Washing Up with Hot and Cold Running Neutrons: Tests of Fundamental Physical Laws

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Abstract. The properties of the Neutron and its interactions with matter have been long applied to tests of fundamental physical principles. An example of such an application is a test of the stability of the fundamental constants of physics based on possible changes in low energy absorption resonances and the isotopic composition of a prehistoric natural reactor that operated two billion years ago in equatorial Africa. A recent re-analysis of this event indicates that some fundamental constants have changed. The focus of the presentation will be on the uses of cold and ultracold neutrons (UCNs), and in particular, the experimental search for the neutron electric dipole moment (EDM) which would be evidence for time reversal asymmetry in the microscopic interactions within the neutron. Ultracold neutrons are neutrons with kinetic energy sufficiently low that they can be reflected from material surfaces for all angles of incidence, allowing UCNs to be stored in material bottles for times approaching the beta decay lifetime of the neutron. Vagaries associated with the production, transport, and storage of UCNs will be described, and an overview progress on development of a new neutron EDM experiment to be operated at LANSCE will be presented. This new experiment has potential to improve the measurement sensitivity by a factor of 100. Although an EDM has not be observed for any elementary particle, experimental limits have been crucial for testing extensions to the so-called Standard Model of Electroweak Interactions. Our anticipated sensitivity will be sufficient to address questions regarding the observed matter-antimatter asymmetry in the Universe.

INTRODUCTION

The work and experiments that will be described here represent an "end-use" of nuclear data; the data that is subsequently obtained by this work is not of mainstream interest, but addresses fundamental issues that might some day be of broader importance in relation to our everyday life. This work relies heavily on the existing high-accuracy nuclear data that has been painstakingly accumulated by many scientists, many of whom were represented at this Conference.

THE OKLO NATURAL REACTOR

One question that has recently been of interest is whether the fundamental constants of physics are changing with time, and in particular, if the fine structure constant $\alpha = e^2/\hbar c = 1/137$ has been the same through the history of the universe. A different speed of light early in the universe would solve a number of problems, reconciling known physics with what happened, e.g., provide a mechanism for "inflation." In the context of String Theory, variable fundamental constants enter in a straightforward fashion. For example, α is dimensionless in our three (spatial) dimension world, but this is not the case for four or more spatial dimensions. The parameters we measure in our world are a projection of processes that occur in higher dimensional space, and in particular, as the volume of a compactified dimension changes, the observed numerical value of α can change.

A very sensitive test for a possible time variation of α (or some other parameter that determines the binding energy of atomic nuclei) can be carried out by isotopic analysis of the fission product ashes left behind from a natural nuclear reactor that operated in a rich uranium deposit some two billion years ago in what is now equatorial Africa, in the country of Gabon.

Two billion years ago, the isotopic fraction of ^{235}U in natural uranium was 3.5%, roughly equivalent to the enrichment used in many modern power reactors. The conditions were just right for this rich ore deposit to go critical, and the reactor operated intermittently for about 100,000 years. By analysis of fission products, with a model for their rate of production and subsequent loss through neutron capture, the total time integrated flux and average effective cross sections can be determined. Correction for diffusion of material with natural isotopic abundance is possible by choosing elements for analysis which have at least one fission product that does not occur naturally. It should be noted that the isotopic abundances of naturally occurring elements on the Earth are very constant (except for Pb and He) and serve as the basis, for example, to determine if rocks are of

CP769, *International Conference on Nuclear Data for Science and Technology,*
edited by R. C. Haight, M. B. Chadwick, T. Kawano, and P. Talou

extraterrestrial origin.

