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CryoEDM: a cryogenic experiment to measure the neutron Electric Dipole Moment

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Abstract. We have constructed an instrument, CryoEDM, to measure the neutron electric dipole moment to a precision of 10^{-28} *e* cm at the Institut Laue-Langevin. The main characteristic is that it is operating entirely in a cryogenic environment, at temperatures of 0.7 K within superfluid helium. Ultracold neutrons are produced in a superthermal source and stored within the superfluid in a storage cell which is held in a magnetic and electric field. NMR measurements are carried out to look for any shifts in the neutron Larmor precession frequency associated with the electric field and the neutrons are detected *in-situ* in the superfluid. Low temperature SQUID magnetometry is used to monitor the magnetic field. We report on the current status of the project that is now being commissioned and give an outlook on the future exploitation of the instrument.

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1. Introduction

Experimental searches for particle electric dipole moments (EDMs) form an important part of particle physics: these experiments provide a possibility to look at the breaking of fundamental symmetries of nature. For particles to have electric dipole moments, the forces concerned in their structure must be asymmetric with regard to space-parity (P) and time reversal (T). T violation also implies, through Lorentz invariance, that the combined charge-parity (CP) symmetry is violated. P violation is a well-known intrinsic feature of the weak interaction, but the combined charge-parity (CP) violation is much less understood and subject of intense research effort both at high energy physics facilities as well as in low energy physics experiments such as EDM searches.

CP violation is required to explain a number of observed phenomena, most importantly the baryon asymmetry [1]: our Universe is predominantly made out of matter despite the fact that the Big Bang should have produced equal amounts of matter and antimatter. CP violation is incorporated in the Standard Model of elctroweak interaction but is orders of magnitude too small to generate the baryon asymmetry as we see it today. The origin of CP violation we are searching for must thus lie beyond the Standard Model.

The neutron is a very good system to look for the required CP violation. The Standard Model gives a contribution to the neutron EDM of the order of 10^{-31} to 10^{-33} e cm which, because it is second order in the weak interaction coupling constant, is very small. Extensions to the Standard Model though, such as additional Higgs fields, right-handed currents or supersymmetric partners invariably give rise to dipole contributions which are of first order. These are necessarily much larger, and are typically of order 10^{-26} to 10^{-28} e cm [2]. The neutron thus allows to look for CP violation without a background signal that would originate from Standard Model interactions.

The EDM experiments so far have given upper limits on the value of the EDM and have placed ever tighter constraints on the models that go beyond the Standard Model. The current upper limit on the neutron EDM, $d_n < 2.9\ 10^{-26}$ e cm [3], is based on a previous measurement by some of the CryoEDM collaboration. The CryoEDM experiment is designed to improve the measurement by two orders of magnitude.

2. Experimental techniques & set-up

2.1. Neutron EDM measurement techniques

The experimental techniques used in the neutron EDM experiment are based on measuring the Larmor precession frequency ν_L of the neutron in a magnetic holding field B_0 to a very high precision. The Larmor frequency is given by $\nu_L = -2B_0\mu_n/h$, where μ_n is the neutron magnetic moment and h is the Planck constant. The presence of an EDM d_n will shift the Larmor frequency by $\pm 2Ed_n/h$ if an electric field E is applied, where the plus and minus signs correspond to the electric field being parallel and antiparallel to the magnetic field. The difference between the Larmor frequencies measured in opposite electric field directions associated with these frequency shifts is directly proportional to the neutron EDM:

$$\Delta\nu_L = -4Ed_n/h$$

The measurement of the precession frequency is performed using Ramsey's method of separated oscillatory fields. Neutrons, polarised parallel to the B_0 holding field, are submitted to two short $\pi/2$ rf pulses separated by a precession period. If the rf pulses are exactly on resonance with the Larmor precession frequency the neutrons will have a final polarisation directed antiparallel to the magnetic field. If the rf frequency is off resonance, the phase difference between the neutron signal and the rf signals will build up with each precession, and it accumulates to a sizeable phase difference at the end of the precession period. The final spin state of the neutrons is dependent on this phase difference. By counting the number of neutrons with polarisation parallel to B_0 as a function of the applied rf, the Larmor frequency can be determined to a high precision. The precession time between the two rf

pulses can be maximised using ultra-cold neutrons, neutrons of energy low enough (of the order of 10^{-7} eV), so that they can be stored in a bottle for long times.
The statistical sensitivity of an EDM measurement is given by

$$\sigma(d_n) \approx \frac{\hbar}{2ETP^2\sqrt{N}}$$

where E is the electric field strength, T is the neutron storage time, P is the neutron polarisation and N is the number of neutrons in a measurement. These are the parameters that need to be optimised to make a high precision EDM measurement.

