Neutron Electric Dipole Moment measurements at the ILL

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Abstract. The origin of the CP violation which created the matter in the universe is one of the enduring mysteries of fundamental physics. Particle electric dipole moments provide a sensitive probe of CP violation from new physics. The article describes past and future work being done at the ILL in Grenoble to search for an electric dipole moment of the neutron.

1. Introduction
Most physicists consider the Standard Model to be only a low-energy effective theory (although an extremely successful one) because of its ad hoc structure and many unexplained parameters, but we have at least one concrete piece of experimental evidence that the Standard Model cannot be the final theory of fundamental interactions. As first pointed out by Sakharov [1], the baryon asymmetry of the universe (BAU) implies CP and T violating interactions in the early universe, however the CP violation observed in the Standard Model is too small by many orders of magnitude to explain the observed BAU [2]. Thus the search is on for laws of physics from beyond the Standard Model which could supply the needed CP violation.

Particle electric dipole moments (EDMs), which are a CP and T odd observable, are a particularly attractive place to search for such new physics. The Standard Model contributions to particle EDMs (which are a background when searching for the physics which leads to the BAU) are zero at one-loop, cancel at the two-loop level, and partially cancel at three loops, such that the resulting EDMs are far below existing limits [3]. New physics, however, tends to predict much higher EDMs because these cancellations do not occur. As one example, supersymmetric theories naively predict a neutron EDM (nEDM) of $\sim 10^{-24} \text{ e·cm}$ [4], to be compared to Standard Model contribution which is $\sim 7$ orders of magnitude smaller. Even within the Standard Model, there is no known a priori reason why QCD should not contain a CP violating phase $\theta_S$. The failure to observe an nEDM discussed below, however, constrains $\theta_S$ to be less than $\sim 10^{-10}$, demonstrating the power of EDM measurements to probe new physics and giving rise to the “strong CP problem” [5] which led to the proposed existence of the axion. The other advantage of EDMs is that the experiments, while extremely technically challenging, are of a modest scale that can be performed by a small collaboration for a tiny fraction of the cost of most modern particle physics experiments. In this report I will concentrate on measurements of the nEDM our group has made at the ILL, although measurements of the electron EDM and of atomic EDMs (and of other particles) are just as critical because the relative values of the EDMs produced in different particles by new physics are completely model dependent, and therefore understanding any new physics observed requires measurements of the EDMS of as wide a range of particles (or systems) as possible.
2. The Neutron Electric Dipole Moment

The basic ideas for nEDM measurements were developed in the 1950’s by Norman Ramsey using the same Ramsey separated oscillator technique, which he originally developed for atomic clocks [6]. The technique relies on measuring the Larmor precession frequency of neutrons in a constant, applied magnetic field, and then looking to see if the frequency shifts when a large electric field is applied due to the additional precession, which would result from the interaction of an nEDM with the applied electric field. Modern experiments all use ultra-cold neutrons (UCN), which are neutrons of such low energy that their wavelengths are long compared to inter-atomic spacings. When such neutrons collide with a wall they see an average potential (called the Fermi potential) arising from the coherent sum from many atoms, and if that potential is repulsive neutrons with a kinetic energy less than the potential can be bottled. This allows the Larmor frequency to be measured over hundreds of seconds, greatly increasing the precision of the measurement (provided that the bottle is clean enough that the neutrons are not absorbed or de-polarized, and that no stray magnetic fields interfere with the measurement).