By measuring the abundance of a particular fission product that is subsequently modified by neutron absorption in the operating reactor, the effective cross section can be determined *at the time the reactor was operating,* provided that an adequate model for neutron moderation and other reactor parameters can be established. If this is the case, and in particular, if the absorption has a low energy resonance, any change in the cross section can be attributed to a change in the location of the resonance. An isotope that satisfies all of these criteria quite well is ^{149}Sm which has a resonance at about 0.09 eV. A re-analysis of previous work indicates that α has varied over the last two billion years, with six-sigma confidence [1]. The principal contribution in [1] is the use of a realistic neutron spectrum compared to the Maxwell-Boltzmann distribution used in the previous analysis. Given the strong absorption by both U and H in the reactor (c)ore, and knowledge of the minimum H concentration to achieve criticality which can be reliably calculated, the velocity spectrum of the neutrons in the reactor is determined effectively as a function of ore temperature. The true spectrum shows a suppression of low-energy neutrons compared to the Maxwell-Boltzmann spectrum, and the overlap of low energy spectrum, taking absorption into account, with the ^{149}Sm resonance is markedly different. With the strong absorption and loss of low energy neutrons, the overlap of the spectrum with the ^{149}Sm resonance is not strongly dependent on temperature. It is reasonable to take the critical point of water as the maximum temperature that could have been maintained while allowing water to exist in sufficient quantity to allow operation of the reactor.

COHERENT SCATTERING LENGTHS

The foregoing is an application of hot neutron physics. A recent example of the type of measurements using thermal (room temperature) neutrons, of interest for fundamental nuclear physics, are a series of experiments performed with the NIST thermal neutron interferometer to determine the n-p, n-d and hopefully, eventually, the n-t coherent scattering lengths [2]. These precision measurements are providing stringent tests of the fundamental many body nuclear interaction and have provided new benchmarks for testing and comparing nuclear models.

ULTRACOLD NEUTRONS AND NEUTRON BETA DECAY

The idea that neutrons of sufficiently low energy will be reflected from certain material surfaces for all angles of incidence is attributed to Fermi, but the first person to take the idea seriously enough to put it into print, and discuss the storage of such low energy neutron in material bottles, was Zel'dovich. He pointed out that storage of such neutrons, with kinetic energy of order 200-300 nano-eV corresponding to velocities of a few m/s, was possible because they would have minimal interaction with the bottle material; the time duration of a reflection (due to quantum mechanical tunneling) is of nanosecond scale, while the time between collisions is of millisecond scale. This means that the effective upscattering or absorption cross section is a million times smaller than the direct neutron-material interaction. Neutrons of such low energy are referred to as ultracold neutrons, or UCNs.

Until recently, the only sources of UCNs were located at research reactors, with the UCN being derived from the low energy tail of the Boltzmann distribution. The actual source simply provides a means to extract these low energy neutrons without excessive loss due to absorption in material windows and losses in transport guides. The most successful schemes actually extract very cold neutrons (VCN) (10-15 m/s) then use gravity to slow down the VCN to the UCN range of 0-5 m/s, noting that UCN lose about 100 neV per m of vertical rise. The VCN penetrate windows with lower loss than UCN, plus most moderators of interest provide a kinetic energy kick to exiting UCNs; vertical extraction compensates for this kick and extends the UCN spectrum to near-zero energy.

These types of sources are limited in flux (or density) by Liouville's theorem, which basically states that the phase space density of a system cannot be increased by conservative processes. Liouville's theorem can be circumvented by use of inelastic scattering of cold neutrons by materials with low neutron absorption held at low temperature. The most famous of the superthermal source concepts is based on superfluid helium held at temperatures of 0.5 K or lower temperature. The basic idea is that the free neutron dispersion curve intersects the phonon-proton dispersion curve for elementary excitations in superfluid helium at two points, 0 K and 11 K. 11 K neutrons incident on a UCN storage bottle filled with superfluid helium will scatter and come to near rest, while the inverse process of upscattering is suppressed by the Boltzmann factor (multiphonon upscattering becomes dominant below 0.7 K, but is very slow, with upscatter lifetime approximately $100/T^7$ sec). The UCN produced by the downscattering remain trapped in the bottle, and the UCN density builds up until the rate of production is equal to the rate of loss. One can expect densities of order 5000/cc for a superthermal helium source operated on an intense cold neutron guide, compared with a record density of order 40/cc obtained from direct extraction from a reactor, representing density available in the tail of the Maxwell-Boltzmann distribution together with finite extraction efficiency, typically a few percent.

