Neutron–Antineutron Oscillations at Project X

Executive Summary

An observation of neutron-antineutron oscillations would constitute a discovery of fundamental importance for cosmology and particle physics. A discovery of this process would prove that all nuclei are ultimately unstable. It would provide the first direct experimental evidence for baryon number violation, which is required to explain the observed baryon asymmetry of the universe according to inflationary cosmology, which sets B to zero in the very early universe. Its discovery would qualitatively change our ideas of the scales relevant for quark-lepton unification and neutrino mass generation. If seen at rates achievable in next-generation searches it must be taken into account for any quantitative understanding of the baryon asymmetry of the universe.

Project X presents two possible paths for more sensitive searches of neutron-antineutron oscillations. The large volume liquid argon detectors considered for neutrino oscillation studies may be able to conduct more sensitive searches for neutron-antineutron oscillations within nuclei. If such a large liquid argon detector is sited underground, the improved vertex resolution possible using liquid argon technology might be exploited to reduce the atmospheric neutrino background which prevents the oscillation limits from large underground detectors using water Cherenkov-based technology from further improvement. A sensitive search for free neutron oscillations could be incorporated into a 1 MW spallation target for slow neutron production. Such a green-field source would be needed to take full advantage of continuing improvements in neutron optics technology which can deliver a much larger number of free neutrons to an annihilation target with a precisely-defined vertex location. Prospects for an essentially background-free measurement using free neutrons are excellent, and any positive observation can be suppressed experimentally by breaking the near degeneracy of the neutron and antineutron states by applying a small magnetic field. The same slow neutrons needed for a sensitive free neutron-antineutron oscillation search are also of potential interest for searches for the neutron electric dipole and other experiments. Existing slow neutron sources at research reactors and spallation sources possess neither the required space nor the access to the cold source needed to take full advantage of advances in neutron optics technology which enable a greatly-improved free neutron oscillation experiment.

The Project X workshop discussed several aspects of the theory of neutron-antineutron oscillations and of the experimental possibilities. We identified a number of issues requiring further study to clarify the physics potential. These issues include the following:

(1) More thorough theoretical calculations of the relationship between the rate of neutron-antineutron oscillation in nuclei and the free neutron-antineutron transition rate. This is needed to judge the relative sensitivities of free neutron and underground detector searches. Improved calculations are in progress using QCD sum rule techniques.

(2) Better calculations of the matrix elements of the 6-quark operators relevant for neutron-antineutron oscillations. These matrix elements can be used to relate the neutron-antineutron transition amplitude to the mass scale probed through the process. QCD-based calculations are now becoming possible on the lattice as a byproduct of techniques developed to calculate NN parity violation amplitudes and first calculations are now in progress.

(3) An effective field theory analysis of all possible $\Delta B = 2$ operators involving Standard Model fields. This analysis (also in progress) could be useful in conjunction with specific models for neutron-antineutron oscillations and improved constraints on new processes from the LHC and other rare decay searches and symmetry tests to judge whether or not the interesting possibility of post-sphaeleron baryogenesis can be eliminated by laboratory experiments and (if so) what is the required experimental sensitivity.

(4) Simulations of the sensitivity of underground liquid argon detectors to the signal from annihilation of an antineutron in the detector nuclei and the signal/background ratio. This is needed both to understand the physics reach of underground liquid argon detectors for setting an upper limit and

also to assess the level at which events can be declared a discovery in the presence of atmospheric neutrino backgrounds.

(5) An analysis of cost versus sensitivity for a free neutron oscillation search using known technology and foreseeable improvements. This analysis will entail the construction of a cost model for various aspects of the experimental design using an assumed slow neutron brightness and spectrum from a cold neutron source, supermirror neutron optics to focus the slow neutrons onto an annihilation detector, a vacuum chamber and magnetic shield, and an antineutron annihilation detector. With the development of the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory (ORNL) and the successful operation of that high-powered source (≤ 1 MW), confidence and expertize exist within the collaboration to design, build, and operate safely an optimized neutron source thet will satisfy the requirements of the NNbar experiment. The development of this target system will include target design and cooling, reflectors and cryogenics, remote handling, nonconventional utilities, shielding, and the analysis of the safety aspects of the system. The design of previous high-powered targets will be considered so that cost can be minimized.

