Preparation for the Neutron Electric Dipole Moment Measurement

(CRYOEDM COLLABORATION)


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ABSTRACT

The experimental preparation for a new series of measurements on the neutron electric dipole moment is described. The scheme comprises extensive use of cryogenics, where sample neutrons (ultracold neutrons (UCN)) are produced by the neutron-phonon interaction in superfluid liquid helium. We review at the end how we enter the $10^{-28}$ cm region in future experiments.

1. General

The existence of the neutron electric dipole moment (nEDM) is not only the evidence of irreversibility of time but will contribute to understanding the baryon-antibaryon asymmetry of the universe. The measurement of a nEDM has been conducted over the last fifty years in search of parity and time reversibility violation for direct experimental evidences as such. According to the current super-symmetric theories, the value of a nEDM is expected to lie somewhere between $10^{-23}$ to $10^{-28}$ cm. The present experimental upper limit is $6.3 \times 10^{-26}$ cm (90% C.L.) [1]. The measurement is usually carried out under a weak magnetic field in the order of $1 \mu$T to fix the neutron spin direction, with a superimposed strong electric field $E$ either parallel or antiparallel to the magnetic field. The difference in frequencies between the split levels for the parallel and antiparallel $E$ is $4dE$, where $d$ is the electric dipole moment. In the early days of measurements, neutrons in a beam with velocity $v$ were used as neutron samples. As it turned out that $d$ is extremely small,
it was realized that the neutron magnetic moment $\mu$ coupled to $v \times E \sin \theta / c^2$, where $\theta$ is the angle between $B$ and $E$, which is not necessarily zero in the experimental reality, would mask the term $4d/E$. This is why ultracold neutrons, whose average velocity is zero, and which behave like a gas are used, and hence the masking effect is much reduced. At UCN velocities, the neutrons attain optical properties and can be confined in a vessel with appropriate material.

In order to supply the ultracold neutrons abundantly, we choose the following mechanism. The dispersion curve of the superfluid liquid helium and the energy-momentum curve of a free neutron cross at a point, where the energy-momentum of the incident neutron can be converted entirely to those of a produced phonon, leaving the neutron with an infinitesimal energy; a UCN. What follows is the averaging out the directions of UCN caused by non specular reflections from the rough surfaces of the vessel [2].

2. UCN production

The UCNs are produced in a horizontal cryostat termed Mark3001, whose technical description will be published elsewhere. It is a successor to Mark3000, which observed for the first time the production of UCN by velocity selected neutrons [3]. In 2001, a modified Mark3001 cryostat, which incorporated for the first time an in situ detection of UCN using silicon detectors, was placed in a cold neutron beam H53 at ILL and its performance was examined. The measured H53 neutron intensity was $2.6 \times 10^7$ cm$^{-2}$s$^{-1}$Å$^{-1}$ at 9 Å, which produced $\sim 1$ cm$^{-3}$s$^{-1}$ UCN [4]. Environmental improvements, such as a dedicated beam filter/polariser; a 2m extension to the UCN source with improved UCN life time, choice of wall with higher Fermi potential, and others, are being done, and the stored UCN density is expected to be $500 \sim 1000$ cm$^{-3}$.

3. S.C. Solenoid, S.C. Magnetic Shield (Ramsey Bloc)

In order to measure electric dipole moments with high precision, it is necessary to have a good homogenous magnetic field uninfluenced by ambient external magnetic dis-
turbances. In the designing stage, these requirements were incorporated into Mark3001. It essentially consists of a superconducting solenoid (685 mmD), set into a superconducting magnetic shield, made out of lead foil wound on a 724 mmO.D. aluminium cylinder. The whole thing is encased in a double layered aluminium cylinder filled with liquid helium between the layers. In order to boost the shielding, the assembly is further shielded with three layers of $\mu$-metal, and the entire assembly is encased in a stainless steel high-vacuum cylinder (1230 mmD) termed Ramsey Bloc. At the University of Sussex, the Bloc was subjected to cooling this spring for the first time outside Japan and the field distributions created by the solenoid plus the superconducting lead shield were studied. It performed well as was designed, and more detailed analyses are on the way (such as magnetic interactions between the s.c. solenoid and the s.c. lead shield during cooling and warming-up, etc.). A technical innovation in the system is the employment of a Sumitomo helium refrigerator used as a liquefier at a slightly higher temperature than 4.2 K in a closed circuit connecting a helium reservoir and the double layered aluminium cylinder encasing the solenoid and the lead shield. The helium consumption of the system becomes zero in this way and the stability of solenoid is ensured as well. The refrigerator and the helium reservoir are located in Tower 2 in Fig. 2.

4. UCN source, guide tube and the Ramsey chamber

The 9 Å neutrons enter from the right in Fig. 2. Ultracold neutrons are produced in the UCN Source filled with superfluid liquid helium and cooled below 0.5 K by a He3 refrigerator in Tower 1. After the UCN have been produced and stored in the source, they are released by opening a valve and transferred through a 90° bend to resonance storage cells set within the Ramsey Bloc. The length of the Ramsey Bloc is about 3 meters. The Ramsey Chamber is placed at its center. It is the vessel where the UCNs are stored for the nEDM measurement. Fig. 3 shows its perspective view (interim version). It has two cells, CELL 1 and 2. A high voltage of 400 KV max. (the supply is not shown in Fig. 2) will be fed from the left in Fig. 3, forming a strong electric field in CELL 2. CELL 1 has no field and serves as a reference cell to
monitor the magnetic field. The UCN are fed from the right through the UCN guide tubes and valves. The timing sequence for filling and emptying the UCN from the cells is controlled by the Valve Control Rods in Fig. 3.

5. Prospect

The CRYOEDM experiment will be carried out at ILL in its present form over the next few years. We expect to store from several hundreds to one thousand of UCN per cubic centimetre in about 150 seconds. This means that we will have an upper limit better than $1 \times 10^{-26}$ e.cm in the first several cycles of run time at ILL. However this number is still not enough to cover the smallest range that supersymmetry theories anticipate. It is obviously advantageous to have a stronger beam, unshared with other experiments and dedicated to a CRYOEDM project. At present ILL has an unused beam hole H112 in the north hall. If this hole were to be used it is expected to deliver a several times stronger beam than the existing H53 beam [5]. One problem is that there are many experiments taking place in the north hall so that it is necessary to extend the beam line more than a hundred meters to accommodate the CRYOEDM apparatus shown in Figure 2. The cost for such a beam line is estimated 2 million dollars. Having this been done, the upper limit will reach the range of $10^{-28}$ e.cm after 5 cycles of running. If this measure is not taken and we continue to use H53, it would take more than 20 cycles to get the same upper-limit. Therefore it is strongly hoped to finance such a beam line in order to know the adequacy of the supersymmetry theory at this level of the neutron electric dipole moment.

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7. References