Search for an Electric Dipole Moment on the Deuteron

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Sensitive searches for an electric dipole moment (EDM) on subatomic particles are an excellent probe of physics beyond the Standard Model [1]. A particle with a static EDM aligned along its spin direction violates time reversal (*T*) symmetry. If this symmetry held, reversing the direction of time would flip the spin direction but not the electric dipole moment, thus changing the relative orientation of these two quantities and demonstrating in a proof by contradiction that the EDM could not exist. Under the *CPT* theorem, such a violation would also imply *CP* violation, an effect that has been known for some time in the decay of the K^0 meson [2]. This *CP* violation has been explained by a phase angle that appears in the interaction of quarks with W bosons. However, this phase cancels from interactions that would lead to an electric dipole moment, thus Standard Model predictions are many orders of magnitude below current experimental limits. Similarly, phase angles that appear within QCD are known to be small. Additional sources of *CP* violation are thought to exist because there is as yet no explanation of such puzzles as the particle-antiparticle asymmetry of the universe or particle masses that fall many orders of magnitude below the grand unification mass. An attractive explanation is a supersymmetry (SUSY) connecting bosons and fermions [3]. In addition to predicting a mirror world of heavier partners to the known fundamental particles, this theory predicts EDMs within the reach of present experiments. It is not known whether such EDMs would be most accessible on leptons, baryons, or even in complex systems bound together by the strong force. Thus multiple searches would be in order.

In principle, a search for an EDM would involve placing a candidate particle in a strong electric field and watching the spin precess about the electric field direction. Such searches work well on neutral particles. The present limit for the neutron is 6.3×10^{-26} e·cm [4] obtained with ultracold neutrons trapped in a containment cell with an applied electric field. A proposal under development at Los Alamos would capture the neutrons in a superfluid ^{4}He bath. Experiments on neutral atoms have pushed to a lower limit of 2.1×10^{-28} e·cm [5], but screening by the atomic electrons increases substantially the limit on the nuclear EDM itself (factor ~500).

EDM searches on *charged* particles would be facilitated if there were a way to store them for long periods in a large electric field. It has been noted that an EDM would have tilted the plane of precession of the muon in the recently reported "g−2" result [6] that used a storage ring to track the precession of the muon spin in a precisely known magnetic field. This additional EDM precession is due to the motional electric field from the ring magnets in the rest frame of the muon beam. This effect can be enhanced (~10^7) by canceling the precession from the anomalous muon moment relative to its momentum in the ring. This requires an external radial electric field in the plane of the storage ring equal to $E=aBc\beta/(1-(1+a)\beta)$ where "a" is the particle's anomalous magnetic moment. Because large electric fields are hard to maintain, this cancellation favors experiments that examine charged particles with small anomalous moments. The muon is thus a good candidate, but so is the deuteron since an experiment can easily be run with $\beta<1$. The spin direction of the muon in the "g−2" experiment was tracked using its weak decay, which favors emission of the electron along the muon spin direction. A letter of intent has been submitted to the Program Committee for the 50-GeV J-PARC facility in Japan to pursue such a measurement on the muon. Because the deuteron is stable, it can be held in a storage ring for a much longer period of time. A measurement of its spin direction requires that a target be inserted into the ring to scatter the deuterons under the influence of the strong force. The EDM Collaboration has been formed to study the feasibility of these experiments. Because of the necessity to have electric and magnetic fields together, new storage rings would have to be constructed to pursue a search for an EDM in this way.

The short-term IUCF contribution to this effort would be in the areas of polarimeter design and polarimeter-ring interactions for the deuteron experiment. The energy for such an experiment has not been decided, but would likely be within the range between 40 and 1000 MeV. While costs would favor building a ring with a smaller energy, polarimeter efficiency and the handling of some systematic error problems would improve as the energy goes up. The polarized deuteron beam would be injected into the ring with its spin aligned along the beam momentum direction. The EDM signal would consist of a precession of the spin out of the plane of the storage ring. Since any signal would be small, the vertical polarization component would grow linearly with time and be detected by a left-right asymmetry in a polarimeter that sampled the circulating beam.

In order to push the statistical precision of this experiment, it is important to devise polarimeters that are both efficient and highly spin sensitive. In this energy range, the most promising and easy to use targets appear to be either hydrogen or carbon. In either case, targets inserted into a typical storage ring tend to remove many particles through multiple Coulomb scattering while only a small fraction are deflected through angles large enough to be sensitive to the spin-dependent parts of the strong interaction. At present, we are pursuing a suggestion that the limiting aperture in the ring be a carbon polarimeter target, and that the target that intercepts the beam have as its only requirement that it multiple scatter particles into the first target. In this way the losses from the ring are actually used as part of the experiment. In particular, this allows the polarimeter target to be thick, thus increasing by a large factor the efficiency of obtaining polarization information from the particles circulating in the ring. Based on the experience with POMME, the efficiency can be as large as several percent [7]. Under these conditions, it is possible to statistically push the EDM sensitivity limit to about 10^{-27} e·cm (corresponding to an EDM precession rate of 2.5×10^{-7} rad/s) with a few months of data collection time.

It is possible to reach such sensitivities only if the systematic errors are controlled to the same level of precision. One subtle source of error arises if the in-plane precession of the beam is not cancelled by the imposed electric field. Then a left-right asymmetry can arise from a t_{21} polarization moment present in the beam due to a small spin alignment error and any tensor polarization component for the deuteron that is left from the polarized ion source. However, if one allows the cancellation error to be large so that the beam polarization in fact *precesses* through a large fraction of a complete turn relative to the momentum during the store in the ring, then a Fourier analysis of polarization measured as a function of time will sort out the EDM vector polarization component from the tensor component. In this concept of the experiment, the EDM signal must have a strength that is inversely proportional to the in-plane revolution frequency. This requirement separates the EDM signal from a variety of other errors, such as contamination of the signal with the vertical asymmetry through a rotational misalignment of the polarimeter detectors. The measurement of a precession curve imposes additional constraints of proper phase and period on the signal that are not available when only the growth of the left-right asymmetry is considered. As is true for many polarization experiments, the direction of beam polarization will be reversed and the results combined as a way to control systematic geometry errors.

Other systematic errors arise from a consideration of the dynamics of the ring as it acts on the deuteron spin. One important requirement is the cancellation of any false signal that arises because the electric field is not perfectly perpendicular to the plane of the circulating beam. This induces a motional radial magnetic field that can also precess the deuteron beam into the vertical direction over time. It has been suggested that this may be cancelled by running the beam in both directions around the ring, which requires that the magnetic field be periodically reversed. Other effects from localized magnetic field imperfections produce errors that are oscillatory around the ring. Multiple polarimeters can address this issue. It has also been suggested that the Coulomb scattering target that intercepts the beam could be a residual gas that floods the entire ring, thus generating ring "losses" into the polarimeter target from every point around the circumference. While such a gas might be beneficial in quenching avalanches that would limit the strength of the electric field, it might also produce leakage currents on the electric field plates that would load the power supplies in ways that are proportional to beam current and thus time dependent. These and several other contributions to the limit of the experiment are still under active consideration.

In FY2004, the EDM Collaboration expects to begin the process of assembling detailed arguments for a funding proposal. In the process, many sources of systematic error must be quantitatively estimated and carefully examined to determined at what level they would limit the sensitivity of this search.

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