A quadrupole spin trapping magnet filled with superfluid helium for a neutron lifetime experiment is being developed by a Harvard-NIST-NCSU-LANL collaboration, with the hopes of determining the neutron lifetime with precision better than 0.1 sec, an improvement by a factor of ten. Such increased accuracy is important for testing the weak interaction model of neutron decay, and an important parameter in late Big Bang nucleosynthesis. The idea behind the experiment is to use the superfluid helium for *in situ* UCN production (in fact, loading a conservative trap generally requires a dissipation mechanism which is a more apt way to think of the superthermal process in this instance), and then use the superfluid helium as a detector. Energetic electrons produce about one photon 500 Å per keV deposited in liquid helium, and this light can be converted to visible by use of a suitable wavelength shifter. The overall idea is to fill the trap with UCN (only one spin state is trapped) and simply watch the UCN undergo beta decay; the scintillation rate follows a simple exponential curve, and in the absence of uncontrolled or unknown loss mechanisms, should determine the beta decay time constant. A prototype trap has been operated at NIST and a larger trap based on superconducting quadrupole magnets designed and built at KEK is planned for the Oak Ridge Spallation Neutron Source. Recent progress is described in [3].

An alternative UCN source material is solid deuterium. At a temperature of 5 K, the rate of nuclear absorption of UCN is equal to the upscattering rate, and at this temperature or lower, solid deuterium serves as an analog to superfluid helium in its potential as a UCN source. Although the nuclear absorption lifetime of UCN in solid deuterium is of order 50 milliseconds (due to D absorption and to H absorption for practically attainable purity deuterium gas), compared to infinity for sufficiently pure and cold superfluid ^{4}He, the scattering power of solid deuterium is much higher and makes a better "current" source of UCN. A UCN source operating from a small spallation target has been demonstrated at LANSCE, and a density of about 140/cc, about three times larger than the previous record maximum at a reactor source, was obtained in June 2000.

A surprising loss mechanism was discovered in the course of the early experiments, in that excited para-deuterium molecules, free to rotate in the solid deuterium matrix (referred to as a quantum solid because of this property), upscatter UCN with about a 1 millisecond lifetime (for deuterium, a spin-1 atom, the molecular ground state is ortho, compared to hydrogen, which has a para ground state). By converting the para to the ortho state using a low temperature catalyst, the para contaminant can be reduced to a acceptably low concentration (from 33% for the room temperature fraction to about 1-2%). The size of a solid deuterium source is determined by the nuclear absorption lifetime and typical UCN velocity; taking $v = 500$ cm/s, a UCN would require about 20 milliseconds to exit a 20 cm cube. Given that the nuclear absorption lifetime is typically 50 milliseconds, it can be seen that increasing the source volume beyond 20 cm^3 will not result in a high production current. With the full para-deuterium concentration, the lifetime is 1 millisecond, which explains the factor of 100 lower-than-expected flux in the early experiments before the elucidation of this loss mechanism.

This work is described in [4], and a UCN factory based on solid deuterium is presently being commissioned in Area B of LANSCE and will take about 10 μA of beam current every second or so. Thus this source operates parasitically within the Clinton P. Anderson Accelerator Facility of LANSCE.

The immediate plan for use of this source is a new experiment to measure the spin-momentum correlation in neutron beta decay. The basic idea is that UCN can be highly polarized with a magnetic field of a few tesla (62 neV/tesla). A strong magnetic field applied to a UCN transport pipe will allow one spin state to pass while reflecting the other. Measurements of spin depolarization rates on materials of interests, which includes diamond-like carbon coated quartz tubing, indicates tolerable loss rates. The decay asymmetry will be measured by trapping and transporting left-vs.-right directed electrons in a strong solenoidal field which delivers the electrons to left and right detectors. A further advantage to the stand-alone UCN source is elimination of gamma background associated with reactor environments.

NEUTRON ELECTRIC DIPOLE MOMENT

Microscopic time reversal asymmetry (or T violation), so far observed only in the decay of certain "strange" particles (B and K_0 mesons), has been incorporated phenomenologically into the so-called Standard Model of electroweak interactions, but its exact nature is unknown. Theories put forward to provide a fundamental understanding of T violation also predict electric dipole moments (EDMs) of the neutron, electron, atoms, and molecules, at levels many orders of magnitude larger than the Standard Model predictions. Although an EDM has never been found, limits on the neutron EDM, for example, have ruled out more fundamental theories (put forward to explain strange meson decay) than any other set of measurements in the history of physics.