General Physics Motivation and Theoretical Aspects

(i) Probing baryon number violation. Baryon number (B) violation has never been seen in a laboratory experiment. Still there are several reasons to suspect that baryon number non-conservation is an integral part of the physics beyond the Standard Model. No known physical principle prevents B from being violated. No new long-range interactions have been observed experimentally as one would expect if the B conservation came from a local conservation law as for electric charge (this is well-tested in searches for the violation of the equivalence principle). B is therefore treated in the Standard Model as a global quantum number. B conservation at the perturbative level in the Standard Model is "accidental" in the sense that it depends on the specific matter content. Theories beyond the standard model should generically be expected to violate B.

(ii) Relation of neutron-antineutron oscillations to cosmology. The observed baryon asymmetry of the universe is often taken as indirect evidence for B violating processes in nature, since it is strongly suspected on theoretical grounds that the baryon number in the very early universe is essentially zero (otherwise it can destroy inflation, for example [1]). It is known that the weak interactions within the Standard Model break baryon number B and lepton number L (although not $B - L$) non–perturbatively [2, 3, 4]. This process is greatly suppressed in our cold universe and has no hope for laboratory observation, but it should be thermally activated when the universe is very hot (temperatures near the electroweak phase transition). It is therefore possible that the cosmological baryon asymmetry can be explained by this process if one accepts the usual Sakharov conditions [5] as the ingredients needed to dynamically generate the baryon asymmetry. The suspected existence of these "sphaeleron" processes naturally divides baryogenesis models into three qualitatively different regimes according to whether or not the B generation comes from (a) an initial L asymmetry from a higher scale which is converted by sphaelerons into a B asymmetry (as in leptogenesis), (b) the phase transition dynamics at the electroweak scale itself in the absence of an initial L asymmetry coupled with new sources of T violation at or near this scale (as in electroweak baryogenesis), (c) some new B violating process at a scale below the electroweak phase transition. The leptogenesis scenario is favored at present by the many theories which violate L at high energy scales, but it is difficult to test. The last two scenarios occur at energy scales low enough to be probed experimentally through searches for B and T violation. The presence of sphaelerons also means that the discovery of a new source of B violation might or might not be relevant for baryogenesis since they might erase any B asymmetry generated at a high scale. Originally it was thought that proton decay predicted by grand unified theories could generate the matter-antimatter asymmetry. However, since sphaleron processes in the Standard Model violate $B + L$ number, any GUT–scale–induced baryon asymmetry would be washed out at the electro-weak phase transition.

(iii) Relation of neutron-antineutron oscillations to particle physics. A true understanding of the physics of baryon number violation would require comprehensive knowledge of the underlying symmetry principles, with distinct selection rules corresponding to different complementary scenarios for unification and for the generation of baryon asymmetry of the Universe. Grand unified theories of matter and forces, which are prime candidates for this physics, predict violation of baryon number. Proton decay with the selection rule $\Delta B = 1$ would imply the existence of new physics at an energy scale of 10^{15} GeV, while $N \to \bar{N}$ oscillation with the selection rule $\Delta B = 2$ would correspond to new physics near and above the TeV scale. These two processes are therefore sensitive to qualitatively different mechanisms. There exist many models (including those with extra space dimensions at TeV scale, for example) with local or global B or $B - L$ symmetry that do not allow proton decay, and where neutron-antineutron oscillation is the only baryon number violating process.