The list of things which all nEDM experiments must supply follows from this description. First, there must be as intense a source of UCN as possible. There must be a way to polarize the neutrons, and a volume in which they can be stored for measuring the Ramsey resonance. The surfaces of this volume must be made of one of a short list of materials which have a large Fermi potential (Be or BeO, diamond-like carbon, etc.), and they must be kept clean to prevent neutron losses. The volume must be immersed in a controlled, uniform magnetic field and screened from other external fields and their fluctuations, and it must be possible to apply (obviously) the largest possible electric field. There must also be a way to monitor the applied magnetic field and any fluctuating stray fields. One measurement cycle consists looking for a difference in the number neutrons in each spin state at the end of two Ramsey cycles with the electric field parallel and anti-parallel to the applied magnetic field. The statistical uncertainty $\sigma$ in such a measurement of the nEDM $d_n$ is just given by:

$$\sigma(d_n) = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

where $\alpha$ is the polarization product (the product of the polarization of the neutrons and the analyzing power of the neutron detection), $E$ is the applied electric field, $T$ is the time the neutrons are stored between the two spin-flip pulses, and $N$ is the number of neutrons detected. The only way to make a more sensitive nEDM experiment is therefore to increase one or more of the four numbers in the denominator (noting that $\alpha$ cannot be bigger than 1, which experiments are already close to, and $T$ has a fundamental limit imposed by the neutron lifetime which experiments have not yet reached). In addition to this statistical sensitivity is a long list of potential systematic uncertainties, most of which are related either to non-uniform magnetic fields (either in space or time) or to leakage currents from the high voltage. Experiments must be carefully designed to make sure that these systematics are small compared to the statistical sensitivity and to provide cross-checks to demonstrate this.

2.1. The RAL/Sussex room temperature nEDM experiment.

The most sensitive measurements to date of the nEDM come from the RAL/Sussex room temperature nEDM experiment [7]. The experiment’s source of UCN is the neutron turbine at the ILL laboratory in Grenoble. In this ingenious device cold neutrons from a liquid-D$_2$ moderator located near the reactor’s core are guided away from the reactor and collided with a counter-rotating turbine blade, which kills their velocity and produces UCN. These UCN are then guided into the nEDM apparatus, which is shown in figure 1. The neutrons first pass through a magnetized iron foil, which transmits only one polarization component of the neutrons. The neutrons fill the storage volume, which is then closed with a mechanical door. The storage volume is contained with HV electrodes which produce an electric field of ~10 kV/cm, and is surrounded by coils to produce a uniform magnetic field which is vertical in the figure. The Ramsey cycle consists of two pulses separated by 130 s, after which the
The apparatus is surrounded by 4-layers of \( \mu \)-metal magnetic shielding, however external magnetic field fluctuations still cause the neutron precession frequency to jump around in an unpredictable fashion. For this reason polarized Hg vapour is introduced into the same volume with the neutrons, and its precession in the magnetic field is monitored by observing the transmission of uv light from a Hg lamp. By looking at the ratio of the neutron to Hg precession frequencies magnetic field fluctuations can be cancelled to the level of a few nG, essentially removing magnetic field fluctuations as a source of systematic uncertainty. More than ten years of measurements with this apparatus failed to show evidence for a non-zero nEDM, resulting in the limit that \( d_n < 2.9 \times 10^{-26} \) e·cm (90% c.l.). At this point the experiment became limited by a subtle systematic in the Hg co-magnetometer system (and by statistics), and it became necessary to move to a new method.

2.2. The RAL/Sussex/Kure/Oxford/ILL Cryo-nEDM Experiment

Obtaining better statistics required moving beyond the neutron turbine as a source of UCN, which in turn resulted in a radical redesign of the apparatus. The new source of UCN is based on the observation by Golub and Pendlebury [8] that 8.9Å neutrons can downscatter to UCN in superfluid LHe, in principle yielding UCN densities far higher than those available from the neutron turbine. This led to the design shown in figure 2. Polarized 8.9Å neutrons from the ILL reactor enter the apparatus through the thin blue source tube at the far right in the figure. The source tube and all the guides and other volumes connected to it are filled with about 250 liters of superfluid LHe at ~0.5 K supplied by cryogenic apparatus developed at Kure University by our collaborator Hajime Yoshiki (the two large vertical cylinders in the figure, shown as solid but in fact filled with apparatus). UCN created by downscattering build up inside the source tube until a plug valve at the end is opened, at which point they fall down the curved neutron guide at the end of the source tube and travel to the

