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Proton Decay

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5.1 Theoretical Perspectives on Proton Decay

The search for proton decay addresses one of the most important open questions in high energy physics. Its discovery would provide a wealth of insight into physics at the deepest level, bearing on the question of a unification of the fundamental forces of nature. Within the Standard Model, proton stability is associated with a conservation law, the conservation of baryon number. Protons and neutrons carry one unit of baryon charge, and there is no other lighter particle that is charged under baryon number in Nature. The proton being lighter than the neutron, conservation of baryon number forbids the decay of the proton. But baryon number is just an accidental symmetry of the Standard Model, which is already violated at the quantum level. Since it is not fundamental, it is expected to be violated in any extension of the Standard Model. If baryon charge conservation were violated, then protons might decay in a variety of ways, for example via the processes $p \to e^+\pi^0$ or $p \to e^+\gamma$. If protons were to decay rapidly, then all chemistry and life as we know it would come to an abrupt end.

Current limits on proton decay suggest that if baryon number is violated, the natural physics scale associated with the baryon number violating processes must be larger than about 10^{15} GeV. The search for proton decay at a large underground detector can therefore dramatically shed light on fundamental aspects of the laws of nature:

- Improved studies of proton decay would enable us to probe nature at the highest energy scale of order 10^{16} GeV, or equivalently 10^{-30} cm—something that would not be possible by any other means.
- The discovery of proton decay would have profound significance for the idea of grand unification, which proposes to unify the basic constituents of matter and also the three basic forces—the strong, weak and electromagnetic. Grand Unified Theories (GUTs) predict that the proton must decay, albeit with a long lifetime exceeding 10^{30} years. While proton decay has yet to be seen, the grand unification idea has turned out to be spectacularly successful as regards its other predictions. These include in particular the phenomena of "coupling unification," amounting to an equality of the strengths of the three forces at very high energies, which has been verified to hold, in the context of low energy supersymmetry, at an energy scale of 10^{16} GeV. Furthermore, a class of grand unified models naturally predicts that the heaviest of the three neutrinos should have a mass in the range of one hundredth to one electron volt, with the next-to-heaviest being an order of magnitude lighter, the two being quantum-mechanical mixtures of what one calls nu-mu and nu-tau. This is in full accord with the discovery of neutrino oscillation. In this sense, proton decay now remains the missing piece of evidence for grand unification.

One can in fact argue, within a class of well-motivated ideas on grand unification, that proton decay should occur at accessible rates, with a lifetime of about 10^{35} years, for protons decaying into a positron plus a neutral pion, and a lifetime of less than a few $\times 10^{34}$ years for protons decaying into an anti-neutrino and a positively charged K-meson. The most stringent limits on proton lifetimes now come from Super-Kamiokande [1]. For the two important decay modes mentioned above, they are:

$$\tau(p \to e^+ \pi^0) > 1.4 \times 10^{34} \text{ yrs}, \qquad \tau(p \to \bar{\nu} K^+) > 4 \times 10^{33} \text{ yrs}. \tag{5.1}$$

These well-motivated models then predict the observation of proton decay if one can improve the current sensitivity (of Super-Kamiokande) by a factor of five to 10. This is why an improved search for proton decay, possible only with a large underground detector, is now most pressing.

5.1.1 Grand Unification and Proton Decay

The decay of the proton [2] is one of the most exciting predictions of the idea of the unification of matter and of forces at the very highest energy scales [3],[4], which is motivated on several grounds (for a review, see [5]). For example, the experimental observation that electric charge is quantized, together with $|Q_{\text{proton}}| = |Q_{\text{electron}}|$ (to better than 1 part in 10^{21}), has a natural explanation in GUTs owing to their non–Abelian nature. The miraculous cancellation of chiral anomalies that occurs among each family of quarks and leptons has a symmetry–based explanation in GUTs. Furthermore, GUTs provide a natural understanding of the quantum numbers of quarks and leptons. With the grouping of quarks with leptons, and particles with antiparticles, in a common GUT multiplet, these theories predict that baryon number would be violated and that the proton must decay. Finally, with the assumption of low energy supersymmetry, motivated by the naturalness of the Higgs boson mass, the strong, weak and electromagnetic gauge couplings are found to unify nicely at a scale $M_X \approx 2 \times 10^{16}$ GeV, the scale of interest for proton decay (see right panel of Fig. 5-1). It should be noted that low energy supersymmetry would allow baryon and lepton number violating interactions of the type QLD^c, $U^cD^cD^c$ and LLE^c in the superpotential (Q, L etc are the quark and lepton superfields). However, these operators can be eliminated by imposing R-parity conservation [6],[7], which could arise from a gauged $B - L$ symmetry [8] that occurs in many unified theories.

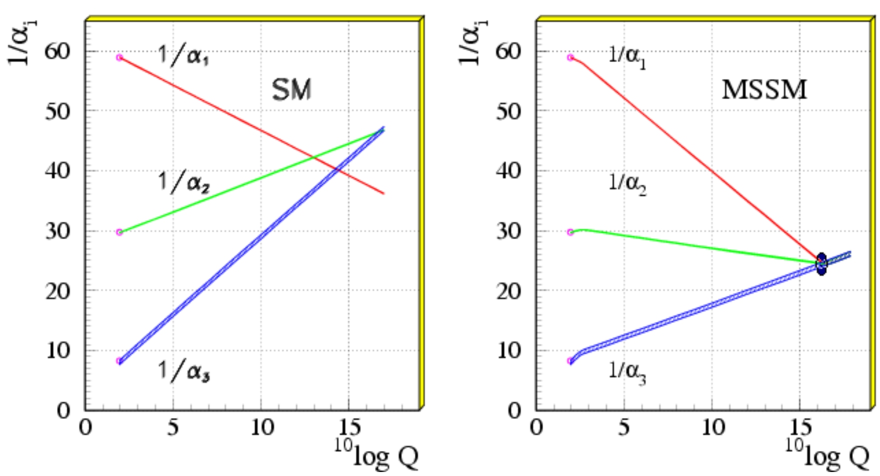

Figure 5-1. *Evolution of the three gauge couplings α_i with momentum Q: Standard Model (left panel) and Minimal Supersymmetric Standard Model (right panel)*

$SU(5)$ is the simplest grand unified group, and it turns out to be the most predictive as regards proton lifetime and the unification of the three gauge couplings, owing to small GUT scale threshold effects. The minimal non-supersymmetric version of $SU(5)$ [3] has already been excluded by the experimental lower limit on $p \to e^+\pi^0$ lifetime and the mismatch of the three gauge couplings when extrapolated to high energies (see left panel of Fig. 5-1). Yet low energy supersymmetry, which is independently motivated by the naturalness of the Higgs boson mass, provides a simple solution to these problems of $SU(5)$, as it increases the prediction of the lifetime for the decay process $p \to e^+\pi^0$ due to the larger value of M_X and also corrects the unification mismatch (see right panel of Fig. 5-1) [5].

Supersymmetric grand unified theories (SUSY GUTs) [9],[10],[11]–[14] are natural extensions of the Standard Model that preserve the attractive features of GUTs such as quantization of electric charge, and lead to the unification of the three gauge couplings. They also explain the existence of the weak scale, which is much smaller than the GUT scale, and provide a dark matter candidate in the lightest SUSY particle. Low energy SUSY brings in a new twist to proton decay, however, as it predicts a new decay mode $p \to \overline{\nu}K^+$ that would be mediated by the colored Higgsino [15],[16], the GUT/SUSY partner of the Higgs doublets (see Fig. 5-2, right panel). Typically, the lifetime for this mode in many models is shorter than the current experimental lower limit.

