutral currents could have been discovered in low-energy nuclear experiments before Gargamelle's neutrino scattering.

The anapole ('not a pole') moment is a parity-violating electromagnetic moment produced by the weak nucleon-nucleon interaction. It is the result of the chirality acquired by the nucleon current that can be naively decomposed into two parts: a dipole moment and a toroidal current that generates a magnetic field only in its interior (anapole).

The nuclear anapole comes from a number of effects, though detailed calculations suggest it is dominated by core polarization by the valence nucleons [27]. This suggestion can be tested by a systematic study of francium isotopes with paired and unpaired neutrons.

The measurement of the ^{133}Cs anapole moment is difficult to reconcile with low-energy nuclear parity-violating experiments (Fig. 4). More cases are needed to understand the basic phenomenon, which is inherently interesting in itself. (It could be said that trying to understand nuclear magnetic moments from two cases would also be a difficult task.)



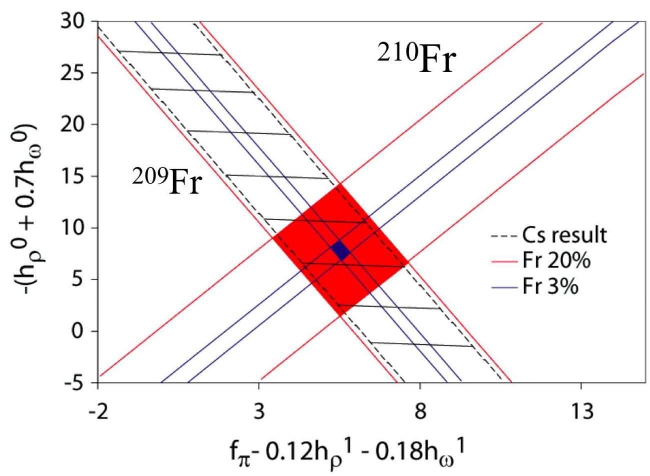


Figure 4: Left: Constraints on isovector and isoscalar weak N-N couplings ($\times 10^7$) from measurement of the anapole moment of ^{133}Cs and natural thallium isotopes, compared to low-energy nuclear parity violating experiments [26] including a recent accurate ^{6}Li(n,alpha) measurement [30]. Right: PROJECTED anapole moments of odd-neutron and even-neutron Fr isotopes would constrain isovector and isoscalar weak N-N couplings in the nuclear medium, if systematic measurements of the odd-even dependence in several francium isotopes successfully show that polarization of the core by the valence neutron is the main effect.

If the anapole moment values continue to disagree with lighter nuclei and few-nucleon systems [26], this could be due to the modification of the couplings in the nuclear medium [29]. The weak N-N interaction has recently been reformulated as an effective field theory, and this formalism provides a good framework in which to ask whether the effective couplings derived from few-body systems will be the same in heavier nuclei [29].

The result could have implications outside of the weak N-N interaction in another problem which has been reformulated as an effective field theory: a possible contribution to neutrinoless $\beta\beta$ decay from exchange of heavy particles [31]. There are four-quark effective operators that are analogous with those in the weak N-N interaction, so the degree of renormalization of the weak N-N interaction could be an important guide to their computation. (See the last two pages of Ref. [29] for a discussion of this issue.)

2.5.1 Anapole moments: experimental overview

An anapole experiment is currently in development. The group at Maryland is primarily responsible for the apparatus. Also contributing to that effort are the groups from William and Mary and San Luis Potosi. The physics method is described in considerable detail in Ref. [24]. We only outline the technique here.

In the Boulder Cs and the Seattle Tl experiments, the anapole was extracted by determining the difference in the atomic parity violation signal on two different hyperfine transitions ($nF \rightarrow n'F'$ and $nF' \rightarrow n'F$), i.e. taking the difference of two very similar numbers. As a result, the relative error on the anapole measurement is much larger than that of the nuclear-spin independent part. One way of addressing this problem is to measure atomic parity violation on a transition where the nuclear-spin independent part is absent, e.g. within a ground state hyperfine manifold, as was proposed long ago [25]. A PV-induced E1 transition between hyperfine states is driven by microwave radiation in a high-finesse cavity (see Fig. 5).