(iv) Connection of neutron-antineutron oscillations to neutrino physics. The discovery of neutrino mass has provided the first direct evidence for physics beyond the standard model. A simple way to understand the small neutrino masses is by the seesaw mechanism which predicts that the neutrino is a Majorana fermion, i.e. it breaks lepton number by two units. Even if the Majorana nature of the neutrino is established through observation of neutrinoless double beta decay, we still need to understand at what scale the dynamics occurs. Since the true anomaly-free symmetry of the Standard Model is the combination $B - L$, if L is broken by two units, it is natural for B to be broken by two units as well. Indeed, quark-lepton unified theories that predict Majorana neutrinos also predict $N \to \bar{N}$ oscillations. A search for $N \to \bar{N}$ oscillations might therefore supplement the search for neutrinoless double beta decay by establishing a common mechanism for these processes. In particular, an observation of $N \to \bar{N}$ would indicate that the small neutrino mass is not a signal of physics at the GUT scale but rather at much lower scales.

Observation of $N - \bar{N}$ oscillations at currently-achievable sensitivity would illuminate physics that affords a mechanism to regenerate the matter-antimatter asymmetry at scales below this transition. Existing theories describing such processes typically also predict colored scalars within the reach of the LHC, along with an observable electric dipole moment for the neutron, and some rare B–meson decay channels.

(iv) Model Independent Analyses

Existing theoretical calculations of the relationship between the rate of neutron-antineutron oscillation in nuclei and the free neutron-antineutron transition rate seen to capture the dominant physics [8], but various processes not previously considered are known to exist. Therefore a calculation which is more directly connected to QCD and can in principle include all contributions to the process would be very valuable. A calculation using QCD sum rule techniques inspired in part by the Project X workshop is now in progress. This calculation will help the scientific community to judge the relative sensitivities of free neutron and underground detector searches.

Existing calculations of the matrix elements of the 6-quark operators relevant for neutron-antineutron oscillations are quite old and use bag model wave functions. These matrix elements are important to evaluate since they can be used to relate the neutron-antineutron transition amplitude to the mass scale probed through the process. We were surprised to learn at the Project X workshop that lattice calculations of the matrix element are not as difficult as one might imagine. Partly motivated by the Project X workshop and partly by recent calculations of matrix elements for NN parity violation, first lattice calculations are now in progress.

To our knowledge an effective field theory analysis of all possible $\Delta B = 2$ operators involving Standard Model fields has not been conducted, although an initial analysis for a certain subclass of operators has been conducted [6]. This analysis could be quite useful in judging the possibility that post-sphaeleron baryogenesis can be eliminated by laboratory experiments. In conjunction with improved constraints on new processes from the LHC and other rare decay searches and symmetry tests along with lattice evaluations of the transition matrix elements of the allowed $\delta B = 2$ operators, it is possible that a sufficiently strong upper bound on neutron-antineutron oscillations could eliminate all possibilities. If this is possible, the required experimental sensitivity to do so is of great interest. This analysis is also in progress.

Experimental Aspects

The probability of $N-\bar{N}$ transformation in vacuum in the absence of magnetic field is $P=(t/\tau)^2$, where t is the free neutron observation time and τ is a characteristic oscillation time determined by new physics processes which induce $\Delta B=2$ transitions. If the scale of the relevant new physics is around (10^4-10^6) GeV, as predicted by various theoretical models, the possible range of $N-\bar{N}$ oscillation time is $\tau \sim (10^9-10^{11})$ seconds. The previous experimental search for free $N-\bar{N}$ transformations using a cold neutron beam from the research reactor at ILL in Grenoble [7] gave a limit on $\tau > 8.6\times 10^7$ seconds. The average velocity of the cold neutrons used was $\sim 700\ m/s$ and the average neutron observation time was $\sim 0.1s$. Antineutron appearance was sought through annihilation in a $\sim 100\mu$ carbon film target, generating a star pattern of several secondary pions viewed by a tracking detector and an energy deposition 1-2 GeV in the surrounding calorimeter. This detection process strongly suppresses backgrounds. For one year of operation ILL free neutron beam experiment saw zero candidate events and no background.