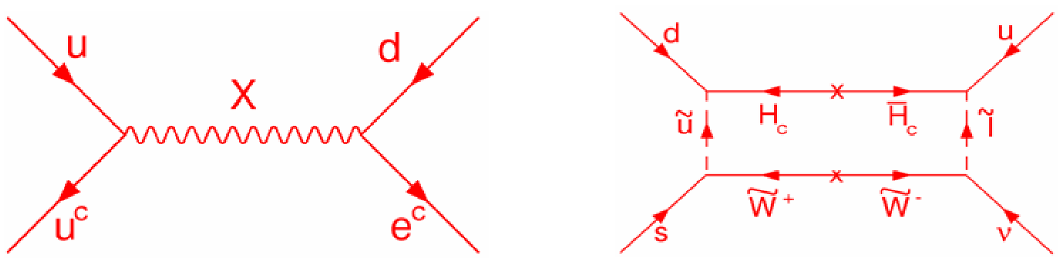

Figure 5-2. *Diagrams inducing proton decay in SUSY GUTs. $p \to e^+\pi^0$ mediated by X gauge boson (left), and $p \to \overline{\nu}K^+$ mediated by colored Higgsino (right).*

In order to evaluate the lifetimes for the $p \to \overline{\nu}K^+$ and $p \to e^+\pi^0$ decay modes in SUSY $SU(5)$ [17], a symmetry breaking sector and a consistent Yukawa coupling sector must be specified. In $SU(5)$, one family of quarks and leptons is organized as $\{10 + \overline{5} + 1\}$, where $10 \supset \{Q, u^c, e^c\}, \overline{5} \supset \{d^c, L\}$, and $1 \sim \nu^c$. $SU(5)$ contains 24 gauge bosons, 12 of which are the gluons, $W^\pm, Z^0$ and the photon, while the remaining 12 are the (X, Y) bosons that transform as $(3, 2, -5/6)$ under $SU(3)_c \times SU(2)_L \times U(1)_Y$. These bosons have both diquark and leptoquark couplings, which lead to baryon number violating processes. The diagram leading to the decay $p \to e^+\pi^0$ is shown in Fig. 5-2, left panel. $SU(5)$ breaks down to the Standard Model symmetry in the supersymmetric limit by employing a 24_H Higgs boson. Additionally, a $\{5_H + \overline{5}_H\}$ pair of Higgs bosons is employed, for electroweak symmetry breaking and the generation of quark and lepton masses.

The masses of the super-heavy particles of the theory can be related to low energy observables in minimal SUSY $SU(5)$ via the renormalization group evolution of the three gauge couplings, which depends through the threshold correction on M_T, the mass of the color triplet Higgsinos which mediate $p \to \overline{\nu}K^+$ decay. In general, agreement with the experimental value of $\alpha_3(M_Z) = 0.1184 \pm 0.0007$ demands the color triplet mass to be lower than the GUT scale. This tends to lead to a rate of proton decay into $\bar{\nu}K^+$ which is in disagreement with observations [18].

It should be noted, however, that the Yukawa sector of minimal SUSY $SU(5)$ enters in a crucial way in the rate of proton decay into $K^+\bar{\nu}$. Minimal $SU(5)$ leads to the relation $M_d = M_\ell^T$, relating the down quark and charged lepton mass matrices. Consequently, the asymptotic relations $m_b^0 = m_\tau^0,\ m_s^0 = m_\mu^0,\ m_d^0 = m_e^0$ follow for the masses of quarks and leptons at the GUT scale. Although the first of these relations agrees reasonably well with observations once it is extrapolated to low energies, the relations involving the two light family fermions are not in agreement with observations. Rather than concluding that the minimal SUSY $SU(5)$ is excluded, it would be beneficial to consider the simplest modification that corrects these bad mass relations, and then explore its prediction for proton decay. One possibility is to add higher dimensional operators to the minimal theory. An alternative possibility, which appears to be simple and predictive, is to add a vector-like pair of $\{5 + \overline{5}\}$ fermions [19]. The quarks and leptons from these multiplets can mix differently with the usual quarks and leptons, and thereby correct the bad mass relations. Optimizing these mixings so as to enhance the dominant $p \to \overline{\nu}K^+$ lifetime, approximate upper limits for the various partial lifetimes are found: $\tau(p \to \overline{\nu}K^+) \sim 4 \cdot 10^{33}$ yrs, $\tau(p \to \mu^+K^0) \sim 6 \cdot 10^{33}$ yrs, and $\tau(p \to \mu^+\pi^0) \sim 1 \cdot 10^{34}$ yrs. In obtaining these numbers, the SUSY particles are assumed to have masses below 2 TeV, and the unification scale is taken to be at least a factor of 50 below the Planck scale, so that quantum gravity effects remain negligible. Here lattice calculations for the proton decay matrix elements have been used [20] [1]. Since the predicted rates are close to the present experimental limits, these models can be tested by improving the current sensitivity for proton lifetime by a factor of ten.

***SO*(10) Unification and Proton Decay**: Models based on $SO(10)$ gauge symmetry are especially attractive since quarks, leptons, anti-quarks, and anti-leptons of a family are unified in a single **16**-dimensional spinor representation of the gauge group [22]. This explains the quantum numbers (electric charge, weak charge, color charge) of fermions, as depicted in Table 1. $SO(10)$ symmetry contains five independent internal spins, denoted as + or − signs (for spin–up and spin–down) in Table 1. Subject to the condition that the number of down spins must be even, there are 16 combinations for the spin orientations, each corresponding to one fermionic degree. The first three spins denote color charges, while the last two are weak charges. In addition to the three independent color spins (r, b, g), there is a fourth color (the fourth row), identified as lepton number [2]. The first and the third columns (and similarly the second and the fourth) are left–right conjugates. Thus $SO(10)$ contains quark–lepton symmetry as well as parity. Thus a right–handed neutrino state (ν^c) is predicted because it is needed to complete the multiplet. Being a singlet of the Standard Model, it naturally acquires a superheavy Majorana mass and leads in a compelling manner to the generation of light neutrino masses via the seesaw mechanism. Hypercharge of each fermion follows from the formula $Y = \frac{1}{3}\Sigma(C) - \frac{1}{2}\Sigma(W)$, where $\Sigma(C)$ is the summation of color spins (first three entries) and $\Sigma(W)$ is the sum of weak spins (last two entries). This leads to quantization of hypercharge, and thus of electric charge. Such a simple organization of matter is remarkably beautiful and can be argued as a hint in favor of GUTs based on $SO(10)$.

$u_r: \{-++\ +-\}$	$d_r: \{-++\ -+\}$	$u_r^c: \{+--\ ++\}$	$d_r^c: \{+--\ --\}$
$u_b: \{+-+\ +-\}$	$d_b: \{+-+\ -+\}$	$u_b^c: \{-+-\ ++\}$	$d_b^c: \{-+-\ --\}$
$u_g: \{++-\ +-\}$	$d_g: \{++-\ -+\}$	$u_g^c: \{--+\ ++\}$	$d_g^c: \{--+\ --\}$
$\nu: \{---\ +-\}$	$e: \{---\ -+\}$	$\nu^c: \{+++\ ++\}$	$e^c: \{+++\ --\}$

Table 5-1. *Quantum numbers of quarks and leptons. The first three signs refer to color charge, and the last two to weak charge. To obtain hypercharge, use* $Y = \frac{1}{3}\Sigma(C) - \frac{1}{2}\Sigma(W)$.