The M1 between these states is allowed and must be suppressed by orders of magnitude in contrast to the optical experiment (see below). Three simultaneous methods to do this are sketched broadly in Fig. 5. Together Ref. [24] estimates that the M1 amplitude can be reduced to less than 1% of the PNC E1 amplitude (see Fig. 5).

Other efforts: anapole moments DeMille at Yale is planning to measure anapole moments by placing diatomic molecules in a strong magnetic field [43]. A collaboration in Russia wants to measure the anapole moment in a potassium cell [44]. The Budker group in Berkeley has been pursuing measurements in ytterbium, which has many stable isotopes available [40], and with the appropriate hyperfine transitions could extract anapole moments. Other suggestions using atomic fountain techniques have recently appeared in the literature [38].

2.5.2 Anapole moments: projected sensitivity and shift/yield requirements

The francium anapole moment project has four major phases: (i) francium trapping and basic spectroscopy; (ii) transfer of Fr sample into the PNC apparatus environment. (iii) observation of the PNC signal (microwave/RF or optical). (iv) isotopic chain measurements, careful study of systematic effects.

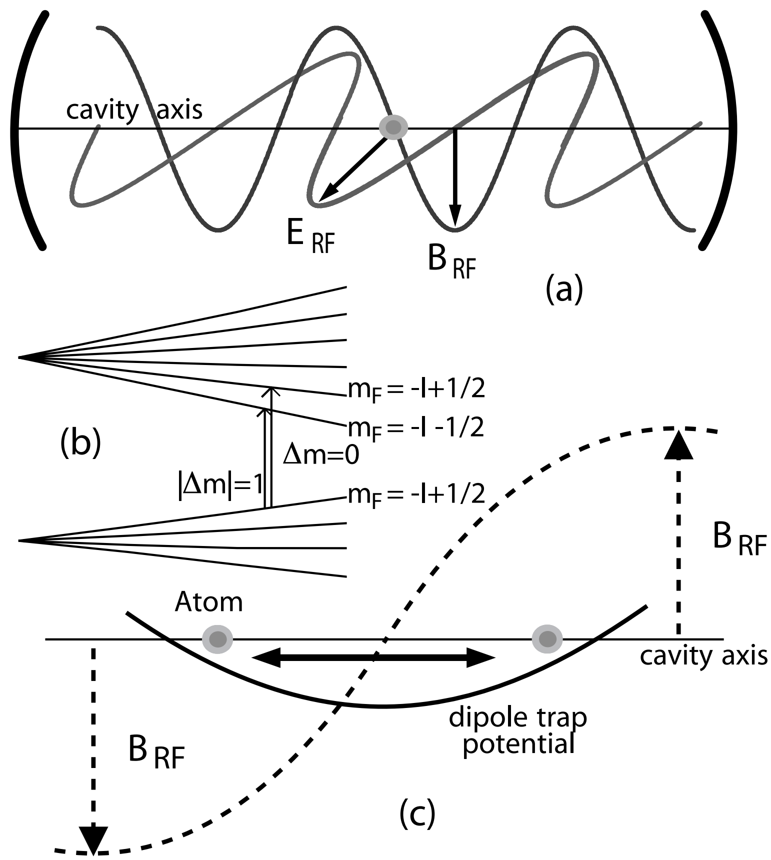


Figure 5: Schematic indications of the suppression of the allowed M1 transition in the anapole experiment. The M1 is off-resonance. The atoms sit on average at the node of the magnetic field, with the additional help of dynamical suppression as the amplitude changes on either side of the node. See Ref. [24].

The microwave/RF anapole experiment could be started with a minimum beam flux of 10^7 Fr atoms per second, i.e. probably $<1\mu$A on the ISAC target. Ultimately an order of magnitude more flux is highly desirable. This would enable the measurement of the anapole moments of a chain of isotopes with 10% accuracy in 250 shifts.

Phase	duration (years)	shifts (12 hrs)
(i)	2	60
(ii)	1	20
(iii)	2	100
(iv)	3	150

Table 3: Minimum shift requirements and timeline for a microwave/RF anapole moment experiment.

The team (senior investigators): Gerald Gwinner of U. Manitoba is the spokesman and is building the M1-Stark mixing experiment in rubidium; Luis Orozco is building the anapole moment experiment at the University of Maryland in stable rubidium with assistance from Seth Aubin at the College of William and Mary; Eduardo Gomez at San Luis Potosi (Mexico); Matt Pearson and John Behr are from the atom trap group at TRIUMF; Victor Flambaum, U. New South Wales, provides theory assistance for anapole moments; Gene Sprouse, Stony Brook.

