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THE SEARCH FOR PROTON DECAY

Report of Working Group B1, Snowmass 94

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The conservation of the quantum number called baryon number, like lepton (or family) number, is an emperical fact even though there are very good reasons to expect otherwise. Experimentalists have been searching for baryon number violating decays of the proton and neutron for decades now without success. Theorists have evolved deep understanding of the relationship between the natural forces in the development of various Grand Unified Theories (GUTs) that nearly universally predict baryon number violating proton decay, or related phenomena like n- $\overline{n}$ oscillations. With this in mind, the Proton Decay Working Group reviewed the current experimental and theoretical status of the search for baryon number violation with an eye to the advancement in the next decade.

§1 Introduction

The (particle physics) standard model is remarkably successful at describing all observed reactions among elementary particles, withstanding the tests of dozens of experiments over the last decade or so. It is commonly held that the standard model is not a complete theory of particle interactions, but instead the low-energy limit of a complete theory (such as a GUT) that has the particles and their interactions unified at a very high-energy scale. The search for new particles or new interactions of known particles is perhaps the only way that a deeper understanding will emerge.

The search for proton decay (baryon number violation) has occupied experimenters for decades, unfortunately without success. General theoretical principles suggest that baryon number may not be a conserved quantum number. If it were, there ought to be a force (and gauge boson) that couples to baryon number just as the electromagnetic force couples to electric charge; no such composition dependant force has ever been observed. We therefore expect that baryon number violating decays or oscillations will occur, although with unknown frequency. It is with this in mind that the subgroup met to discuss the current status of the search for proton decay and look at the progress that might be made in the next decade. This summary of those meetings begins with a brief theoretical overview. There are then synopses of the proton decay searches from the active experimental groups.

§2 A Theoretical Perspective

As the standard model of electroweak interactions based on the gauge symmetry $SU(3)_c \times SU(2)_L \times U(1)_Y$ keeps accumulating its trophies of success from one experiment after another, a key question facing particle physicists today is the nature of new physics beyond the standard model. There are many unanswered questions in the standard model such as the stability of the weak scale, origin of fermion mass hierarchies, solution to the strong CP problem, origin of matter in the universe, massive neutrinos, etc., that make it imperative that there be new physics beyond the weak scale. Specific issues of interest for this working group are twofold: (i) first, are there compelling scenarios of new physics that contain baryon violation as an integral part and (ii) second, do they lead to *predictions* for proton lifetime that are accessible to the next round of experiments? In this section, we will argue that the answers to the first two questions are definitely *yes*. We will then argue that there are baryon non-conserving signatures in near-electroweak TeV scale theories that involve low mass lepto-quarks as well as diquarks; therefore searching for those decay modes will complement the ongoing search for lepto-quarks in collider experiments.

Before discussing the detailed predictions/expectations for proton lifetime in various scenarios of new physics, we wish to point out the importance of the selection rules in $\Delta B \neq 0$ processes as a "barometer" of the scale of new physics [1, 2, 3, 4]. The point is that any baryon violating operator that arises from physics beyond the standard model must respect $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance and in the effective field theory below the TeV scale, these operators will manifest themselves as non-renormalizable operators. Denoting the quark and lepton doublets by Q and L and the singlets by u^c, d^c *and* e^c, one finds that in non-supersymmetric theories, the lowest dimensional operator (i. e. $QQQL$ etc.) has dimension $d = 6$ and conserves $B - L$ quantum number. It therefore scales like M^{-2} and the present limits on proton lifetime imply that $M \geq 10^{15}$ GeV or so. Thus observation of proton decay modes that respect the $B - L$ quantum number (e. g. $p \rightarrow e^+ + \pi^0$) will be a proof of the existence of new physics at scales of order of the typical grand unification scale ($\simeq 10^{15}$ GeV). On the other hand, there are processes such as neutron-anti-neutron oscillation[2], $p \rightarrow \ell\ell\ell$ decay[3], double proton decay (i.e. $pp \rightarrow e^+e^+$)[4] which scale respectively as M^{-5}, M^{-5} and M^{-8} and therefore probe new physics at much lower scales such as 100 TeV to a few TeV respectively. Therefore discovery of any baryon non-conserving process thru its selection rule will provide evidence not only for new physics but also about the scale of this new physics.

§2.1 Grand unification and proton lifetime; Generalities:

Grand unified theories (GUTs) are attractive from many points of view such as unification of forces (and therefore the gauge symmetries and couplings), unification of fermions (which provide the hope to understand the hierarchy and the structure observed in the fermion sector), understanding of electric charge quantization(ECQ) and origin of matter etc. After an initial explosion of interest in GUTs in the late 70's and early 80's, lack of any evidence for proton decay as well as the emergence of new theoretical ideas which could explain both the origin of matter as well as the quantization of electric charge led to a lull in the activity in this field.

A recent revival of interest in GUTs has been caused for two reasons: one is the precision measurement of the three gauge couplings at LEP and second, the indications of possible non-vanishing masses for neutrinos in order to understand the deficit neutrinos from the sun. Two amazing facts emerge from the precision measurements of the three gauge couplings: one is that if we assume the scale of supersymmetry breaking to be at the weak scale (in the TeV range), then the rate of variation of the gauge couplings with energy (or the slopes of the beta function) is completely fixed and implies a unification of couplings at a scale of about 2×10^{16} GeV; alternatively, if we take a nonsupersymmetric theory but supplement it with the hypothesis that the gauge symmetry expands at some scale M_I to $SU(2)_L \times SU(2)_R \times G$ where $G \equiv U(1)_{B-L} \times SU(3)_c$ or $SU(4)_c$, then again the the slopes of the beta function are fixed and unification of gauge couplings occur at about the same scale as above with $M_I \simeq 10^{12}$ GeV or so. The reason the first result is of interest is that the SUSY scale being around a Tev is one attractive way to stabilize the weak scale against radiative corrections. On the other hand, if solar neutrino results are an indication of non-vanishing neutrino masses, the values of neutrino masses that fit the solar neutrino data in the very elegant MSW scheme imply (via the so-called see-saw mechanism) a scale of $B - L$ symmetry breaking which is precisely in the range predicted by LEP data in conjunction with an SO(10) grand unified theory.