As in the case of $SU(5)$, when embedded with low energy supersymmetry so that the mass of the Higgs boson is stabilized, the three gauge couplings of the Standard Model (SM) nearly unify at an energy scale

[1]Alternative computational methods, which suggest some level of suppression of these operators [21], are affected by large theoretical uncertainties

of $M_X \approx 2 \cdot 10^{16}$ GeV in $SO(10)$ models. The light neutrino masses inferred from neutrino oscillation data ($m_{\nu_3} \sim 0.05$ eV) suggest the Majorana mass of the heaviest of the three ν^c's to be $M_{\nu^c} \sim 10^{14}$ GeV, which is close to M_X. In a class of $SO(10)$ models discussed further here, $M_{\nu^c} \sim M_X^2/M_{\rm Pl} \sim 10^{14}$ GeV quite naturally. The lepton number violating decays of ν^c can elegantly explain the observed baryon asymmetry of the universe via leptogenesis. Furthermore, the unified setup of quarks and leptons in $SO(10)$ serves as a powerful framework in realizing predictive schemes for the masses and mixings of all fermions, including the neutrinos, in association with flavor symmetries in many cases. All these features make SUSY $SO(10)$ models compelling candidates for the study of proton decay.

Even without supersymmetry, $SO(10)$ models are fully consistent with the unification of the three gauge couplings and the experimental limit on proton lifetime, unlike non–SUSY $SU(5)$. This is possible since $SO(10)$ can break to the SM via an intermediate symmetry such as $SU(4)_C \times SU(2)_L \times SU(2)_R$. Such models would predict that a proton would decay predominantly to $e^+\pi^0$ with a lifetime in the range $10^{33} - 10^{36}$ yrs, depending on which intermediate gauge symmetry is realized [23].

In SUSY $SO(10)$ models, symmetry breaking can occur in two interesting ways. One type adopts a **126** of Higgs, a tensor, which couples directly to the ν^c states and generates large Majorana masses for them. This class of models has the attractive feature that the R–parity of the Minimal Supersymmetry Standard Model (MSSM), which is so crucial for identifying the lightest SUSY particle as the dark matter candidate, is an automatic symmetry, which is part of $SO(10)$. In this category, a class of minimal $SO(10)$ models employing a single $\overline{\mathbf{126}}$ and a single **10** of Higgs bosons that couple to the fermions has been developed [24]. Owing to their minimality, these models are quite predictive as regards the neutrino mass spectrum and oscillation angles. Small quark mixing angles and large neutrino oscillation angles emerge simultaneously in these models, despite their parity at the fundamental level. The neutrino oscillation angle θ_{13} is predicted to be large in these models, $\sin^2\theta_{13} \geq 0.02$. Proton decay studies of these models [25] show that at least some of the modes among $p \to \overline{\nu}\pi^+$, $n \to \overline{\nu}\pi^0$, $p \to \mu^+\pi^0$ and $p \to \mu^+ K^0$ have inverse decay rates of order 10^{34} yrs, while that for $p \to e^+\pi^0$ is of order 10^{35} yrs.

The second type of SUSY $SO(10)$ model adopts a set of low-dimensional Higgs fields for symmetry breaking [26]–[32]. This includes spinors $\mathbf{16}+\overline{\mathbf{16}}$, vectors **10** and an adjoint **45** which acquires a vacuum expectation value along the $B-L$ direction of the form $\langle A\rangle = {\rm i}\sigma_2 \otimes {\rm Diag}\,(a,\ a,\ a,\ 0,\ 0)$. This has quite an interesting effect [26], [27], since it would leave a pair of Higgs doublets from the **10** naturally light, while giving superheavy mass to the color triplets – a feature that is necessary to avoid rapid proton decay – when the **45** couples to the vector **10**–plets. These models predict that the heaviest of the light neutrinos has a mass that is naturally of order one tenth of an eV, consistent with atmospheric neutrino oscillation data. This setup also allows for a predictive system for fermion masses and mixings, in combination with a flavor symmetry. Models that appear rather different in the fermion mass matrix sector result in very similar predictions for $p \to \overline{\nu}K^+$ inverse decay rate, which has been found to be typically shorter than a few times 10^{34} yrs.

Recent work in the same class of SUSY $SO(10)$ models has shown that there is an interesting correlation between the inverse decay rates for the $p \to \overline{\nu}K^+$ and $p \to e^+\pi^0$ modes. The amplitude for the former scales inversely as the three-halves power of that for the latter, with only a mild dependence on the SUSY spectrum in the constant of proportionality [32]. This intriguing correlation leads to the most interesting result that the empirical lower limit of the lifetime for $p \to \overline{\nu}K^+$ decay provides a theoretical upper limit on the lifetime for $p \to e^+\pi^0$ decay, and vice versa, as noted below.

$$\begin{aligned}
\tau(p \to e^+\pi^0) &\leq 5.7 \times 10^{34}\ \text{yrs}\,, \\
\tau(p \to \overline{\nu}K^+) &\leq \left(4 \times 10^{34}\ \text{yrs}\right) \cdot \left(\frac{m_{\tilde{q}}}{1.8\ \text{TeV}}\right)^4 \cdot \left(\frac{m_{\tilde{W}}}{190\ \text{GeV}}\right)^2 \cdot \left(\frac{3}{\tan\beta}\right)^2\ .
\end{aligned} \tag{5.2}$$

These predictions are accessible to future experiments, with an improvement in current sensitivity by about a factor of 10.

Thus, well-motivated supersymmetric GUTs generically predict proton decay rates that can be probed by next-generation experiments. One could conceive, however, variations of these predictions by either cancellation of contributions from different B- and L-violating dimension-five operators [33], by suppression of Higgsino couplings with matter, by judicious choice of the flavor structure [34], or by the largeness of the scalar masses (see, for example, [35]). For further studies see [36]–[40], and for a connection between the inflation mechanism and the proton decay rate, see, for example, [41].

Let us stress in closing that an important prediction of the simple $SU(5)$ and $SO(10)$ GUTs is that proton decay modes obey the selection rule $\Delta(B-L)=0$ and are mediated by effective operators with dim=6. A general effective operator analysis of baryon number violation reveals two conclusions [42]. One is that $\Delta B \neq 0$ operators with dim=7 always predict that $|\Delta(B-L)|=2$, which leads to decays such as $n \to e^- + \pi^+$. A similar such class of operators is those with dim=9, which leads to processes such as $n-\bar{n}$ oscillations. If these higher dimensional operators, involving mass scales that are far below the conventional GUT scale, are found to be relevant, then minimal SUSY GUTs would be excluded. In this case, however, the empirical successes of minimal SUSY GUTs would have to be regarded as fortuitous. Searches for these $(B-L)$-violating processes would thus be helpful in judging the validity of minimal SUSY GUTs.

5.1.2 Proton Decay in Extra Dimensional GUTs

The issues of Higgs doublet-triplet splitting and GUT symmetry breaking have been addressed within four-dimensional GUTs as discussed above. In higher dimensions it is possible to solve these two problems in an elegant way via boundary conditions in the extra dimensions [43]. Moreover, the successes of SUSY GUTs can be maintained [44],[45]. String theories that manifest the nice features of 4D SUSY GUTs have been constructed with a discrete Z_4^R symmetry. This symmetry prevents dimension 3 and 4 and 5 lepton and baryon number violating operators, which are potentially dangerous, to all orders in perturbation theory. The μ-term also vanishes perturbatively. However non-perturbative effects will generate a μ-term of order the SUSY breaking scale. On the other hand, the low energy theory is guaranteed to be invariant under matter parity. Thus the lightest SUSY particle is stable and is a perfect dark matter candidate.

