Electric Dipole Moment of the Neutron

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The search for physics beyond that encompassed by the Standard Model has been a major research theme since the Standard Model was formulated. Even though physicists are convinced that the model is incomplete, it is the Standard Model's remarkable success that no new physics has been found besides neutrino oscillations. At high energies, experiments are designed to look for new particles. At low energies, precise experiments are designed to look for processes that are not allowed in the Standard Model. The searches are equally important and often indirectly probe energies not reachable by direct particle-production experiments. An important example is the search for the electric dipole moment (EDM) of the neutron. Since the theoretical predictions for the size of the neutron EDM are so small, the gap between the Standard Model predictions (10^{-31} e · cm, where e = –1.6 × 10^{-19} coulomb) and current experimental sensitivity (6 × 10^{-26} e · cm) is the territory for new discoveries. New theories that can account for the matter–antimatter asymmetry, such as supersymmetry, predict values for the neutron EDM in this range.

The neutron is a particle with spin, a quantum mechanical concept analogous to the neutron being a top rotating around an axis through its center. The neutron EDM may be pictured as a separation of positive and negative charges along the spin axis—see Figure 1a. Those charges must add to zero because the neutron has no net charge. The EDM is measured in units of separation distance for a unit of charge. Experiments already limit that separation distance in the neutron to an incredibly small size. For example, if the neutron were the size of the earth, the maximum separation allowed would be less than 10^{-5} meter (approximately one-tenth the diameter of a human hair). New experimental techniques, however, allow that limit to be improved by another factor of 100. Such sensitivities allow testing some important theoretical extensions of the Standard Model.

The three most popular ideas that will be tested are the possible violation of time reversal symmetry by the strong force, the existence of supersymmetry, and the origins of the matter–antimatter asymmetry in the universe. Time reversal is the symmetry in nature predicting that physics should remain the same whether time runs forward or backward. For certain mesons called kaons, which are made of a strange quark and a down antiquark, this symmetry is broken by the weak force. There is no known reason, however, forbidding the strong force from violating time reversal symmetry as well. Yet, previous EDM experiments have shown that time reversal symmetry is nearly perfect for neutrons. Theoreticians have some ideas why the effect might be small, but it is important to further test those ideas. Supersymmetry, a popular theory that invents a whole new set of particles needed to solve inconsistencies in the Standard Model, predicts a nonzero neutron EDM within the range of the next generation of experiments. The observed matter–antimatter asymmetry of the universe could be explained by a time reversal asymmetry, but the asymmetry observed with kaons is believed to be insufficiently large. A new phenomenon appears to be needed. A new EDM search could discover the needed source of time reversal that could explain this big mystery of our universe.

Because the neutron has spin (and therefore a magnetic moment that points in the same direction as the spin), the neutron feels a torque in a uniform magnetic field, **B** (Figure 1). If the spin direction is perpendicular to the magnetic field, the neutron will precess about the magnetic field direction. In the same way, if the neutron has an EDM, it will precess about an electric field, **E**. The difference is that the spatial transformation properties of magnetic and electric fields are different so that the existence of an EDM violates time reversal symmetry. An EDM experiment consists of measuring the precession rate of an ensemble of neutrons in a weak magnetic field and searching for a very small change in the precession rate when a strong electric field is applied parallel to the magnetic field.

The figure of merit for neutron EDM experiments is $E(N\tau)^{1/2}$, where N is the number of neutrons in the ensemble, and τ is the time they are under the influence of the fields. Based on this formula, the ideal experiment maximizes the strength of the electric field, the number of neutrons in the measurement region, and the time the neutrons remain in the bottle. The new techniques for improving the EDM measurement sensitivity involve producing ultracold neutrons (UCNs) in a bottle that can store them for a time approaching the natural decay time of the free neutron (~900 seconds) and placing the bottle inside a region where the static electric and magnetic fields are uniform and parallel, as described above. UCNs can be bottled if the container has walls built of a material that repels the neutrons.

UCNs are copiously produced in the bottle by cold neutrons if the bottle is filled with low-temperature ultrapure liquid helium-4 (which has spin 0).

The change in precession rate due to the electric field is so small that fluctuations in the magnetic field could mimic an EDM signal. In order to eliminate this systematic effect, another species with a similar response to a magnetic field (that is, a similar magnetic moment) but without an EDM is placed inside the measurement volume. Helium-3, a light isotope of helium, has the same spin as the neutron. Moreover, it can exist inside the liquid helium and occupy the same space as the neutrons. The helium-3 atoms provide a control measurement to reduce many systematic effects.