2.6 Atomic PNC in francium: physics motivations

Atomic parity violation 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 neutron's weak charge, 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 is sensitive to the proton's weak charge. The SLAC E158 Moeller scattering is sensitive to the electron's weak charge. Different standard model extensions then contribute differently [33]. E.g., the atomic parity 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. As another example, Moeller scattering is purely leptonic and so has no sensitivity to leptoquarks, so the atomic parity weak charge can then provide the sensitivity to those. Fig. 6(right) from Ref. [34] shows the present constraints on weak quark couplings from parity violating electron scattering and from atomic parity violation.

Fig. 6 shows measurements of the Weinberg angle [33]. The low-energy experiments still have competitive sensitivity to certain specific standard model extensions than the LEP electroweak measurements— LEP's precision is better, but the low-energy experiments seeking terms interfering with the Z exchange can have inherently more sensitivity to tree-level exchange because they work on the tail of the Z resonance. It should be stressed that Fig. 6 cannot do justice to the highly complementary nature of the low-energy experiments, as it only plots the sensitivity to one Standard Model parameter, $\sin^2\theta_W$. Since Qweak and APNC probe different quark combinations and E158 leptons, the sensitivities to physics beyond the SM is very different.

An explicit example is given by a recent review on constraints on new Z' bosons by Langacker [49]. Limits on the mass of new Z' bosons in several models and their mixing angle with the standard model Z are shown in his figure 1 and his table 4. The mixing angle constraints from 'global precision electroweak' fits are dominated by the LEP measurements at the Z pole, while the mass constraints come mainly from the 'low'-energy atomic PNC and electron scattering experiments. Those mass limits are at ≈ 600 GeV at 90% confidence, while direct searches at the Tevatron (assuming decays into standard model particles only) and at LEP 2 have recently reached better limits of ≈ 800 GeV. The mass reach of the low-energy measurements scales roughly with the square root of their accuracy, so improvements of 2 to 4 in accuracy would again provide useful information.

Constraints on parity-violating low-energy physics Recently a new scalar particle with mass on the order of a few MeV, along with a new exchange boson with slightly greater mass, has been invoked to explain a possible excess of 511 keV photons at the galactic centre. Atomic PNC places severe constraints on parity-violating interactions at low energy, so it could immediately be concluded that the new exchange boson must have purely vector, parity-conserving couplings [50]. This demonstrates the power of the atomic PNC measurements to constrain exotic physics which can suprisingly evade all other constraints.