Nucleon decay in theories with a Z_4^R symmetry [46],[47] is dominated by dimension 6 operators which lead to the classic decay modes, $p \to e^+\pi^0, \bar{\nu}\pi^+$ and $n \to \bar{\nu}\pi^0, e^+\pi^-$. The lifetime for these modes is of order $\tau \sim \frac{M_C^4}{\alpha_G^2 m_p^5}$ where M_C is the compactification scale of the extra dimension. This scale is typically less than the 4D GUT scale, *i.e.*, $M_C \leq M_G \approx 3 \times 10^{16}$ GeV. Thus the rate for nucleon decay in these modes is typically also within the reach of the next generation of experiments. Moreover, due to the different dominant decay modes, the observation of proton decay may allow one to distinguish minimal four-dimensional unification models from extra-dimensional ones.

5.2 Current and Proposed Proton Decay Search Experiments

5.2.1 Current Proton Decay Search Experiments

The current limits for proton decay searches are dominated by results from the Super-Kamiokande experiment. In the past there have been several large underground detectors that set the lower limits on the partial lifetime of various decay modes. Those were IMB and SOUDAN in the United States, Kamiokande in Japan, and Frejus in France. Among these, IMB and Kamiokande were water Cherenkov detectors, and SOUDAN and Frejus were iron tracking detectors. Since Super-Kamiokande has far surpassed the limits set by previous experiments, the challenge for the next-generation detectors will be improving the sensitivities beyond the Super-Kamiokande limits.

In the following section we describe the current proton/nucleon decay search status with the Super-Kamiokande detector.

5.2.1.1 Status of Super-Kamiokande Proton Decay Searches

The Super-Kamiokande water Cherenkov detector has excellent capability to search for nucleon decay. The 22,500-ton fiducial mass of the detector has 7.5×10^{33} protons and 6.0×10^{33} neutrons. Fully contained atmospheric neutrino interactions in the $\sim$ GeV range constitute the background to nucleon decay searches by means of neutral- and charged-current neutrino-nucleon interactions in the water. The experiment has been collecting data since 1996 and there have been four distinct data-taking periods, called SK-I, -II, -III, and -IV. During the SK-I, -III, and -IV periods, $\sim$11,000 inward-facing 20-inch photomultiplier tubes (PMTs) were distributed evenly on the entire inner detector (ID) surface to provide 40% photocathode coverage. Recovery from an accident that destroyed roughly half of the PMTs in the inner detector marked the beginning of the SK-II period, where the remaining functional PMTs were redistributed evenly across the ID surface, giving $\sim$20% photocathode coverage. This period of reduced coverage is notable for future generation water Cherenkov detectors because the Super-K nucleon decay and atmospheric neutrino analyses show that the reduction in photocathode coverage does not have a large adverse effect on the nucleon decay detection efficiency.

The two most commonly discussed decay modes are $p \to e^+\pi^0$ and $p \to \overline{\nu}K^+$. However, there are a large number of other decay modes also predicted by GUTs. Different GUTs predict that different modes will have the dominant branching fraction, making it critical for experiments to search in every mode that is accessible to their respective detectors. Non-observation of nucleon decay places strong constraints that model-builders must evade; an equally important (but more exciting) outcome is that the observation of differing rates in more than one decay channel could provide enough extra information to allow distinction among the various models of grand unification theories.

There are several methods of searching for nucleon decay in Super-K. The most straightforward method is to define a set of selection criteria that maximize the signal detection efficiency and minimize the background. The $p \to e^+\pi^0$ mode is a good example of this technique. As can be seen in Fig. 5-3, the signal region is defined by a box indicating the expected ranges of total reconstructed momentum and invariant proton mass. The background events that pass all other selection cuts (atmospheric neutrino interactions) do not typically fall into the range of momentum and invariant mass that one expects for proton decay events, making this a low-background search mode. Other searches with a similar technique have been also performed using Super-K data.

A second technique is used for some decay modes in which a low background cannot be achieved. For these modes, a "bump search" is done. An example of this is the $n \to \overline{\nu}\pi^0$ mode, where one must look for a mono-energetic peak of single π^0's on top of a background consisting mostly of neutral-current atmospheric neutrino events with a single π^0. For this type of search, understanding the shape of the background event spectrum is critical.

A third technique, which is used for the SUSY GUT favored $p \to \overline{\nu}K^+$ mode, uses a combination of the first two techniques, and an additional trick that helps to reduce the amount of background by tagging the mono-energetic low energy photon from the de-excitation of the excited nucleus that is left after the decay of a proton in ^{16}O. Using a combination of these techniques allows the measurement to push the limit on the proton decay lifetime further than using any of the individual methods.

Finally, decay modes that have a unique event topology can be searched for in Super-K as well. One example of this is dinucleon decay into two kaons, $^{16}O(pp) \to K^+K^+$. In order to improve sensitivity to the kaon modes, an improved kaon-like particle identification algorithm was implemented and a new multiple vertex finder that looks for the displaced vertices of the two kaon decays was developed. These improved tools allow Super-K to set the strongest lower limit on the partial lifetime for dinucleon decay to two kaons, which in turn can be used to constrain some supersymmetric models.

The results of all Super-K single nucleon decay searches using the various techniques described above are shown in Fig 5-3 compared with measurements from past experiments. Although no signs of nucleon decay have been seen yet, such an observation would mark a revolutionary discovery in particle physics. We need to continue searching in the current generation of large detectors, and high priority should be placed on nucleon decay searches in the next generation of neutrino detectors as well.

5.2.2 Proposed Proton Decay Search Experiments

There have been many next-generation large underground/underwater/under-ice detectors proposed to search for proton decays and do neutrino physics since UNO[48] was proposed at the first Next generation Nucleon decay and Neutrino detector (NNN) workshop at Stony Brook, New York in 1999. Some of these proposals are inactive or discontinued, while others are being actively discussed in various parts of the world. The proposed detectors can be categorized broadly in three distinctive technologies: water Cherenkov detectors, liquid argon TPCs and scintillator detectors. Table 5-2 shows a summary of these detectors categorized by technology and region.

Table 5-2. *NNN detector proposals categorized by technology and region. The detector proposals listed in parenthesis are considered inactive or discontinued.*

	Water Cherenkov	Liquid Argon	Scintillator
Europe	MEMPHYS	MODULAr, GLACIER	LENA
Japan	HyperK, Deep-TITAND (T2KK)	GLAO	
U.S.	LBNE-WCh, PINGU (UNO, 3M)	LBNE-LAr (LANDD)	TASD (SciPIO)

In the following sections some of the notable proposals contributed to this report are presented.