$N-\bar{N}$ transformations are also sought using bound neutrons inside the nuclei of large underground detectors built for proton decay and neutrino oscillaltion experiments. Super-Kamiokande set a limit of $\tau_A > 1.89\times 10^{32}$ years for $N-\bar{N}$ transformation in oxygen nuclei in 2011. $N-\bar{N}$ transformations inside nuclei are greatly suppressed by the different interactions of neutrons and antineutrons in nuclei, paramerized by a dimensional factor R that relates τ_A to the free $N-\bar{N}$ oscillation time τ as $\tau_A = R\tau^2$. The limit for the free $N-\bar{N}$ oscillation time from the recent Super-Kamiokande experiment ranges from $2.4\times 10^8 s$ to $3.5\times 10^8 s$ depending on the theoretical model for nuclear suppression R. The Super-Kamiokande limit was derived from 24 observed candidate events with estimated background of 24.1 events from atmospheric neutrino interactions in the detector. This atmospheric neutrino background makes further improvement of $N-\bar{N}$ search in water-Cherenkov detectors larger than Super-Kamiokande difficult and makes it impossible to claim a discovery.

Neutron-antineutron oscillations: opportunities at Project X

Two different approaches to search for $N-\bar{N}$ oscillations can be pursued within the envelope of Project X. One possibility is to use the improved vertex reconstruction capabilities foreseen for the large liquid argon detector under development for long baseline neutrino oscillation measurements. Another is to conduct a more sensitive search for free neutron oscillations.

(i) Searches for neutron-antineutron oscillations in nuclei at Project X.

The large volume liquid argon detectors considered for neutrino oscillation studies within Project X may be able to conduct more sensitive searches for neutron-antineutron oscillations within nuclei. If such a large liquid argon detector is sited underground, the improved vertex resolution might be exploited to reduce the atmospheric neutrino background which prevents the oscillation limits from large underground detectors using water Cherenkov-based technology from further improvement. Improved Monte Carlo event generators can be employed in simulations of the liquid argon detector response in the presence of atmospheric neutrino background to estimate the signal to background ratio. It is also possible to conduct more detailed analyses to sharpen the existing limits for antineutron annihilation in nuclei somewhat by removing certain simplifications used in the event generators and by relaxing some analysis assumptions which are (arguably) overconservative.

(ii) Free Neutron-antineutron oscillations at Project X.

Another is to conduct a sensitive search for free neutron oscillations with a 1 MW spallation target for slow neutron production. Such a green-field source would be needed to take full advantage of continuing improvements in neutron optics technology which can deliver a much larger number of free neutrons to an annihilation target with a precisely-defined vertex location. A search for $N - \bar{N}$ oscillations with free neutrons possesses excellent background rejection, it allows also for the possibility to turn off the signal using a small magnetic field, and therefore has enormous potential in exploring the stability of matter. Thus, for example, a limit on the free-neutron oscillation time $\tau > 10^{10}$ s would correspond to the limit on matter stability of $\tau_A = 1.6 - 3.1 \times 10^{35}$ years.

The figure of merit for a free-neutron $N - \bar{N}$–search experiments is $N_n \times t^2$, where N_n is the number of free neutrons subserved and t is the observation time. Any apparatus will involve the delivery of a high flux of free neutrons from the slow neutron source through a vacuum vessel (vacuum better that 10^{-5} Pa) with magnetic shielding ($1nT$) to a 100 micron thin foil surrounded by an antineutron annihilation detector. A dedicated spallation neutron source at Project X can be optimized for the production of slow neutrons and their delivery to an antineutron annihilation target with the use of modern neutron moderators and cryogenic technology. An increase in the delivery of slow neutrons to the annihilation target can be achieved by maximizing the phase space acceptance for neutron extraction around the cryogenic converter with advanced super-mirrors, whose performance far exceeds that available to the ILL-based experiment and represents the single most important contributor to an improved experimental sensitivity. The optimization of parameters of the cold neutron source fed by the spallation target, the supermirror optics, the vacuum and magnetic shielding, and the annihilation detector will require detailed R&D studies. A horizontal version of the experiment might be considered as a first-phase measurement, whereas a vertical layout of the experiment could take advantage of gravity to increase the free observation time.

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