Neutron-Anti-Neutron Oscillations:
The Need for a High Sensitivity Search at DUSEL

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Abstract

The process of neutron–antineutron ($n-\bar{n}$) oscillation is an important way to probe the basic instability of matter that is believed to be at the heart of our understanding the origin of matter in the Universe. It complements the searches for proton decay, which have been conducted for the past two decades and are ongoing. At the Deep Underground Science and Engineering Laboratory, $n-\bar{n}$ oscillation time scales of order 10^{10} sec. can be probed, with the potential to reveal answers to many fundamental questions in elementary particle physics, with implications for nuclear physics, cosmology and astrophysics: Is the neutron its own antiparticle? What is the degree of instability of matter? What is the basic mechanism for the creation of matter over antimatter in the Universe? Are there extra space–like dimensions? Is there a hidden "parallel" Universe? What is the nature of dark matter in the Universe?

I. INTRODUCTION

A key concept that has emerged from recent theoretical studies seeking the ultimate unity of matter and forces is that at the fundamental level, matter is predicted to be unstable. The apparent stability of the Universe is a consequence of the fact that matter instability occurs on a time scale which is more than a trillion trillion (10^{24}) times the age of the Universe. A further argument that reinforces this belief is the realization during the past four decades that matter instability is indeed essential if one wants to understand why the observed Universe is made only of matter and no antimatter. The challenge for physics is to discover how matter instability manifests itself and what the degree of this instability is.

There are two known ways in which matter instability can be manifest: (i) the decay of a proton (or a neutron which is otherwise stably bound in a nucleus), discussed in another part of the white paper, and (ii) spontaneous conversion of neutron (n) to anti–neutron ($\bar{n}$), called $n-\bar{n}$ oscillation (see Fig. 1), the subject of this part of the white paper. Spontaneous conversion of other electrically neutral particles such as K-,B-meson into their antiparticles has already been experimentally established, providing ground-breaking information about the fundamental forces and constituents of matter. They have guided the course of elementary particle physics for the past half-century. The $n-\bar{n}$ oscillation is even more profound and is expected to provide insight into many fundamental issues confronting particle physics today.

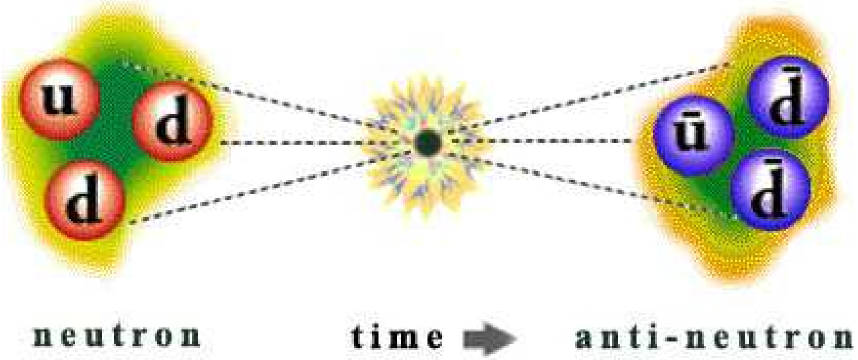

FIG. 1: Neutron oscillating into anti-neutron.