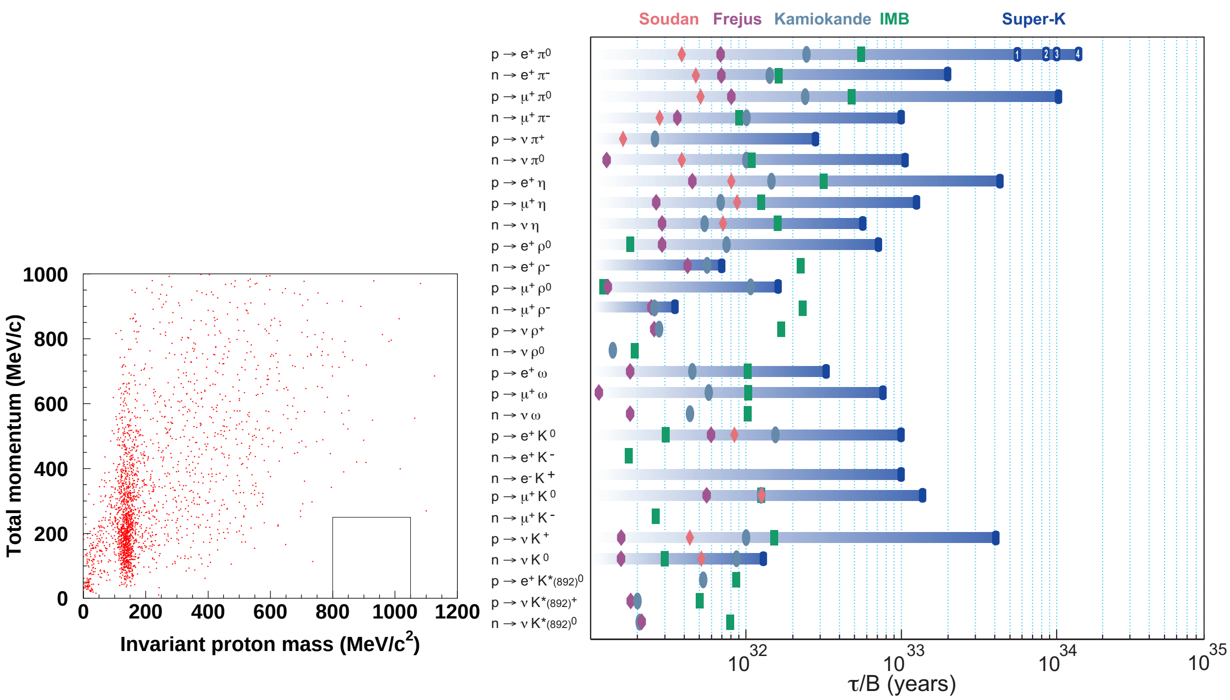

Figure 5-3. *Left Panel: SK-I+II+III+IV fully-contained dataset, with the $p \to e^+\pi^0$ signal region shown by the black box. Right Panel: Summary of experimental proton decay searches by Super-K (dark blue gradient band with marker) and previous experiments, Soudan (pink diamonds), Frejus (purple hexagons), Kamiokande (light blue ovals), and IMB (light green rectangles) [1].*

5.2.2.1 Proton Decay Searches with the Long Baseline Neutrino Experiment (LBNE)

LBNE is planning for two types of detectors at an underground site in Homestake, South Dakota: a 200 kt water Cherenkov (WCh) detector or a 34 kt liquid Argon (LAr) TPC. These detectors have complementary strengths in the search for proton decay, and either represents a considerable step forward from existing facilities. (At the time of this writing the LAr option has been chosen for the LBNE far detector technology. However, in order to be complete the proton decay sensitivities of both detector options are described in this report.)

Liquid Argon TPC: This detector would be a significant size scale-up of the current largest liquid Argon TPCs, the 300 t ICARUS modules that came into full underground operation in 2010. The plan is for two separate modules, each of 16.5 kt fiducial mass. While this is less than a factor of two larger than Super-K (22 kt), the ability to observe charged particle tracks below the Cherenkov threshold in water means that some modes poorly observed in Super-K would be much better measured in LBNE LAr. For example, there is a significant sensitivity increase for the supersymmetric grand unified theories motivated mode $p \to \bar{\nu}K^+$. The charged kaon, with a momentum of 340 MeV/c (neglecting nuclear effects), has a range of 14 cm in LAr, so ionization energy loss measurements are expected to give high particle identification efficiency. The K^+ will also decay at rest to fully reconstructable final states such as a muon with reconstructed momentum of 236 MeV/c and no other visible particle, a clear signature for $K^+ \to \mu^+\nu$ (65% branching fraction). Therefore efficiency in excess of 90% with very low background from atmospheric neutrinos is quite plausible. In contrast, since the K^+ has a relativistic gamma of 1.2, below the water Cherenkov threshold of 1.5, in Super-K this mode is measured only by the less-efficient gamma tag method. The LAr efficiency for this mode is roughly a factor of five higher than Super-K, as shown in Fig. 5-4. The top curve in the left panel shows the sensitivity that could be reached assuming the full active volume can be used. Also shown are the expectations if only one module is built (dotted) or a significant fiducial volume cut is needed (dashed) to reduce cosmogenic backgrounds. The most serious background is from neutral kaons produced by cosmic ray interactions in the surrounding rock that subsequently undergo charge exchange in the sensitive volume. These could result in the appearance of a charged kaon that mimics proton decay if the K^+ has the right momentum. This background process will be studied by measuring the rate of such events in momentum sidebands, but cutting out candidates near the side walls will eliminate such events at a cost of reduced fiducial mass. In the Bueno *et al.* paper [49], several different overburden and active veto scenarios were considered, with fiducial cuts as much as 7 meters from the wall, resulting in fiducial mass reductions ranging from 66% to 90%. A 2-meter cut from the sidewalls of the planned LBNE detector, reduces the volume by 70% from $14\times15\times71$ meters^3 to $14\times11\times67$ meters^3, corresponding roughly to the dotted lines in Fig. 5-4. The current LBNE reference design locates the LAr at the 4850-ft level of Homestake to mitigate this background; if the detector is located at the 800-ft level a substantial muon tracking veto system will also be required.

The $p \to e^+\pi^0$ mode can be detected in LAr with an expected efficiency somewhat lower than the 45% efficiency achieved in WCh, which is set by the irreducible pion absorption rate in the nucleus. Although not yet calculated explicitly, the expected efficiency reduction should scale roughly with the linear size of the nucleus. Thus a naive estimate would be $45\% \times (16/39)^{1/3} = 33\%$. Even with a very low background rate of 0.1 events per 100 kt-years [49], the improvement in sensitivity compared to Super-K is not significant.

Water Cherenkov Detector: The water Cherenkov detector planned is roughly nine times larger than Super-K, and hence for modes with no background sensitivity will simply scale with volume. For modes like $p \to e^+\pi^0$ some amount of background is expected in the LBNE regime based on measurements done by the

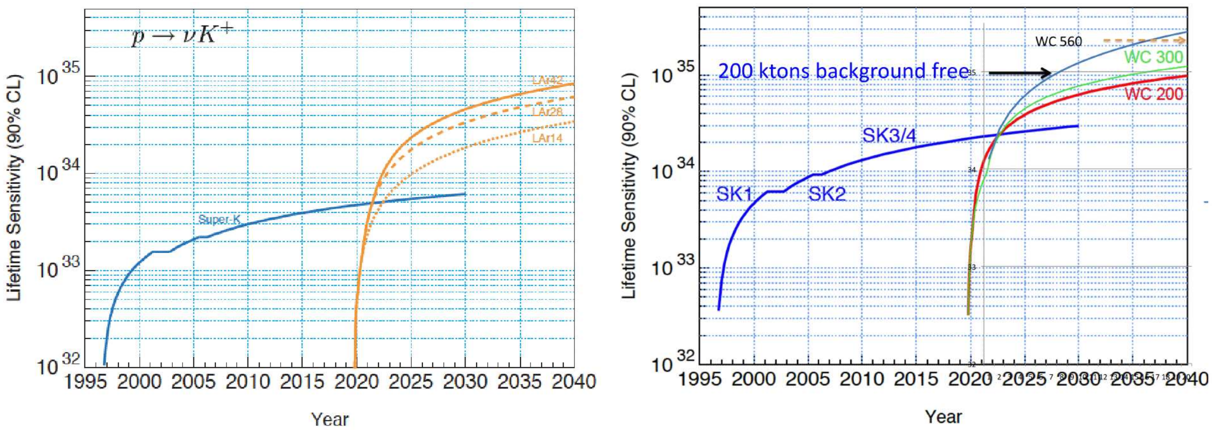

Figure 5-4. *The LBNE projected sensitivities for proton decay searches as a function of calendar year. Left panel: the sensitivity of the liquid argon detector option for the $p \to \bar{\nu}K^+$ mode; Right panel: the sensitivity of the water Cherenkov detector option for the $p \to e^+\pi^0$ mode. The dashed arrow marked as "WC 560" is the expected sensitivity by Hyper-K around year 2040, assuming, of course, it will be built as proposed.*

K2K experiment, which also validated the neutrino simulations used for the water Cherenkov experiments. The level of expected background is 2 events/Mton/year, all from atmospheric neutrino interactions.

