The EDM of an atom is a permanent separation of charge along the axis of the total angular momentum: \( \langle \vec{d} \rangle = d\langle \vec{J} \rangle \), that is the atom is permanently electrically polarized due to forces on the atomic electrons. Measurement of an atomic EDM is a direct signal of time-reversal (T) and parity (P) violation and, due to the CPT theorem (C refers to charge-conjugation symmetry), directly probes CP violation. For example in a diamagnetic atom, electron spins pair, and thus there are two leading contributions to \( \vec{d} \): the dipole charge distribution within the nucleus and a nuclear-spin-dependent electron-nuclear interaction arising from tensor currents. In addition, for nuclear spin greater than 1/2, higher P-odd/T-odd moments of the nucleus, such as a magnetic-quadrupole moment induce an atomic EDM.

In the Standard Model, complex phases that induce EDMs have two sources: the strong-interaction parameter \( \theta_{QCD} \), and complex weak-interaction amplitudes that mix heavy and light quark flavors as described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The dimensionless parameter \( \theta_{QCD} \) is apparently very small, or its effects are cancelled by other non-Standard Model interactions in multiple systems (i.e. the neutron and \(^{199}\text{Hg}\)). The CKM matrix parameterizes the amplitudes for weak interactions, and includes a single complex phase. Mixing of the heavier quark generations can induce an EDM through this phase; however cancellations of leading order contributions mean that EDMs arise at the three- and four-loop level leading to CKM EDMs smaller, by many orders of magnitude, than the current experimental limits in any system. For the electron, \( d_e^{SM} \approx 10^{-38} \text{ cm} \); for the neutron \( d_n^{SM} \approx 10^{-32} \text{ cm} \). It has also become appreciated that our universe, made up of more matter than antimatter, which may have its origin in baryogenesis. Sakharov recognized that baryogenesis has three required elements: 1) baryon-number violation; 2) CP violation; 3) non-equilibrium expansion [1]. For example, proton or quark couplings to leptons, e.g. proton decay, are predicted by grand-unified theories. CP violation from the CKM matrix would produce far too small a baryon asymmetry and it is therefore necessary to find CP violation in physics beyond the Standard Model that would, in turn, produce EDMs much larger than Standard-Model EDMs [2–4]. Most significant extensions of the Standard Model introduce additional phases that could produce the baryon asymmetry and could lead to an EDM many orders of magnitude larger that the CKM values [5]. 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 [6].

A large number of systems have been investigated in the search for an EDM including the neutron, where it all started, diamagnetic and paramagnetic atoms and molecules and elementary particles such as the muon. So far, all experiments are consistent with zero EDM, with the neutron and \(^{199}\text{Hg}\) setting the most meaningful limits on hadronic systems and thus constraining \( \theta_{QCD} \). While ambitious efforts are underway to extend sensitivity to the neutron EDM by one to two orders of magnitude, the \(^{199}\text{Hg}\) effort is nearing saturation. It is thus important to look to other systems with advantages and promise to extend the sensitivity to CP violation. One such system is a heavy atom of a rare isotope, for which the nucleus has octupole strength or permanent deformation. In such a system, the dipole charge distribution in the nucleus, characterized by the Schiff moment, may be significantly enhanced compared to \(^{199}\text{Hg}\). This enhancement is due to the parity-odd moment arising from quadrupole-octupole interference, and the enhanced E1 polarizability effected by closely spaced levels of the same \( J \) and opposite parity. The strongest octupole correlations occur near \( A = 88 \) and \( N = 134 \), and isotopes \(^{221/223}\text{Rn} \) (\( N = 135-137 \)) and \(^{228}\text{Ra} \) (\( Z = 88 \)) are promising for both practical experimental reasons and as candidates for octupole-enhanced Schiff moments. Enhancements of the atomic EDM by a factor of 100 or more compared to \(^{199}\text{Hg}\) have been predicted by models using Skyrme-Hartree-Fock for \(^{222}\text{Ra} \) [7] and Woods-Saxon and Nilsson potentials in the case of \(^{223}\text{Rn} \) [9, 10]; however the uncertainties on the size of possible enhancements are quite large, in part due to uncertainty in the \(^{199}\text{Hg}\) Schiff moment, and, in the case of \(^{221/223}\text{Rn} \) isotopes, the absence of nuclear structure data.