2.2. Experimental set-up

The main characteristic of the CryoEDM set-up is that it is operating entirely in a cryogenic environment at temperatures of 0.7 K: ultra-cold neutrons (UCNs) are produced in a super-thermal source, stored within superfluid helium and afterwards detected also within the superfluid. Clearly this adds a degree of complexity to the design and operation of the experiment but the gains are compelling. The UCN densities produced are orders of magnitude higher than in previous experiments and the electric field sustainable in liquid helium is also considerably stronger.
We operate a large cryogenic system to reach the temperatures required for the UCN production and EDM measurements: a ^{3}He circulation cryostat cools the helium down to a base temperature of 420 mK in conjunction with two other cryostats that hold liquid helium for thermal and magnetic shields. The ^{3}He circulation is driven by a pump station consisting of four large roots pumps operating in series. A separate pumping station ensures that the general liquid He system, serving the cryogenics operation and supplying helium to the UCN source, is kept at low temperatures. This provides the cryogenic basis around which we have constructed the EDM experiment. Figure 1 shows a picture of the CryoEDM apparatus installed at the ILL showing the EDM measurement region and some of the cryostats. A drawing of a cross section of the apparatus is shown in Figure 2

Figure 1: The experimental apparatus installed on the H53 beam position at ILL. In the foreground the measurement region with its magnetic shields is seen. The superthermal UCN source coupled to the measurement region is in the background of the picture

The experimental set-up furthermore comprises the following parts:

2.2.1. The primary neutron beam. The experiment is running on the H53 cold neutron beam at ILL. Before the beam enters the source it is spin polarised by a 2.3 meter long neutron polariser developed for the experiment. The polariser also acts as a filter: the incoming neutron spectrum is cut off at a wavelength below 4.5 Å and the transmission linearly increases to 100% at 9 Å. Filtering the primary beam in this way reduces radiation background by a large factor and it protects the ^{3}He circulation and transfer cryostats from being activated. The capture flux is measured to be 3×10^9 cm^{-2} s^{-1} at the H53 guide exit. The capture flux of the polarised beam is 1.5×10^9 cm^{-2} s^{-1} with a polarisation measured to be over 90% at 9Å, the polariser has a slightly focusing arrangement. Measurements of the energy spectrum of the polarised neutron beam entering the experiment showed the flux to be 3×10^7 cm^{-2} s^{-1} Å^{-1} at 9 Å. These numbers are sufficiently high to perform an improved nEDM measurement using CryoEDM.

2.2.2. The superthermal UCN source. The UCN are produced by down scattering the 9 Å neutrons in superfluid helium at a temperature of about 0.65 K. In this process a phonon is created in the helium that balances the energy and momentum lost by the neutron. With the intensity of the primary beam at H53 the UCN production rate is 1 cc^{-1} s^{-1} [4] and can generate high UCN densities. There is a number of UCN loss channels that needs to be kept under control in order to retain the produced UCN. A possible loss is through upscattering: a phonon being absorbed by a neutron will raise the energy of the neutron and the UCN is lost for the experiment. The temperature of the helium must be kept well below 1K to minimise the phonon density and thus to suppress this process. Another loss channel would be through absorbtion by ^{3}He: ^{3}He has a very large absorption cross section for neutrons of UCN energy. The helium in which the UCN are created must be isotopically pure ^{4}He which does not absorb neutrons. In our experiment we produce our own isotopically pure ^{4}He by operating a series of so-called superleaks [5]. Liquid helium from the main tank in the cryostat is passed through these superleaks and the superfluid component only, the ^{4}He, will be passed on to the UCN source. The purity of the helium has been measured and showed a ^{3}He abundance better than 10^{-10} which is low enough to ensure long UCN storage lifetimes.

2.2.3. *UCN guide system and UCN valves.* The UCN guides need to be able to store and transport

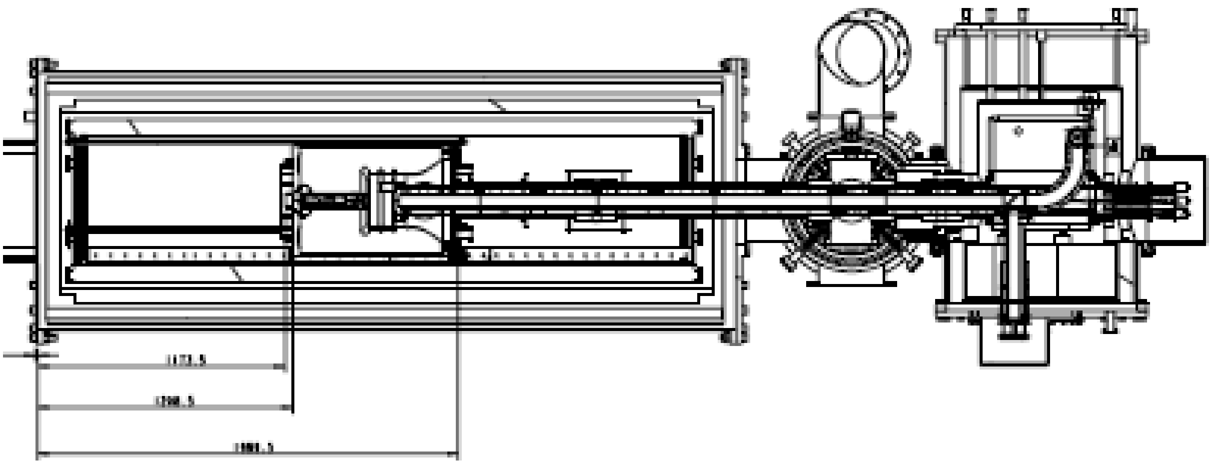

Figure 2: A cross section of part of the experimental apparatus. The storage cells are mounted at the centre of the magnetic shields and are coupled to the superthermal UCN source on the right with UCN guides. The detector chamber is situated under the transfer cryostat. The UCN source is at right angle to this cross section and is not shown.