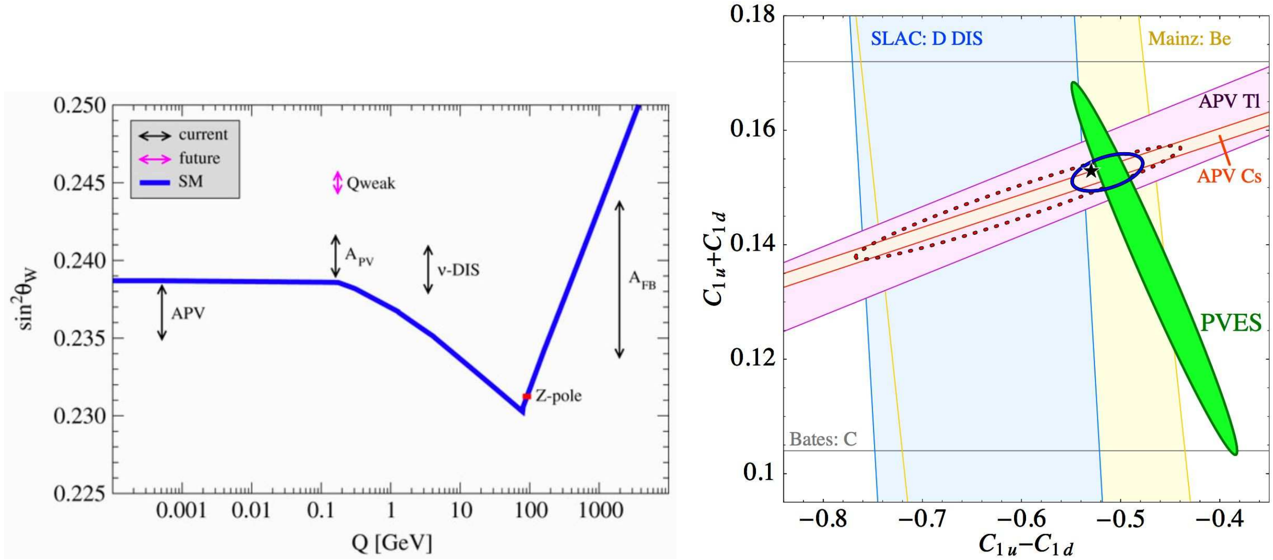


Figure 6: Left: Measurements of the weak neutral current strength as a function of momentum transfer. Despite their lower precision, the 'low'-energy experiments retain useful sensitivity to exchange of new bosons because they reside on the tail of the standard model Z resonance. This is Fig. 8 of Ref. [33]. Right: Constraints on weak quark couplings from electron scattering and atomic parity violation from Ref. [34], showing their complementarity.

2.6.1 Status of atomic PNC measurements

The weak interaction in atoms induces a mixing of states of different parity, observable through PNC measurements. Transitions that were forbidden due to selection rules become allowed through the presence of the weak interaction. The transition amplitudes are generally small and an interference method is commonly used to measure them. A typical observable has the form

$$|A_{PC} + A_{PNC}|^2 = |A_{PC}|^2 + 2Re(A_{PC}A^*_{PNC}) + |A_{PNC}|^2, \tag{1}$$

where A_{PC} and A_{PNC} represent the parity conserving and parity non-conserving amplitudes. The second term on the right side corresponds to the interference term and can be isolated because it changes sign under a parity transformation. The last term is usually negligible.

All recent and on-going experiments in atomic PNC rely on the large heavy nucleus (large Z) enhancement factor proposed by the Bouchiats. These experiments follow two main strategies (see recent review by M.-A. Bouchiat [35]). The first one is optical activity in an atomic vapor. This method has been applied to reach experimental precision of 2% in bismuth, 1.2% in lead, and 1.2% in thallium.

The second strategy measures the excitation rate of a highly forbidden transition. The electric dipole transition between the 6s and 7s levels in cesium becomes allowed through the weak interaction. Interference between this transition and the one induced by the Stark effect due to the presence of an static electric field generates a signal proportional to the weak charge. The best atomic PNC measurement to date uses this method to reach a precision of 0.35% [47, 48].

Other methods have been proposed and some work is already on the way. We have mentioned above Budker's work in optical transitions in ytterbium [40]. The Bouchiat group in Paris has

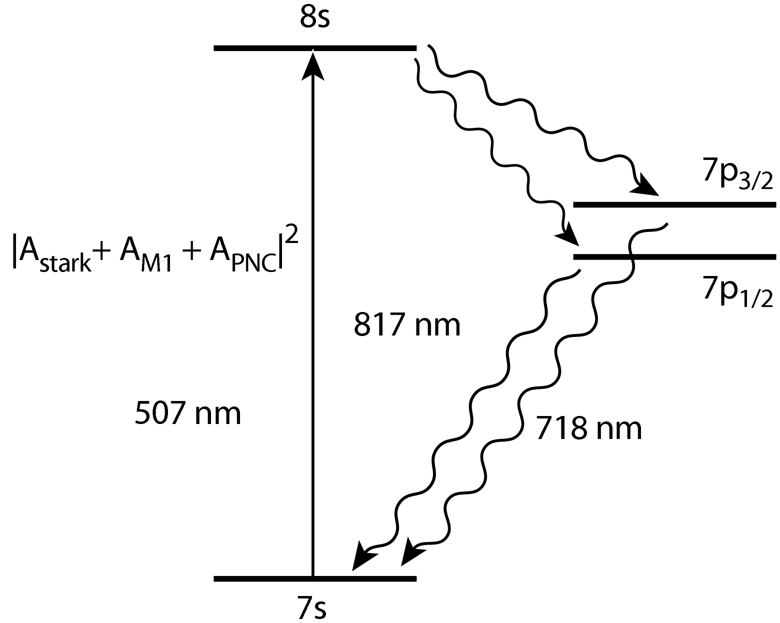


Figure 7: The most relevant atomic levels for Stark mixing experiments in francium.

worked on the highly forbidden $6s$ to $7s$ electric dipole transition in a cesium cell but detects the ocurrence of the transition using stimulated emission rather than fluorescence; this effort has ended after reaching 2.6% statistical accuracy [37]. The Bouchiat group has also considered more than one interesting method using laser-cooled atoms [36, 39]. There are experiments by the Fortson group in Seattle using a single barium ion and the KVI group using a single radium ion [41, 42]. The group at Legnaro and the current collaboration are working towards a PNC measurement using francium [45]. This list is not intended to encompass all the efforts, but represents some of the groups interested in PNC at present.