We are focusing our efforts on potential EDM measurements with radon isotopes for several reasons. Most importantly, precision measurements with polarized noble gases in cells have demonstrated the feasibility of an EDM experiment. For \(^{129}\text{Xe} \), we found \( D = 0.7 \pm 3.4 \times 10^{-27} \text{ cm} \) [11], and a number of techniques have been developed including spin-exchange-optical-pumping (SEOP) using rubidium, construction of EDM cells and wall coatings that reduce wall interactions, in particular for spin greater than 1/2. The half-lives of \(^{221/223}\text{Rn} \) are of order 20-30
minutes, so an on-line experiment at an isotope production facility is essential. We have proposed the RadonEDM experiment (S-929) at TRIUMF’s ISAC, on-line isotope separator-facility, which has been approved with high priority. Our experimental program includes development of on-line techniques including collection of rare-gas isotopes and transfer to a cell, optical pumping and techniques for detection of spin precession based on gamma-ray anisotropy, beta asymmetry and laser techniques.

For polarized rare-isotope nuclei, the excited states of the daughter nucleus populated by beta decay are generally aligned, that is, there is a distribution of magnetic sublevels that can lead to an angular distribution with a \(P_2(\cos \theta)\) distribution of gamma-ray emission. We have used gamma anisotropies to detect nuclear polarization in \(^{209}\)Rn [12], and in earlier work, anisotropies were measured for \(^{223}\)Rn as well as \(^{209}\)Rn [13]. At TRIUMF, the large-coverage HPGe gamma-detector array TIGRESS or the new GRIFFIN array may be used, however the limited gamma-ray count rate in HPGe would limit the statistical precision to less than would be possible with anticipated radon-isotope production rates. One alternative that would not be count-rate limited would be detection of the beta asymmetry with current-mode detectors, and investigation of candidate detector technologies is underway. Both the gamma-anisotropy and beta-asymmetry detection techniques have analyzing power (the maximum modulation of the signal for full polarization) expected to be limited to 0.1-0.2. The sensitivity of the EDM measurement is proportional to analyzing power, thus laser-based techniques are also under investigation. Direct polarimetry from the ground state of atomic radon requires 178 nm light, in the extreme UV. While these wavelengths are in principle accessible with frequency-summing techniques in crystals, two-photon magnetometry is a promising technique. We are currently developing two-photon magnetometry for \(^{129}\)Xe that may be also useful as a co-magnetometer in neutron-EDM measurements. In this scenario, laser light produced by quadrupling 1024 nm light (Ti:Sapphire or fiber laser) is circularly polarized so that two photons are only absorbed in \(\Delta m_F = 2\) transitions. By choosing a transition from the \(F = 1/2, L = 0\) ground state to an \(F = 3/2, L = 2\) excited state, only the \(m_F = -1/2\) ground state will be depopulated for absorption of two \(\sigma^+\) photons. The analyzing power for two-photon transitions can be close to unity as long as the density is sufficient. The two-photon technique is also promising for the RadonEDM project.

It is essential to establish the Schiff moment enhancement through the combination of experimental study of the nuclear structure of \(^{221/223}\)Rn and theory progress. We currently have a multiple-lab program to study the structure of these isotopes. At TRIUMF, spallation on uranium is now producing yields of radon, francium and potentially astatine isotopes. The goal is to use the \(8\pi\) detector to measure the angular distributions of beta-gamma coincidences for excited-state transitions populated by \(^{221/223}\)Rn at decay and to assign spins and parities. At NSCL (Michigan State), an approved experiment (Experiment 10017) will identify gamma rays from \(^{221/223}\)Rn excited states populated in fragmentation of a \(^{238}\)U beam. At ISOLDE (CERN), a program of study of octupole collectivity of isotopes including radon as well as radium isotopes using coulomb excitation is underway (IS475).

EDM measurements in radon isotopes will ultimately be limited by production rates. Fragmentation can produce useful quantities of these isotopes for development, and the beam-dump at FRIB may be a source for harvesting large quantities for an EDM measurement. Isotope-separator techniques, such as those used at TRIUMF and ISOLDE, have direct yields that are much higher, and would be a great advantage for the future of this program.