The quantity of helium-3 must be controlled carefully because helium-3 atoms absorb neutrons. The amount needs to be quite small to keep the neutron storage time long, about one helium-3 atom for every 10^{10} helium-4 atoms. However, the helium-3 absorption is highly spin-dependent and provides for the method of measurement. If both the neutrons and the helium-3 atoms are polarized (that is, the spins of each species are separately aligned), the neutrons are absorbed only when the spins of the neutron and helium-3 are pointing opposite to each other. As the magnetic moments of the two species differ by 10 percent, they oscillate between being aligned and antialigned. Thus, the neutron absorption rate is proportional to the beat frequency of the two rates of precession. When the neutrons are absorbed into a helium-3 nucleus, the positively charged reaction products (a tritium nucleus and a proton) scintillate in the liquid helium, emitting light in the hard ultraviolet. That light can be observed with a photosensitive detector if it is wavelength-shifted into the visible spectrum by scattering from an organic fluor lining on the surface of the measurement cell. That detection process is illustrated in Figure 2. The other piece of the experimental signal is a direct measurement of the precession rate of helium-3, which is accomplished by detecting the magnetization of the helium-3 with a superconducting quantum-interference device. In summary, the experiment consists of measuring the characteristic frequencies of two oscillating signals: one from the scintillation light produced by neutron absorption and one from the precession of the helium-3 nuclei. The signal for a nonzero EDM is a slight shift in the absorption frequency when the strong electric field is applied (Figure 3).

The apparatus to produce the conditions described is quite complicated and is shown as an engineering schematic in Figure 4. The essential parts are labeled. The final experiment requires the most intense source of neutrons available, and this experi-

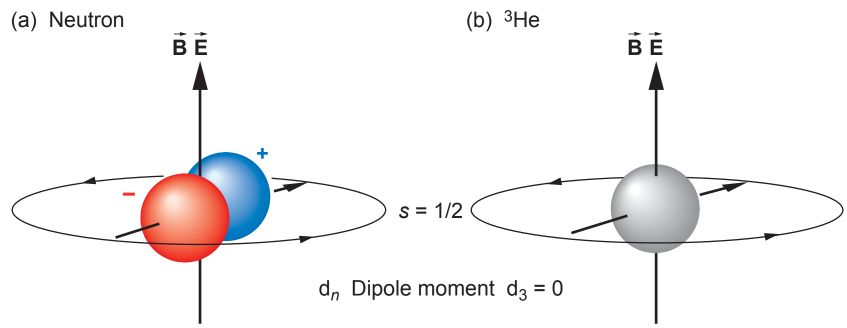

Figure 1. Possible Electric Dipole Moment of the Neutron
The neutron has a net charge of zero. A dipole moment would appear as a separation between a positive and negative charge along the spin axis of the neutron, as illustrated in (a). Helium-3, shown in (b), is known to have no EDM. The spin axes of both neutrons and helium-3 nuclei precess in the applied magnetic field B but at different rates. Applying an electric field E changes the precession rate of the neutrons in proportion to their EDM but not that of the helium-3 nuclei.

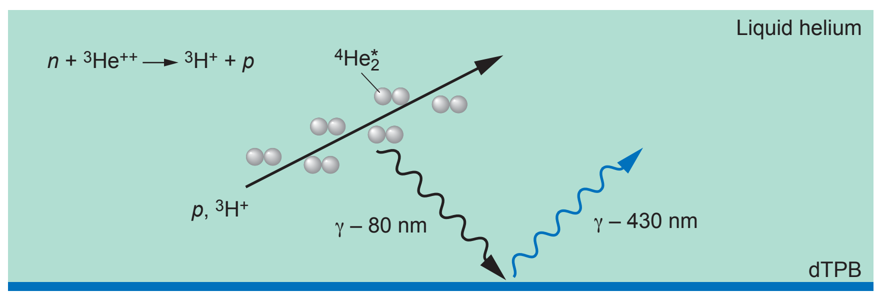

Figure 2. Detection of Neutron Absorption by Helium-3
The capture of a neutron by a helium-3 nucleus creates a proton and a hydrogen-3 nucleus (tritium). The energy from these particles excites helium molecules to higher energies, which then de-excite by emitting very short wavelength ultraviolet photons. Interaction with a deuterated-TPB organic fluor lining converts those ultraviolet photons into visible photons, which can be more readily detected.