It was pointed out in the early 1970's that since a neutron (n) is electrically neutral, it could convert itself to an anti-neutron ($\bar{n}$), and, moreover, that this conversion process could provide a way to understand the observed fact that there is an asymmetry between the amount of matter and antimatter in the Universe. In the early 1980's, reasonable and consistent particle physics models were discovered which predicted that neutrons are their own anti-particles, similar to massive neutrinos being their own anti-particles, and that $n-\bar{n}$ oscillation should occur at an observable rate. This led to increased experimental as well as theoretical interest in this process. The existence of free $n-\bar{n}$ oscillations would also mean that neutrons inside nuclei would become anti-neutrons and make nuclei unstable. However, due to the difference between the way neutrons and anti-neutrons behave in the presence of nuclear forces, matter stability is highly suppressed. As a result, oscillation times of a year would correspond to about 10^{30} years for nuclear instability. Ongoing proton decay experiments also found lower limits on nuclear instability time scales due to $n-\bar{n}$ oscillation in nuclei in the same range. It was realized that available reactor neutrons could be used to probe $n-\bar{n}$ oscillations with oscillation times precisely in the range of a year to few years. There are, however, severe limitations to discovering $n-\bar{n}$ oscillations inside nuclei, due to atmospheric neutrino backgrounds. Uncertainties concerning the relevant nuclear properties also make it difficult to pin down precisely the value of the oscillation time. Thus it seems that the most promising way to search for this process further is to search for $n-\bar{n}$ oscillations with free neutrons. This is what we propose to carry out at the DUSEL facility.

A. Present experimental situation

The only free $n-\bar{n}$ oscillation experiment carried out to date was at the European laboratory at Institut Laue-Langevin (ILL), where a lower limit on the oscillation time scales of $\tau_{n-\bar{n}} > 0.86 \times 10^8$ sec (90 % CL) was established. This lower limit can be interpreted as follows. A free neutron, which itself is unstable with a mean lifetime of $\tau_n = 886 \pm 1$ sec., does not oscillate to an anti-neutron in the time span of 0.86×10^8 sec. (or 2.7 years). There are theoretical reasons to believe that an oscillation time which is a factor of 100 above this limit could probe some very interesting new ideas in physics beyond the Standard Model. As noted earlier, the oscillation rate of a free neutron in vacuum can be much faster than that inside a nucleus, where it is suppressed by internuclear forces. In fact, analysis of $n-\bar{n}$ oscillations in matter yields the relation between the free neutron oscillation time and the nuclear neutron oscillation time given by $\tau_{nuc} = R\tau^2_{n-\bar{n}}$, where R is a nucleus-dependent factor. Detailed nuclear physics calculations yield $R(^{16}\mathrm{O}) \simeq 0.5 \times 10^{23}$ s^{-1} and $R(^{56}\mathrm{Fe}) \simeq 0.7 \times 10^{23}$ s^{-1}. So the current lower bound on the free neutron oscillation time, $\tau_{n-\bar{n}} > 0.86 \times 10^8$ sec., corresponds to a lower limit on the nuclear decay time of about $\tau_{nuc} \gtrsim 1 \times 10^{31}$ yrs. Recent and ongoing proton decay searches are sensitive to similar lifetimes for the $n-\bar{n}$ oscillation mode. The Soudan-2 experiment has reported a lower limit $\tau_{nuc} > 0.72 \times 10^{32}$ yrs., which corresponds to the lower bound $\tau_{n-\bar{n}} \gtrsim 2 \times 10^8$ sec. Therefore, such an apparently small free neutron oscillation time is not in conflict with matter stability bounds.

II. WHY IS IT IMPORTANT TO CONDUCT A HIGH SENSITIVITY SEARCH FOR $n-\bar{n}$ OSCILLATION AT DUSEL?

There are several reasons to conduct a high-sensitivity search for $n-\bar{n}$ oscillations, as enumerated below. DUSEL would serve as an ideal site for this search.