The observed matter-antimatter asymmetry in the Universe provides further motivation for EDM searches. The basic idea, due to Sakharov, is that the observed asymmetry could have resulted if the reaction rates for particles and antiparticles are different, combined with baryon number non-conservation. If this is the case, in an early stage of the Universe when baryons and photons were in equilibrium, as the Universe expanded and cooled, the baryons and antibaryons would not be equal in number and thus did not completely mutually annihilate to photons; the current ratio of photon:baryon:antibaryon density (or number) in the Universe is about $10^{10} : 1 : 10^{-10}$. The time reversal asymmetry required to achieve this "large" fraction of baryons relative to photons is many orders of magnitude larger than allowed by the Standard Model. This alone provides tremendous motivation to continue EDM searches.

We are planning a new neutron EDM experiment based on UCN production in superfluid helium that has been doped with a small concentration of polarized ^{3}He. The most sensitive neutron EDM experiments have employed UCN, and by *in situ* production of UCN in a superfluid helium bath, we anticipate at least a factor of 100 improvement in sensitivity. The improvement comes from an increase in UCN density by a factor of 1000, increase in storage and measurement time by a factor of five, and increase of the applied electric field by a factor of five. The first two lead to a sensitivity increase by the square-root of the improvement factor, while the improvement due to the electric field is linear. The increase in electric field is possible because of the excellent dielectric properties of liquid helium which we have demonstrated in a half-scale test apparatus.

Because an EDM would be detected by a change in precession frequency of a UCN in a weak magnetic field (10 mG) when the direction of an electric field, applied parallel to the magnetic field, is reversed, control of spurious magnetic fields is crucial. The polarized ^{3}He atoms serve as a magnetometer and UCN spin precession analyzer through the highly spin-dependent mutual absorption cross section (the ^{3}He EDM is essentially zero). The charge particles released in the UCN-^{3}He reaction lead to scintillation light, and the rate of scintillation pulse production is proportional to $1-\cos\theta$ where θ is the angle between the UCN and ^{3}He spins. Because the magnetic moments are equal to within 10%, the sensitivity to background magnetic field changes is reduced by an order of magnitude. However, it is possible to do much better by separately monitoring the ^{3}He spin precession by use of SQUID magnetometers (the field expected from the 10^{-10} atomic fraction of ^{3}He is large enough to be detected directly with modern high-sensitivity SQUIDs), or by employing a trick to make the effective magnetic moments equal by use of radiofrequency dressing techniques. These ideas are fully developed in [5] and are being pursued vigorously at LANL, in collaboration with UIUC, Caltech, Simon Fraser U., UCB, NCSU, Harvard, Duke, HMI, and Univ. Kentucky, among others.

As an aside, the rate of diffusion of ^{3}He in superfluid helium as a function of temperature is an important parameter in the design of this experiment. By use of neutron tomography of a sample of superfluid helium that was doped with ^{3}He and contained in a cell, the ^{3}He distribution was mapped out as a function of heat introduced at a point in the cell. The tomography was based on scintillations produced when a thin pencil beam of cold neutrons was sent through the cell, which provided a measure of the integral of the ^{3}He density along the neutron path. The experimental apparatus, comprising the cell which was connected to and cooled by a dilution refrigerator, could be translated in two dimensions in a plane perpendicular to the neutron beam. This allowed the integrated density to be mapped out, and the diffusion constant (or, more accurately the mobility) of ^{3}He in superfluid helium could be directly determined. This represents a new use of neutron beams in condensed matter studies [6].

This technique was further applied to the imaging of normal-component flow (which carries along the ^{3}He impurity at temperatures around 1 K), and provided a spectacular demonstration of the so-called HEVAC effect where heat is transported in the vacuum above the superfluid bath by a flux of ^{4}He atoms that evaporate from and subsequently recondense into the bath at different locations [7].

CONCLUSION

This report describes a few experiments to determine the basic structure of matter and its field interactions. These experiments rely on the existence of a high accuracy database of nuclear constants in their understanding, implementation, and operation. Hopefully these efforts, aimed toward basic understandings of the Universe, will themselves provide nuclear data usable to the broad community and not merely serve as a basis for the self-apotheosis of the workers involved in these efforts, which is the usual self-destructive result when mere mortals attempt to elucidate the fundamental character of Mother Nature.

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