The right panel in Fig. 5-4 shows the sensitivity that could be reached in this mode assuming no background improvements are made (red line). In fact, it may be possible to significantly reduce this background if a neutron detection capability (such as addition of Gadolinium) is realized. This is due to the fact that while 80% of proton decays in water should not have associated neutrons, atmospheric neutrino interactions are likely to produce one or more neutrons. These neutrons come from direct production via anti-neutrinos on oxygen, final state scattering of hadrons and π^- capture on oxygen, and nuclear de-excitation. The figure shows the sensitivity reached if improvements allow rejection of all atmospheric neutrino backgrounds (blue line). The actual efficiency for background rejection will require measurements in a neutrino beam, and such an experiment is being planned for the FNAL booster neutrino beam.

5.2.2.2 Proton Decay Searches with the Hyper-Kamiokande Experiment

A next-generation underground water Cherenkov detector, Hyper-Kamiokande (Hyper-K), is proposed in Japan. If built, it will serve as a far detector of a long baseline neutrino oscillation experiment envisioned for the upgraded J-PARC, and as a detector capable of observing — — — far beyond the sensitivity of Super-K — — — nucleon decays, atmospheric neutrinos, and neutrinos from astronomical origins. The baseline design of Hyper-K is based on the highly successful Super-K, taking full advantage of a well-proven technology. The total (fiducial) mass of the detector is 0.99 (0.56) million metric tons, which is about 20 (25) times larger than that of Super-K. The details of the proposed experimental setup are described in the earlier sections, and also can be found in the recently published Hyper-K Letter of Intent Abe:2011ts.

The sensitivity of Hyper-K for nucleon decays has been studied with a Monte Carlo (MC) simulation based on the Super-Kamiokande analysis. An estimate of the atmospheric neutrino background is necessarily included in the study.

Sensitivity study for the $p \rightarrow e^+\pi^0$ mode: Signal candidates for $p \rightarrow e^+\pi^0$ mode are selected with the same selection criteria used by the present Super-K analysis. The overall proton decay efficiency of $p \rightarrow e^+\pi^0$ is estimated to be 45%. The main background source of the proton decay search is the atmospheric neutrino events, which can occasionally produce an electron and a π^0 in the final state. The remaining background events are estimated to be 1.6 events/Megaton·year from the atmospheric neutrino MC simulation. This result of the MC simulation has been experimentally confirmed by the K2K experiment [51].

Fig. 5-5 shows the sensitivity for proton decay with a 90% CL as a function of the detector exposure. A 1.0×10^{35} years partial lifetime can be reached with a 4 Megaton·year exposure, which corresponds to eight years' running of Hyper-K; by contrast, it would take Super-K 178 years to reach this level.

Sensitivity study for the $p \rightarrow \overline{\nu} K^+$ mode: For the $p \rightarrow \overline{\nu} K^+$ mode K^+ itself is not visible in a water Cherenkov detector due to having a low, sub-Cherenkov threshold, momentum. However, K^+ can be identified by the decay products of $K^+ \rightarrow \mu^+ + \nu$ (64% branching fraction) and $K^+ \rightarrow \pi^+ + \pi^0$ (21% branching fraction). The muons and pions from the K^+ decays have monochromatic momenta due to being produced via two-body decays. Furthermore, when a proton in an oxygen nucleus decays, the proton hole is filled by de-excitation of another proton, resulting in γ ray emission. The probability of a 6 MeV γ ray being emitted is about 40%. This 6 MeV γ is a characteristic signal used to identify a proton decay and to reduce the atmospheric neutrino background. There are three established methods for the $p \rightarrow \overline{\nu} K^+$ mode search [52]: (1) look for single muon events with a de-excitation γ ray just before the time of the muon, since the γ ray is emitted at the time of K^+ production; (2) search for an excess of muon events with a momentum of 236 MeV/c in the momentum distribution; and (3) search for π^0 events with a momentum of 205 MeV/c. The detection efficiencies are calculated to be 7.1% for method (1), 43% for method (2), and 6.7% for method (3). The background rates from atmospheric neutrinos are 1.6, 1940, and 6.7 events/Megaton·year for methods (1), (2), and (3), respectively. The number of atmospheric neutrino background events is estimated to be 9.0 events. Fig. 5-5 shows the 90% CL sensitivity curve for the $p \rightarrow \overline{\nu} K^+$ mode, by combining all three methods, as a function of the detector exposure.

Table 5-3 shows the summary of the study for the highlighted modes, $p \rightarrow e^+\pi^0$ and $p \rightarrow \overline{\nu} K^+$. If the proton lifetime is shorter than 5.7×10^{34} years for the $p \rightarrow e^+\pi^0$ mode, or shorter than 1.0×10^{34} years for $p \rightarrow \overline{\nu} K^+$, a proton decay signal over the atmospheric neutrino background events could be discovered at a 3σ significance by collecting data corresponding to a 5.6 Megaton·year exposure.

Table 5-3. *Summary of the sensitivity study for a 5.6 Megaton·year exposure for the $p \rightarrow e^+\pi^0$ and $p \rightarrow \overline{\nu} K^+$ modes. For $p \rightarrow \overline{\nu} K^+$, method (1) μ + 6MeVγ is labeled "Meth.1", method (2) (μ) as "Meth.2", and method (3) $\pi^+\pi^0$ as "Meth.3".*

	$p \rightarrow e^+\pi^0$	$p \rightarrow \overline{\nu} K^+$		
		Meth.1	Meth.2	Meth.3
Efficiency (%)	45	7.1	43	6.7
Background (/Mton·yr)	1.6	1.6	1940	6.7
90% Sensitivity ($\times 10^{34}$ yrs)	13	2.5		
3σ Discovery potential ($\times 10^{34}$ yrs)	5.7	1.0		

There is no question that in order to explore order of magnitude longer lifetime regions than Super-K, a larger detector is absolutely necessary. As seen in this sensitivity study, if built, Hyper-K will open up a new era in the search for nucleon decay, as would LBNE.

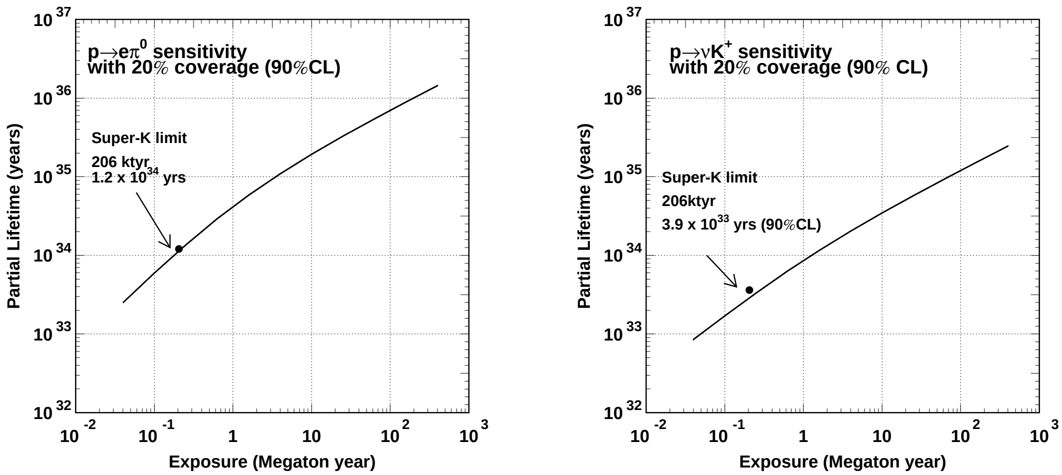

Figure 5-5. *Sensitivities of the Hyper-Kamiokande proton decay search as a function of detector exposure. Left Panel: for the* $p \to e^+\pi^0$ *mode; Right Panel: for the* $p \to \bar{\nu}K^+$ *mode*

5.2.2.3 Proton Decay Searches with the Low Energy Neutrino Astronomy (LENA) Experiment

LENA (Low Energy Neutrino Astronomy) is a proposed unsegmented liquid-scintillator detector of 50 kt target mass proposed as a true multi-purpose facility. LENA at the Pyhäsalmi mine (Finland) is one of three detector options discussed within the European LAGUNO-LBNO design study. The details of the proposed detector design are described in the "Neutrinos" chapter of this report.