A. Why the conventional proton decay search experiments are not adequate

If $n-\bar{n}$ oscillations exist, a neutron inside the nucleus could oscillate to an anti-neutron, which would subsequently annihilate with surrounding nucleons to give typically five pions with an invariant mass of two GeV. This will make nuclei unstable. Thus, in principle, conventional searches for proton decay (and decays of neutrons otherwise stably bound in nuclei) can probe for $n-\bar{n}$ oscillations. The relation $\tau_{nuc.} = R\tau^2_{n-\bar{n}}$ enables one to deduce the limit or value for $\tau_{n-\bar{n}}$ from the limit or value for the nuclear instability time τ_{nuc}. However, proton decay experiments are not a very sensitive way to probe $\tau_{n-\bar{n}}$, compared to a direct search, for the following reasons. The first point is that an order-of-magnitude increase in τ_{nuc} only leads to a factor of three improvement in $\tau_{n-\bar{n}}$. More importantly, because of the presence of backgrounds, the lower limits on τ_{nuc} that can be derived go at most like the square root of the exposure time. Hence, if the fiducial volume of the proton decay search detector increases by a factor of 25 (as is being contemplated for the next generation of proton decay searches), the lower limit on τ_{nuc} will increase at most by a factor of five, and the limit on $\tau_{n-\bar{n}}$ will go up only by a factor of 2.4. The published Soudan-2 limit on τ_{nuc} yields $\tau_{n-\bar{n}} \gtrsim 2 \times 10^8$ sec., and the preliminary Super-K limit yields $\tau_{n-\bar{n}} \gtrsim 3 \times 10^8$ sec. The $\tau_{n-\bar{n}}$ reach of the planned experiments to search for proton decay is only about $\tau_{n-\bar{n}} \simeq 7 \times 10^8$ sec, which is far lower than the reach of $\tau_{n-\bar{n}} \simeq 10^{10} - 10^{11}$ sec anticipated for the free neutron search experiments being contemplated. Fig. 2 displays the current and future sensitivity of matter instability lifetime from $n-\bar{n}$ oscillations as well as from proton decay searches.

B. What can we learn about the fundamental forces in Nature and the working of the Universe from the $n-\bar{n}$ search?

Neutron-anti-neutron oscillations touch upon many areas of physics ranging from elementary particle physics to nuclear physics to astrophysics and cosmology. The potential of the search for $n-\bar{n}$ oscillations as a probe of physics beyond the Standard Model is comparable to that of neutrino oscillations, which led to the very important discovery of neutrino masses and mixing. We now enumerate the most significant questions that will be addressed by an

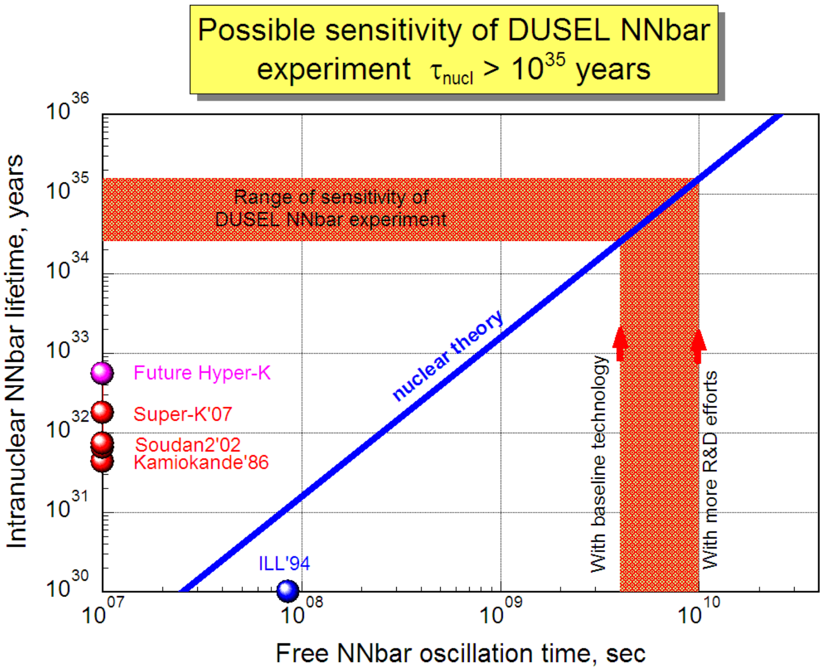

FIG. 2: Sensitivity of DUSEL NNbar experiment on matter instability lifetime.

$n - \bar{n}$ oscillation search.