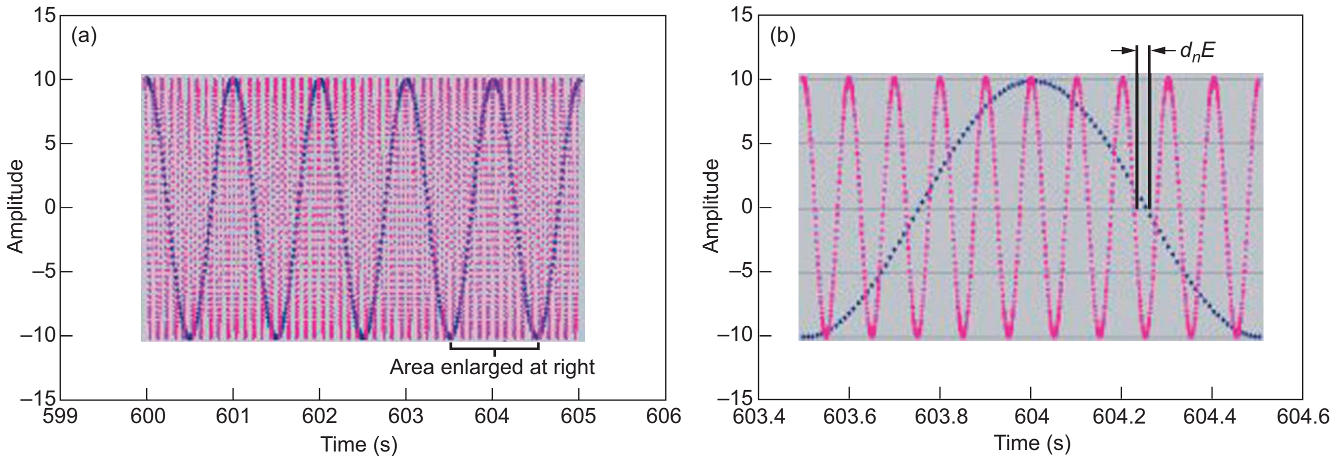

Figure 3. Signals Measured in the EDM Experiment
(a) The expected oscillation signals correspond to the helium-3 spin precession rate (fast) and the neutron absorption signal (slow). (b) The two signals are shown on an expanded scale, and the small shift in frequency that would be produced by a neutron EDM in the presence of an applied strong electric field is indicated schematically.

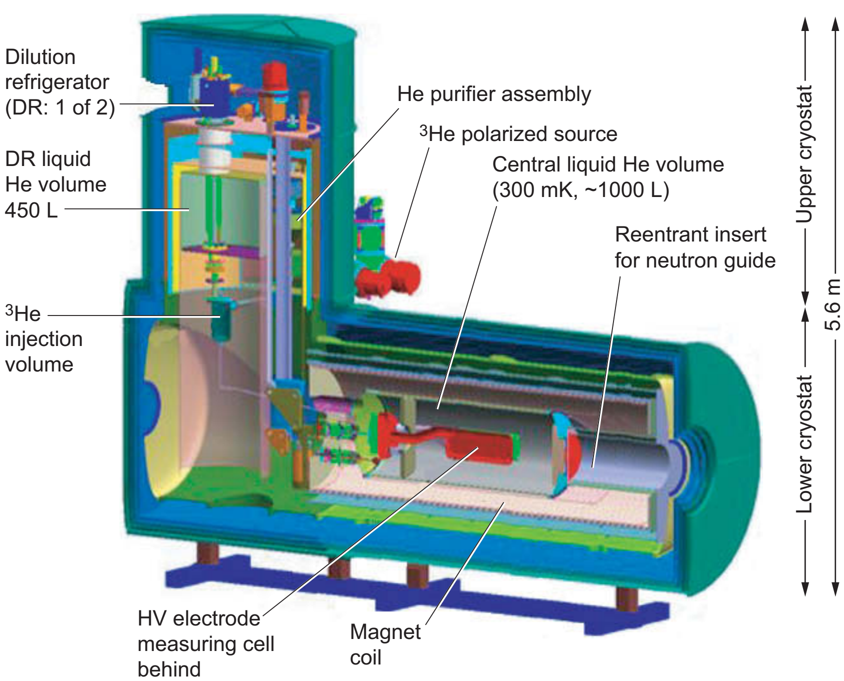

Figure 4. Current Design Concept for the Neutron EDM Experiment
This cutaway view shows the major components of the experiment.

ment will eventually be operated at the new Spallation Neutron Source under construction at Oak Ridge National Laboratory in Tennessee. However, there is a great deal of innovation involved in the method described, and the experimental team has engaged in an extensive research and development program to verify that all the ideas will work. Much of the developmental work is being performed at the Los Alamos Neutron Science Center (LANSCE).

The figure of merit for EDM experiments required a long storage time. A measurement of the storage time for UCNs in a cryogenic bottle coated with wavelength shifter is one of many experimental tests that are required to establish the feasibility of the experiment. This storage time measurement is well suited to LANSCE because the facility has an intense new source of UCNs that is being assembled for another experiment (see the article "Neutron β-Decay and Precision Tests of the Standard Model" on page 214). The idea is to take UCNs from the source, place them in the appropriate bottle, and see how many come out after some interval of time. By making a series of measurements for different times between loading and counting the neutrons, one measures the storage time. After extracting the effects of natural decay and other losses of neutrons, the partial lifetime induced by the bottle walls can be measured.

The project plan calls for all the auxiliary measurements to be completed by the end of 2006. At that time, construction can begin within a year. The Department of Energy has recently given the first stage of approval to the experiment. The experiment should be ready to acquire data at the Spallation Neutron Source in 2012. The real excitement will begin if those data indicate a nonzero value for the EDM of the neutron. ■