2.6.2 Considerations for a PNC experiment in francium

2.6.3 Atomic PNC in francium: further experimental techniques

So far, there has been no parity non-conservation measurement in neutral atoms performed utilizing the new technologies of laser cooling and trapping. In order to create a road-map for an experiment one could assume a transition rate measurement following closely the technique used by the Boulder group in cesium [47, 48]. We start with a Stark shift to induce a parity conserving amplitude between the $7s$ and $8s$ levels of francium and look how this electromagnetic term will interfere with the weak interaction amplitude giving rise to a left-right asymmetry with respect to the system of coordinates defined by the static electric field $\mathbf{E}$, static magnetic field $\mathbf{B}$, and the Poynting vector $\mathbf{S}$ of the excitation field, such that the observable is proportional to $\mathbf{B} \cdot (\mathbf{S} \times \mathbf{E})$.

Francium atoms would accumulate in a magneto-optic trap (MOT). Then, after further cooling to control their velocities, they would be transferred to another region where a dipole trap will keep them ready for the measurement, which would be performed by moving the dipole trap with the atoms into the mode of a high finesse interferometer tuned to the $7s$ to $8s$ transition in a region with a DC electric field present. If an atom gets excited it will decay via the $7p$ state, but could also be ionized. Optical pumping techniques allow one to recycle the atom that has performed the parity non-conserving transition many times enhancing the probability to detect the signature photon. Redundancy in the reversal of the coordinates would suppress systematic errors. There is a strong assumption implicit in this statement that needs to be thoroughly studied: the trap does not affect the measurement.

2.6.4 Ramping up to atomic PNC: 'Forbidden' M1 in atomic francium

The strength of the 'forbidden' M1 in atomic francium is sensitive to relativistic corrections to many-body perturbation theory. The percentage correction in the rubidium atom from this effect is predicted to be larger [28]. These effects are useful tests of the atomic theory needed to extract weak coupling coefficients from atomic parity-violation experiments.

Thus a logical precursor to any optical APNC experiment in francium is the spectroscopy of the $7s \rightarrow 8s$ transition (see Fig. 7). Spectroscopy on this line can follow a path of increasingly difficult measurements that will help to hone the experimental skills, but starts out with a level of difficulty comparable to the spectroscopic work done at Stony Brook. Initially, the line needs to be found and observed, which is best done by driving the Stark-induced amplitude in a strong electric field (several kV/cm) in a configuration of parallel external field and laser polarization, where the large scalar transition polarizability α provides a (relatively) strong signal. Proton beam currents below 1 μA should suffice. With crossed field and polarization, the hundred times weaker transitions characterized by the vector transition polarizability β is then in reach and the ratio α/β can be determined. Observing the E1-M1 interference by flipping fields similar to the APNC procedure, produces intensity modulation at the 1 % level, about a hundred times larger than the modulation expected in APNC. This step represents a milestone. It requires the implementation of reversible, high-quality fields in the trap environment, and the quality of the signal will give crucial information about the prospects of observing a 10^{-4} modulation to better than 1 % — the eventual goal in APNC.

2.6.5 Signal-to-noise ratio for atomic PNC

To estimate the requirements for a parity non-conservation measurement in francium it is good to take the Boulder Cs experiment as a guide [47, 48]. The most important quantity to estimate is the signal-to-noise ratio since that will determine many of the requirements of the experiment.