1. Is the neutron its own anti-particle?

A search for $n - \bar{n}$ oscillations will probe new forces among particles at distance scales about a hundred times shorter than the ones that will be probed by the Large Hadron Collider (LHC). In specific models with low energy supersymmetry, the length scale of new physics probed in an $n - \bar{n}$ oscillation search can be one hundred million times shorter than the ones probed by the LHC. The discovery of neutrino masses is already providing one such probe of extremely tiny distances. Neutrinoless double beta decay experiments aim to test whether the neutrino is its own anti-particle, which is implied by many appealing theories explaining its small mass. If this is the case, then there are reasons to think that the neutron is also its own anti-particle, since both the neutrino and the neutron are linked by a symmetry of the Standard Model called the B-L symmetry (see below). This gives greater motivation for the existence, at an observable level, of the phenomenon of $n - \bar{n}$ oscillation which is the experimental manifestation of the neutron being its own anti-particle.

2. A new fundamental symmetry probed by $n - \bar{n}$ oscillations

To see which symmetry is probed in $n - \bar{n}$ oscillation searches, it is useful to compare with the situation involving neutrinos again. If the neutrino is its own antiparticle, this breaks total lepton number, L, by two units ($|\Delta L| = 2$). At an earlier time, most physicists believed that total lepton number was an exact symmetry, while at present, most physicists believe that it is broken. The process of neutrinoless double beta decay probes the scale of lepton number symmetry breaking. The Standard Model does not conserve L or B separately, but conserves their difference $B-L$. In a theoretical framework in which quarks and leptons are unified, one can get $|\Delta B| = 2$ processes. This happens, for example, in a class of unification models where the three colors of quarks combine with a lepton index to be part of a higher symmetry group $SU(4)$ which contains the familiar gauge force of strong interactions based on the color gauge group $SU(3)_c$. Such a framework automatically leads to the process of $n - \bar{n}$ oscillation without inducing proton decay. The scales of neutrino mass physics and of $n - \bar{n}$ oscillations are then essentially the same, and the observation of the latter will provide important complementary information about the detailed nature of the physics of neutrino mass. There exist plausible models where this connection is clearly visible and where the $n-\bar{n}$ oscillation time is accessible to planned searches. For $n-\bar{n}$ oscillations to be observable, the scale of $B-L$ breaking must be in the 100 TeV range, which is fundamentally different from the popular approach based on grand unified theories (GUT's), where this breaking scale is around 10^{16} GeV. Thus, an observation of $n-\bar{n}$ oscillations would force us to fundamentally alter our thinking about unification of forces away from the conventional GUT approaches to partial unification at intermediate scales or possibly new physics at the TeV scale, such as TeV^{-1}-sized extra dimensions.

3. $n - \bar{n}$ oscillation as a probe of extra dimensions

There is currently a great deal of interest in the possibility that there may be extra hidden space-like dimensions in nature. Motivations for this arise from string theory, specifically in frameworks where the Standard Model fields themselves, in addition to gravity modes, propagate in these extra dimensions. One of the appeals of these models is that they can provide an explanation of the observed generational hierarchy in fermion masses; the differences in mass between various particles, e.g., up, down, and strange quarks, would be due to the fact that their chiral components are located at different sites in these extra dimensions. In such situations, it has been shown quantitatively that, while proton decay which involves quarks as well as leptons can be naturally suppressed, $n-\bar{n}$ oscillation, which involves only quarks, is generally unsuppressed, and can be in the observable range.

4. Implications for cosmology

The existence of $n - \bar{n}$ oscillations at an observable rate would also have profound implications for the origin of matter-antimatter asymmetry and thus the origin of a net excess of matter in the Universe. This is due to the fact that observable $n - \bar{n}$ oscillations would imply that process that violate baryon number would remain in equilibrium to very low temperatures, thereby erasing any matter-antimatter asymmetry generated in earlier epochs, as envisioned in currently popular scenarios such as leptogenesis. This would then require new ways to understand the origin of matter. Recently, such new mechanisms have been proposed, which can be independently tested at colliders. In these models, baryon asymmetry is induced after the Universe undergoes the electroweak phase transition. Successful baryogenesis, in a class of models of this type, requires that $n - \bar{n}$ oscillations be observable, with $\tau_{n-\bar{n}} \sim 10^{10}$ sec.