While the emphasis of the LENA physics program is on low-energy neutrinos and anti-neutrinos (E<100 MeV), the experiment can also contribute to several aspects of neutrino and particle physics at GeV energies. Actually, the search for proton decay into kaons and antineutrinos was one of the first items considered to play an integral part in the LENA concept, since the visibility of the kaon's energy deposition in the scintillator substantially increases the detection efficiency in comparison to water Cherenkov detectors.

Currently, the best limits on proton lifetime are held by Super-Kamiokande, and it seems unlikely that LENA will substantially improve the limit for $p \to e^+\pi^0$. However, the sensitivity for the decay mode $p \to \bar{\nu}K^+$ is an order of magnitude larger than in water Cherenkov detectors. Moreover, the search in LENA is expected to be background-free for about 10 years, allowing a lifetime limit of $\tau_p > 4{\times}10^{34}$ yrs (90 % CL) if no event is observed.

Within the target volume of LENA, about $1.6{\times}10^{34}$ protons, both from carbon and hydrogen nuclei, are candidates for the decay. As all decay particles must be contained inside the active volume, the fiducial volume is about 5 % smaller.

In the case of protons from hydrogen nuclei ($\sim 0.25{\times}10^{34}$ protons in the fiducial volume of LENA), the proton can be assumed at rest. Therefore, the proton decay $p \to \bar{\nu}K^+$ can be considered a two-body decay problem, where K^+ and $\bar{\nu}$ always receive the same energy (105 and 339 MeV, respectively). The large sensitivity of LENA for this decay channel arises from the visibility of the ionization signal generated by the kinetic energy deposition of the kaon. A water Cherenkov detector is blind to this signal, as the kaon is produced below the Cherenkov threshold in water, reducing the detection sensitivity.

In LENA, the prompt signal of the decelerating kaon is followed by the signal arising from the decay particle(s): After $\tau_{K^+} = 12.8\,\mathrm{ns}$, the kaon decays either by $K^+ \rightarrow \mu^+\nu_\mu$ (63.43 %) or by $K^+ \rightarrow \pi^+\pi^0$ (21.13 %). In 90% of these cases, the kaon decays at rest. If so, the second signal is again monoenergetic, either corresponding to the 152 MeV kinetic energy of the μ^+ or 246 MeV from the kinetic energy of the π^+ and the rest mass of the π^0 (which decays into two gamma rays, creating electromagnetic showers). A third signal arising from the decay of the muon will be observed with a comparably large time delay.

If the proton decays inside a carbon nucleus ($\sim$1.2$\times$10^{34} protons in the fiducial volume), further nuclear effects have to be considered. First of all, since the protons are bound to the nucleus, their effective mass will be reduced by the nuclear binding energy E_b, 37 MeV and 16 MeV for protons in s-states and p-states, respectively. Secondly, decay kinematics will be altered compared to free protons due to the Fermi motion of the proton. The experimental signature of the proton decay in LENA is not substantially affected by nuclear effects or the kaon decay mode: A coincidence signal arising from the kinetic energy deposited by the kaon and from the delayed energy deposit of its decay particles will be observed.

The main background source in the energy range of the proton decay is atmospheric muon neutrinos ν_μ. Via weak charge-current interactions, these ν_μ create muons inside the detector, with a substantial fraction in the energy range relevant for the proton decay search. Moreover, additional kaons can be produced in deep inelastic scattering reactions adding to the ν_μ background.

The double signature of kaon energy deposition and decay can be used to discriminate atmospheric ν_μ events as long as the kaon decay is sufficiently delayed to produce a discernible double signal, *i.e.*, the delay is large compared to the time resolution of the detector. MC simulations show (based on 2×10^4 proton decay and muon events in the relevant energy regime) that an analysis cut can be defined which rejects all muons and retains a detection efficiency of $\varepsilon_p \approx 65\,\%$ for proton decay. The sensitivity ε_p is an order of magnitude larger than the one obtained in the Super-Kamiokande analysis, corresponding to a similar increase in the proton lifetime limit. The corresponding background rejection efficiency is at least $\varepsilon_\mu \geq 1 - 5\times10^{-5}$. This results in an upper limit of $\sim$0.05 muon events per year that are misidentified as proton decay events.

In the case of charged-current reactions of atmospheric ν_μ's at larger energies, hadrons can be produced along with the final state muon. These events are dangerous if they are able to mimic the double signature of the proton decay. While this is not the case in pion and hyperon production, interaction modes creating an additional kaon in the final state may be mistaken as signal events. In principle, these events can be discriminated by the additional decay electron of the muon created in the charged-current reaction. However, this signal is sometimes covered by the muon signal itself: Monte Carlo simulations return an upper limit of 0.06 irreducible background events per year for this channel.

Based on the efficiencies of the rise time cut, the sensitivity of LENA for the proton decay search can be determined. Combining the expected background rates from atmospheric neutrino-induced muon and kaon production, a rate of 0.11 background events per year or 1.1 events in 10 years can be obtained. In case there is no signal observed in LENA within these 10 years, the lower limit for the lifetime of the proton will be placed at $\tau_p > 4\times10^{34}$ yrs at 90 % CL If one candidate is detected, the lower limit will be reduced to $\tau_p > 3\times10^{34}$ yrs (90 % CL). LENA might also provide relevant sensitivity levels to other nucleon decay channels. While the analysis presented here is independent of the tracking capabilities of the detector, in others (e.g. $p \rightarrow e^+\pi^0$) the possibility of reconstructing the decay vertex might be necessary to discriminate background signals. However, these aspects require further studies.

5.3 Neutron Anti-Neutron ($n - \bar{n}$) Oscillation

5.3.1 Theoretical Motivation for $n - \bar{n}$ Oscillation Searches

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. Thus, discovery of 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 discovery of $n - \bar{n}$ oscillation with the selection rule $\Delta B = 2$ would point to new physics near and above the TeV scale. There also exist many models, including those with extra space dimensions at TeV scale, with local or global B or $B - L$ symmetry that do not allow proton decay, and where $n - \bar{n}$ oscillation is the only observable baryon number violating process.

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 $n - \bar{n}$ oscillations. The search for $n - \bar{n}$ oscillations will therefore supplement neutrinoless double beta decay experiments in establishing a common mechanism of these processes. In particular, an observation of $n - \bar{n}$ oscillation may indicate that the small neutrino mass is not a signal of physics at the GUT scale but rather at the scale not much above a TeV.