The approach of Stark mixing works as an amplifier in the full sense of the word, it enlarges the signal, but it also brings noise. The Stark-induced part of the signal in photons per second is given in equation 2, this signal will contribute the shot noise to the measurement,

$$S_{\text{stark}} = \frac{16\pi^3}{3h\epsilon_o\lambda^3} E^2\beta^2 I_o N. \tag{2}$$

The parity non-conservation signal in photons per second is

$$S_{\text{pnc}} = \frac{16\pi^3}{3h\epsilon_o\lambda^3} 2E\beta \, \text{Im}(E_{\text{pnc}}) I_o N, \tag{3}$$

where β is the vector Stark polarizability, E is the dc electric field used for the Stark mixing interference, N the number of atoms in the interaction volume, λ the wavelength of the transition,

$\mathrm{Im}(E_{\mathrm{pnc}})$ is the parity non-conservation amplitude expressed as an equivalent electric field, and I_o the normalized (to atomic saturation) intensity of the excitation source. Assuming only shot noise as the dominant source of noise, the signal to noise ratio achieved in one second is:

$$\frac{S_{\mathrm{pnc}}}{N_{\mathrm{noise}}} = 2\Big(\frac{16\pi^3}{3h\epsilon_o\lambda^3}\Big)^{1/2}\mathrm{Im}(E_{\mathrm{pnc}})\sqrt{I_o N}. \qquad (4)$$

The calculated value from Dzuba *et al.* [51] for $\mathrm{Im}(E_{\mathrm{pnc}})$ of 1.5×10^{-10} in atomic units is eighteen times larger than in cesium.

A serious complication for a trap-based experiment is photoionization in the excited state by the intense 507 nm radiation, which was already discussed in [46]. At intensities of 800 kW/cm^2 as used by Wood et al. [47, 48], the probability for photoionization per excitation was 10 %. In a beam experiment, where each atom is used only once, this is not particularly concerning. In a trap scenario, each atoms must be re-used over a time span of up to seconds, and hence, the photoionization rate must be brought down to a compatible level (accidentally, in Fr the situation is worse, as the 507 nm light can ionize into the continuum from both the $8s$ and the $7p_{3/2}$ states). This can be remedied by reducing the light intensity by a factor of 300, which will bring the photoionization rate down to about 1 Hz, yielding a 7s-8s excitation rate of 30 Hz per atom. For guidance, we can refer to the Cs experiment which had a $6s-7s$ excitation rate of 10^{10} Hz and find that 3×10^8 trapped atoms lead to the same signal, but the fluorescence modulation upon parity reversals is 2×10^{-4}, about an order of magnitude larger. The signal-to-noise with is then

$$S/N = 2\times10^{-4}\sqrt{30tN},$$

where t is the observation time in seconds and N the number of atoms in the trap. Or, the time to obtain a S/N with a certain excitation rate R and N atoms in the trap and an asymmetry A is

$$t = \frac{(S/N)^2}{A^2RN}.$$

Based on these purely statistical considerations, a 1.0 % APNC measurement requires about 2.5 hours using 10^6 trapped atoms; ten times more atoms would allow a 0.1 % test in 25 hours. It must be stressed that *much* more time has to be spent to deal with systematic effects. As mentioned above for the anapole moment, APNC development work can start with the expected yields in the present target stations. The new target stations would be needed for the full program.

2.6.6 Neutron radius question

Since the weak charge in atoms stems mostly from the neutrons, there is some dependence on the neutron distribution in the nucleus, a quantity with few reliable experimental probes. The neutron radius measurement with parity-violating electron scattering at Jefferson Lab ('PRex' [52]) would result in an uncertainty on the weak charge in ^{212}Fr of 0.2% [53]. Isotopic ratios would need a next generation neutron radius experiment [53].

Work at Stony Brook investigated the hyperfine anomaly in $^{208-212}$Fr [32]. Different atomic wavefunctions have different overlap with the nucleus, so a changing spatial distribution of nuclear magnetism will change the relative hyperfine splittings. For the odd-neutron isotopes, this effect is sensitive to the spatial wavefunction of the valence neutron, in a manner similar to magnetic multipoles in electron scattering. This effect will be measured in the chain of francium isotopes in an approved experiment, S1010.

2.7 Electron EDM in francium: physics motivation

The physics motivation is largely shared with radon EDM, in the sense of searching for new sources of time reversal violation. Electron EDM's have different sensitivity to the new physics sources, as we showed in Table 1 and Fig. 1.