5. Dark matter and connection with neutron–anti-neutron oscillations

There are some attractive models where neutron–anti-neutron oscillations also provide a probe of the nature of dark matter. A particularly intriguing suggestion is the possible existence of a parallel Universe with an identical duplicate of the observed matter and forces. Such a scenario could emerge from superstring theory. In that case, one expects all the particles that we know, protons, neutrons, etc., to have their mirror partners. Then the possibility arises that the neutron could oscillate into a mirror neutron. The same experiment that probes for $n - \bar{n}$ oscillations could also probe for such processes. Hydrogen atoms composed of mirror particles would serve as the dark matter of the Universe in this scenario. A possible connection between $n - \bar{n}$ oscillations and a dark matter candidate arises in models of low-scale baryogenesis which also have supersymmetry. The lightest stable superparticle in these models is not the neutralino, but the partner of the particle that generated the baryon asymmetry.

C. Experimental Setup at DUSEL

DUSEL, with its Vertical Facility, can provide a unique opportunity to advance the search for $n - \bar{n}$ transitions by a sensitivity factor more than 1000 as compared with the present experimental limits. This sensitivity will be equivalent to reaching the lifetime for internuclear $n - \bar{n}$ transition of $\tau_{nuc} \sim 1 \times 10^{35}$ years. The major advantage of the vertical layout as compared with the alternative approach having a horizontal layout is the mitigation of the effect of the Earth's gravity on the motion of cold neutrons over the long flight length. In the baseline $n - \bar{n}$ experimental configuration, a 1-km long vertical shaft of 5-7 meters diameter would be equipped with a vacuum tube and Earth magnetic field compensation system. A 3.5 MW research reactor of TRIGA type operating in steady-state mode and installed on the top of the shaft would serve as the source of neutrons. Neutrons would be slowed down by a cryogenic liquid deuterium moderator to typical velocities below 1 km/s and dropped from the top of the vacuum tube through the focusing supermirror reflector system on an annihilation detector located at the bottom of the vertical tube. The background rate in the DUSEL $n - \bar{n}$ detector would be extremely low, allowing a single observed event to be a discovery. Active magnetic shielding of the flight tube would allow on/off switching of the $n - \bar{n}$ transitions if the latter are observed. The proposed $n - \bar{n}$ experimental configuration is based on well-established technologies; the main challenge is in the engineering and vertical construction of the experiment. Further factors that can enhance the sensitivity of the vertical $n - \bar{n}$ search are a larger shaft length, larger reflection range of supermirrors (recently developed at KEK, Japan), development of a new "very cold" cryogenic moderator, and higher-power research reactor.

The 3.5 MW TRIGA reactor at the DUSEL Vertical Facility can be installed on the surface at the distance of about 2 km from the main underground experimental campus. The antineutrino flux produced by the reactor can be easily estimated as 62 antineutrinos per kiloton-year (e.g. by rescaling from the KamLAND detector, where reactors with 120 GW thermal power at the average distance of 180 km produce 263 antineutrino events per kiloton-year). This antineutrino flux certainly can be an essential background for geo-neutrino detection experiment at DUSEL, but, due to its controllable nature, it can be precisely measured. The flux of solar neutrinos to be coped with by the major experiments at the underground DUSEL site will be substantially larger than the flux of TRIGA antineutrinos. Given the large distance between the underground campus and the reactor, the background of thermal neutrons produced by the TRIGA reactor can be efficiently reduced to the level of environmental thermal neutron flux by simple passive shielding.