![Diagram of the RAL/Sussex room temperature nEDM experiment described in text.](image-url)
Ramsey cell, which is in the current design is actually two cells, one of which has high voltage and contains the neutrons on which the nEDM measurements are made. The other cell has no HV and acts as a magnetometer. Once the Ramsey cycle has been completed the neutrons travel back down the guide, in which a trap door is opened to allow them to fall into a tube below the guide which ends in a set of neutron detectors (normal solid state detectors coated with a thin layer containing lithium, where the neutrons undergo $^6\text{Li} + n \rightarrow t + \alpha$ and the resulting heavy charged particles are detected). The Ramsey cells are surrounded with a set of superconducting Pb shields and $\mu$-metal shields to screen external B fields.

In principle this design should allow all four of the parameters mentioned above which determine the sensitivity of the nEDM to be improved. The neutrons are polarized to $>95\%$ before they are downscattered, and the ultra-clean high vacuum environment required by the cryogenic system should mean that they will retain that polarization while they repeatedly bounce off of the walls of the apparatus better than in the existing experiment. The same ultra-clean environment should also produce better neutron storage lifetimes than in the existing experiment. LHe is actually a better insulator than vacuum, so we believe we will be able to maintain higher E fields in the new apparatus, and the downscattering mechanism should produce UCN densities more than 2 orders of magnitude higher than in the existing experiment. These factors combined mean that in the experiment’s current position at the end of the H53 beamline at the ILL it should achieve statistical precision in a single 50-day reactor cycle, which is about an order of magnitude more sensitive than the existing limit quoted above. The plan is to run the experiment in this location until a long shutdown of the reactor in 2012, at which time we would move it to a new location being prepared by the ILL inside the reactor containment vessel where we would have $\sim$6x the cold neutron flux. At the same time we would make various improvements such as going to a 4-cell design for the Ramsey cell, allowing both signs of E field to be measured simultaneously. In that location we would have statistical sensitivity two orders of magnitude below the existing limit in a run lasting a couple of years.

Of course the statistical sensitivity is meaningless if there are systematic effects which are larger, so great attention has been paid in the construction of the apparatus to minimize systematics which would mimic an nEDM. One challenge is that the co-extensive Hg magnetometer of the room temperature experiment will not work at LHe temperatures (although note that that experiment had become limited by a systematic in the Hg magnetometry, so we need to move beyond that technique in any case). The advantage of the co-magnetometer was that it sampled the same volume as the neutrons, so fairly large field fluctuations could be corrected for and were therefore tolerated. In the new experiment the approach will be to greatly improve the magnetic shielding to reduce the fluctuations until they do not affect the measurement, and to confirm this by measuring the fluctuations of the field at selected points using SQUID magnetometers developed at Oxford. This will be checked by the cell with no HV, where the neutrons will be affected by any fluctuations but see no HV and thus have no effect due to an nEDM.

Construction of the apparatus has now been completed, and all parts of it have been run (although not all at the same time!). Firstly, we have verified that we can produce 250 liters of LHe at $\sim$0.5K and produce UCN within it. We have quantitatively confirmed the mechanism for the production of UCN [9]. We have verified that neutrons retain their polarization during the downscattering process, and that polarization storage times are acceptable. We are now beginning to run the entire apparatus, and should begin making first nEDM measurements very soon.
3. Conclusions
Finding the CP violation underlying the observed BAU remains one of the most tantalizing questions in fundamental physics. Particle EDMs offer one of the most sensitive probes of the new physics required to produce this CP violation, and should be pursued until insurmountable experimental limits are reached (and we are nowhere near that stage for any of the main targets). The nEDM experiments pursued by our groups at the ILL have produced the world’s most sensitive measurement to date of the nEDM, and our new experiment should extend that sensitivity by about two orders of magnitude over the next decade. Similar improvements are also pending in the electron and atomic EDMs, which will test a much wider range of models and offer the possibility of getting a better handle on any new physics by comparing EDMs from different particles. This is an exciting area of experimental physics where progress should be rapid – watch this space!

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