2.7.1 Electron EDM in francium: experimental organization and techniques

A group at Lawrence Berkeley Lab has published a prototype experiment to measure the electron EDM with a cesium atomic fountain [54] including characterization of systematic errors and an outline of upgrades needed to make it competitive. Francium can be trapped in similar numbers to stable cesium, and the higher-Z atom would enhance sensitivity by more than an order of magnitude. H. Gould submitted a letter-of-intent for a francium EDM experiment at TRIUMF in the late 90's.

A collaboration is now forming, following a 'medium-energy' physics plan (http://homepage.mac.com/gould137). There are presently 5 investigators refining potential systematic errors in various components via hardware and calculations. After it is determined what designs can work, then the apparatus can be built. It is probably a 5-year effort to make measurements in cesium. It would then be a natural extension for such a collaboration to do an experiment in francium, where an electron EDM produces an atomic EDM an order of magnitude larger [55]. Canadian university and lab collaborators would be welcomed and essential.

Electron EDM projected sensitivity Ref. [54] demonstrates techniques that may be used to improve the electron EDM sensitivity by two orders of magnitude, assuming 2×10^{14} detected atoms. An additional order of magnitude more sensitivity could then be gained by doing an experiment with the same precision using the francium atom. This is similar to the number of atoms to be detected in the atomic PNC measurements.

3 Summaries

3.1 Beamtime/Timeline summary

The RadonEDM experiment proposal assumed 10μA of proton beam on a relatively thick target (see details below) for 100 days of beamtime, which would best be done in a dedicated actinide target station in the new system. Development work would be done at lower current and for shorter periods, so could commence with the present target stations. A method is outlined in Section 2.4.3 that could take advantage of higher count rates.

The anapole moments of francium can be measured at yields of 10^8/sec or better, requiring about 1μA of proton beam on thin targets for the best cases. We showed in Section 2.5.2 the S1065 proposal timeline, requiring 40 days of development work over 3 years that could be done in the existing stations. Actual observation of the parity-violating anapole signal is expected to take 50 days over 2 years, and the measurement would take 75 days over 3 years; these beamtimes would be best done in a dedicated actinide target station in the new stations.

Atomic PNC measurements are expected to require 10^8/sec yields, which is still possible with 1μA of beam on a thick target for the most abundant isotopes. Anticipated timelines might be similar to the anapole experiment. Beams of 10μA would enable a greater number of isotopes to be measured to extend the neutron number reach, helping with the neutron radius phenomenology and the new physics.

The total number of "production-mode" days for these programs is therefore in excess of 350, not including the possibility of extra time needed for further systematic error elimination, and not including any estimate yet for a francium EDM experiment nor for a very high-current radon EDM experiment.

3.2 Physics summary

This physics program would extend TRIUMF's long tradition in precision measurement into the neutral current sector. Searches for CP violation using EDM's in atoms and eventually the electron would complement possible neutron EDM's and participation in the hunt for neutrino mass matrix phases to make a comprehensive search for the source of the baryon asymmetry.

The radon experiments combine laser-driven spin exchange optical pumping with state-of-the art gamma ray spectroscopy at extremely high count rates along with detailed nuclear structure interpretation. The francium experiments combine efficient laser trapping and cooling with extremely precise new methods.

3.3 What is required: a dedicated target station

TRIUMF currently holds several of the best experiments in the charged current sector. The success stories with the best physics reach— precision μ decay and $\pi \to e\nu$ — have had a dedicated beamline available for their entire duration.

The outlined programs in precision measurement in atomic systems will require similarly exacting eliminating of systematic errors. No matter what yields are achieved, the relentless patience needed to hunt down and eliminate systematic errors will always require on-tap availability of the isotopes as simple to the experimenters as heating an alkali oven.

The TRIUMF neutral atom trap project, for example, is well accustomed to making reliable, turn-key collection trap technology so that efforts can go into experiments with the small amounts of ISAC beamtime available. We note that the development of this reliable front end was done initially with large amounts of beamtime, with dedicated running periods available twice a year or more. It is possible in the β decay experiments to determine systematic errors off-line from precision analyses of the redundantly measured kinematic observables. The neutral current experiments are much more exacting and complex and could not be completed in such a mode.

Startup of these experiments can be done with finite amounts of beamtime in coexistence with the rest of the ISAC program in the existing target stations.

But to fully implement these experiments and achieve their enormous promise, it is clear that a dedicated target station for 500 MeV protons on actinide targets will be needed for several years. We believe we have presented a compelling case for this.

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