UCN with minimal losses. In addition our UCN source also serves as a guide through which the 9 Å primary beam passes the superfluid helium so the guide needs to be reflective for cold neutrons. Furthermore, the guides need to be made and placed such that the polarisation of the UCN is not lost. To comply with these requirements the neutron guides have been made from copper coated with a layer of beryllium. Beryllium has a high Fermi potential of 250 neV and makes good UCN storage material. The UCN source is a 3m long tube tube of diameter 68 mm, providing a total volume of some 10 litres for UCN production. The source tube is connected to the transport guides that lead to the storage cells.
The experiment is fitted with four UCN valves that are operated in the superfluid helium. The valves are used to keep the UCN stored in a part of the experiment and to let the UCN move between the different chambers of the experiment. A defined storage time in the UCN source and in the storage cells can thus be set and the UCN can be directed towards the detector chamber at the end of a data cycle.

2.2.4. Magnetic field and shielding. The magnetic shielding consists of three layers of mu-metal and a superconducting lead screen that is kept in a cylinder filled with liquid helium at a temperature of 4K. A holding field of 50 mG is generated by a superconducting NbTi solenoid, this solenoid is wound on a former kept in the helium filled cylinder just inside superconducting lead screen. Various trim coils are mounted around the storage chambers that can optimise the holding field and increase its homogeneity further. The magnetic shields assembly has its own independent helium cryostat and cryocoolers.

2.2.5. UCN storage cells. The UCN are stored in a double cell arrangement where the actual Ramsey resonance operations take place. The cells consist of two BeO cylinders each capped with Ti electrodes coated with 1 μm of diamond like carbon [6]. The cells hold a volume of 2.2 litres each. The common electrode between the two cells is kept at ground potential as is the electrode through which the UCN enter the cells. On the third electrode a voltage is applied, one cell is thus holding an electric field and is neighboured by a cell being in a neutral electric field. The neutron precession measurements in the two cells are treated separately and give a handle on systematic effects that would change the neutron precession frequency and generate a false EDM signal. The storage cells are placed in a superfluid containment vessel made of a non magnetic titanium alloy at the centre of the magnetic shielding.

Figure 3: The UCN detector assembly. The surface barrier detectors are coated with ^{6}LiF for neutron to charged particle conversion and an Fe layer for UCN polarisation analysis purposes

2.2.6. UCN detectors and polarisation measurement. The detector system (Figure 3) consists of a set of solid state surface barrier detectors covered with ^{6}LiF. The signal in the detector is generated by the alpha and triton particles from the n(^{6}Li,^{3}H)^{4}He reaction [7]. This is a system that has been shown to work efficiently within superfluid helium [8]. The detectors are placed in a magnetic field that the UCN will have followed adiabatically. Two of the detectors have an additional Fe layer on top of the ^{6}Li coating that will reflect one spin state of the UCN. The ratio in neutron counts in the detectors with Fe layer to the counts in the detectors without Fe layer is a measure of the UCN polarisation.

2.2.7. Magnetometry. SQUID magnetometers are used to monitor the magnetic field changes inside the SCV. For this an assembly of superconducting pick-up loops are fed back to the SQUIDS. The SQUIDS are operating in a section between the UCN source and magnetic shields inside a cryogenic tube that is filled with the superfluid. The pick-up loops are situated under the neutral electrode and can monitor different components of the field changes in the SCV. In addition to the SQUIDS cryogenic fluxgates measure the magnetic field inside the shields to provide an absolute field measurement close to the storage cells.

3. Performance & Outlook

One of the major challenges in the experiment is cooling down apparatus of this size to the sub-Kelvin temperatures that is required for producing and storing UCN. We have run the cryogenic apparatus in various configurations in order to characterise the performance of the separate parts of the set-up and have cooled down the full apparatus as part of the commissioning process. We now have an operational superthermal UCN source with a measured UCN production rate sufficiently high for us to reach a sensitivity of the order of 10^{-27} e cm at the current H53 beam position.

UCN detection is operational to a high efficiency as is the polarisation analysis of the UCN. The magnetic shields and both the fluxgate and SQUID magnetometry is operational, additional improvements are envisaged to enhance the shielding properties further.

The experiment is now in its commissioning phase and we envisage to make a nEDM measurement of the order of 10^{-27} e cm at the H53 beam position at ILL. In a later stage (year 2012) the experiment will move to a higher intensity 9 Å beam at ILL that will allow for a 10^{-28} e cm measurement which is the design aim of the apparatus.

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