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 $B - L$ conserving GUT–scale–induced baryon asymmetry would be washed out at the electroweak phase transition [54]. As noted before, lepton number violating decays of the right–handed neutrino within minimal $SO(10)$–type GUTs can naturally explain the observed matter-antimatter asymmetry via the process of leptogenesis [55]. Observation of $n - \overline{n}$ oscillations at currently achievable sensitivity would, however, hint at a new mechanism for the generation of matter-antimatter asymmetry, since the baryon excess generated by leptogenesis would be washed away. It has been shown that the same physics that leads to $n - \overline{n}$ oscillation also provides a mechanism for baryogenesis at scales below the electroweak phase transition. Existing theories describing such processes typically also predict colored scalars within the reach of the LHC, along with an observable electric dipole moment of the neutron and some rare B-meson decay channels.

The probability of $n - \bar{n}$ transformation in vacuum in the absence of a magnetic field is $P \cong (t/\tau)^2$, where t is the free neutron propagation time in vacuum and τ is a characteristic oscillation time determined by new physics processes that 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. (See [53] for a review and more detailed discussion of $n - \bar{n}$ oscillation.)

5.3.2 Current and Proposed $n-\bar{n}$ Oscillation Search Experiments

5.3.2.1 Current $n-\bar{n}$ Oscillation Search Experiments

Transformation of neutrons to antineutrons with neutrons bound inside nuclei has been sought in large underground proton decay and neutrino detectors: inside iron by the Soudan-2 experiment, inside deuterium by the SNO experiment, and inside oxygen by the Super-Kamiokande experiment [56]. Compared to free neutron transformation in vacuum, the intranuclear $n-\bar{n}$ transformation is strongly suppressed by the difference of nuclear potential for neutrons and antineutrons. This suppression was calculated by quantum mechanical nuclear theoretical models [57][58].

An antineutron transformed from the neutron inside the nucleus is expected to annihilate quickly with one of the surrounding nucleons and to produce multiple secondary hadrons, mainly pions that will be available for detection. Experimentally the search for $n-\bar{n}$ transformation in all the above-mentioned experiments is limited by atmospheric neutrino backgrounds. The best result so far was obtained in the Super-Kamiokande experiment, where 24 $n-\bar{n}$ oscillation candidate events were observed for 1489 days with an estimated atmospheric neutrino background of 24.1 events. Based on this observation, the lower limit on the lifetime for neutrons bound in ^{16}O was calculated to be 1.89×10^{32} years at the 90% CL [56].

The lifetime limit for bound nucleons in an ^{16}O nucleus (T) can be converted to the $n-\bar{n}$ oscillation time for a free neutron (τ) using the relationship: $T(\text{intranuclear}) = R \cdot \tau^2_{n-\bar{n}}(\text{free})$, where R is the nuclear suppression factor [56]. Thus, the corresponding limit for the oscillation time of free neutrons from the Super-K limit can be calculated as 2.44×10^8 s using $R = 1.0 \times 10^{23}\text{s}^{-1}$ from [57]. For a more recent theoretical model[58] with $R = 0.52 \times 10^{23}\text{s}^{-1}$, one can find a limit for the free neutron oscillation time of 3.38×10^8 s.

5.3.2.2 Proposed $n-\bar{n}$ Oscillation Search Experiments

As described above, the presence of a large atmospheric neutrino background makes further improvement beyond the Super-K result on $n-\bar{n}$ oscillations in next-generation water Chrenkov detectors difficult. Alternatively, a search for $n-\bar{n}$ oscillations with free neutrons possesses excellent background rejection, also allowing the possibility of turning 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 previous experimental search for free $n-\bar{n}$ transformations using a cold neutron beam from the research reactor at Institute Laune-Langevin (ILL) in Grenoble gave a limit on $\tau > 8.6 \times 10^7$ seconds in 1991 [59]. The average velocity of the cold neutrons used was ~ 700 m/s and the average neutron observation time was ~ 0.1 s. 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 of 1-2 GeV in the surrounding calorimeter. This detection process strongly suppresses backgrounds. In one year of operation this ILL experiment saw zero candidate events.

The figure of merit for a free-neutron $n-\bar{n}$ search experiment is $N_n \times t^2$, where N_n is the number of free neutrons observed and t is the observation time. A dedicated spallation neutron source coupled to a high-intensity beam provided by Project X could be optimized for the enhanced production of slow ultra-cold (UCN) and very-cold (VCN) neutrons (velocities below ~ 100 m/s) with the use of modern neutron optics, neutron moderators, and cryogenic technologies. Significant progress has been made in the field of neutron optics since the time of the ILL experiment, and recent advances in neutron source design promise to enhance the brightness of moderators as well as reduce their effective spectral temperature. Furthermore, the existing

105m vertical shaft at Fermilab could be used to develop a vertical layout of the experiment, which provides additional gains by employing gravity to increase even further the observation time. The optimization of parameters for the target/moderator/cold-source design, neutron optical layout, neutron flight vessel (with vacuum better than 10^{-5} Pa and magnetic shielding down to 1 nT) and annihilation detector will require detailed R&D studies. An optimized design that employs all these advances would support an experiment that can achieve major improvements over the ILL sensitivity.

Experimental goal: Assuming beam power of 0.2-0.5 MW on the spallation target (e.g. with a 3 GeV proton or deuteron beam from the Project X linac), the goal of a new $n - \bar{n}$ search experiment will be to improve the sensitivity to $n - \bar{n}$ transformation probability by 3-4 orders of magnitude beyond that in the ILL-based experiment and to probe the range of the free neutron oscillation time around 10^{10} s. An antineutron annihilation detector with negligible background could allow a single observed $n - \bar{n}$ event to be a discovery. The active magnetic shielding should be tunable to suppress oscillations if needed to confirm a signal.

Timeline of $\boldsymbol{n - \bar{n}}$ experiment:An $n - \bar{n}$ experiment can be implemented with the "Nuclei" beamline of the 3 GeV linac of Project X as a 0.2 – 0.5 MW spallation target, or possibly with Main Injector or Booster beams of lower power. Two to three years of R&D research is required for the configuration optimization and the conceptual design. Provided that the vertical shaft is available, the construction stage of the experiment will take approximately 3–4 years. The anticipated running time of an $n - \bar{n}$ experiment would be 3–4 years.

5.4 Conclusions

While yet to be seen, proton decay is an indispensable tool for probing Nature at truly high energies. It remains the missing piece for evidence of grand unification. The dramatic meeting of the three gauge couplings at a scale of about 2×10^{16} GeV, which is found to occur in the context of low energy supersymmetry, and the tiny neutrino masses as observed in the neutrino oscillation experiments, lend strong support to the idea of supersymmetric grand unification. Moreover, grand unified theories that are in accord with the observed masses and mixings of all fermions, including neutrinos, typically predict proton lifetimes within a factor of five to 10 of current Super-Kamiokande limits. This is why an improved search for proton decay is now most pressing. This can only be done with a large detector built deep underground. Such a detector, coupled to a long-baseline intense neutrino beam (as would be available from Fermilab), can simultaneously sensitively study neutrino oscillations so as to shed light on neutrino mixing parameters, mass-ordering, and most importantly CP violation in the neutrino system. And it can help efficiently study supernova neutrinos. In short, such a detector would have a unique multi-purpose value with high discovery potential in all three areas.

Diverse next-generation nucleon decay and neutrino detectors based on a plausible extrapolation of existing technologies are being discussed in Europe, Japan and the US. Building such a large underground detector coupled to a long-baseline neutrino beam in the US, in a timely fashion, would not only probe a set of fundamental issues in physics, but would enable the US to assume a leadership position by having a stellar facility that would be an asset to the world as a whole. Sensitive searches for proton decay, measurements of neutrino oscillation parameters and observation of supernova neutrinos with such a large underground detector should thus be given high priority in the intensity frontier program. Proton decay, if found, would no doubt constitute a landmark discovery for mankind.

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