Taking these arguments seriously, one is led to contemplate two possible scenarios for grand unification: one is the supersymmetric SU(5)[5] and the second one is non-supersymmetric SO(10). The predictions for proton lifetime in both these theories has been studied extensively in recent days (for SUSY-SU(5) in [6] and for SO(10) in[7]).

§2.2 SUSY SU(5) and proton decay:

In general supersymmetric theories, the existence of superpartners of the quarks and leptons allows one to write down a dimension 5 operator that leads to $\Delta B \neq 0$ and $\Delta(B-L) = 0$ processes. In the context of the specific SUSY SU(5) model, these operators arise from the exchange of heavy color triplet Higgsinos and the above mentioned dimensionality means that they scale like $\simeq {M_U}^{-1}$. As a result, they dominate over the conventional gauge boson exchange graphs, which gave the dominant proton decay mode in non-SUSY theories such as $SU(5)$ and moreover, the symmetry properties of the $d = 5$ operator imply that the $B - L$ conserving decay mode so familiar in non-SUSY theories such as $SU(5)$ are not allowed; instead the leading decay mode becomes $p \rightarrow K^+\bar{\nu}_\mu$. The box graph that converts the raw dim 5 operator into a four-Fermi operator involves the exchange of gluinos, charginos etc. It has been shown by Arnowitt and Nath[6] that the dominant graph arises from chargino exchange and is directly proportional to the chargino mass. So a heavier chargino would lead to a more unstable proton. This dependence has been shown for proton lifetime in fig.1. One can conclude from this figure that if the decay mode $p \rightarrow K^+\bar{\nu}_\mu$ is not seen at the level of $\tau_p = 5 \times 10^{33}$ *years*, then the chargino must be light enough to be seen at LEP II; otherwise, SUSY-SU(5) will be ruled out. One caveat is that the minimal SUSY-SU(5) which leads to all these conclusions does not have a realistic fermion spectrum (e.g. it predicts the experimentally inconsistent relation $m_e/\ m_\mu \ = \ m_d/\ m_s$) and any extension of the model to correct this feature will introduce uncertainties into these predictions since unlike in the non-SUSY GUT models the proton decay predictions arise from the same coupligs in the theory that predict fermion masses.

§2.3 Non-SUSY SO(10) and proton decay:

As mentioned earlier, an alternative scenario that leads to unification of gauge couplings with a well-motivated physics input is the non-SUSY SO(10). In the minimal version of the theory, there are four possible models depending on the four possible intermediate symmetries, of the form $SU(2)_L \times SU(2)_R \times G_a$ (where $G_a \ = \ (I)\ SU(4)_c \times D;\ (II)\ SU(4)_c\ \ (III)\ SU(3)_c \times\ U(1)_{B-L} \times D$ and $(IV)\ SU(3)_c \times U(1)_{B-L}$, D denotes the discrete Z_2 gauge symmetry which is contained in SO(10)) that SO(10) can break to, depending on the choice of Higgs multiplets . All these models have enough free parameters in the Yukawa couplings so that all fermion masses can be accomodated. The dominant proton decay mode in this model is the classic decay mode $p \rightarrow e^+\pi^0$; the predictions for proton lifetime in this case has been studied in two papers recently[7] and the results are (quoted from the first paper of ref. 7):

$$\begin{aligned}
Model\ I : \tau_p \ &= \ 1.44 \times 10^{32.1 \pm .7 \pm 1 \pm 1.8} years \\
Model\ II : \tau_p \ &= \ 1.44 \times 10^{37.4 \pm .7 \pm 1^{+.5}_{-5}} years \\
Model\ III : \tau_p \ &= \ 1.44 \times 10^{34.2 \pm .7 \pm .8 \pm 1.7} years \\
Model\ IV : \tau_p \ &= \ 1.44 \times 10^{37.7 \pm .7 \pm .9^{+.5}_{-2}} years
\end{aligned}$$

In the above predictions, the first uncertainty is due to hadronic matrix elements, second is due to uncertainty in the gauge couplings and the last one is due to the heavy particle threshold corrections. In case I, we have presented an extremely conservative estimate of the threshold uncertainties but it is more likely to be of order $\simeq .2$ so that, if no evidence for proton decay mode $p \rightarrow e^+\pi^0$ is found at SuperKamiokande, then this model will be ruled out. Another signature of the inherent left-right symmetry of the SO(10) models is the equality of the branching ratios $B(p \rightarrow e^+\pi^0) = B(p \rightarrow \bar{\nu}\pi^+)$.

Finally, there is a different appraoach to minimal SO(10)[8], where a one step breaking of SO(10) down to standard model is made consistent with unification and LEP data by using the heavy particle threshold corrections. A prediction of this model is that proton lifetime must be less than 10^{34} years after all threshold corrections are taken into account. Therefore, this model will also be ruled out if no proton decay is seen at SuperKamiokande at the expected level. We conclude this section by pointing out that even null results at SuperKamiokande and ICARUS are going to provide us with important information about the future directions in grand unified theories by ruling out several very interesting GUT models.

§2.4 Baryon non-conservation as a probe of new physics at low scale:

Baryon number violating processes mediated by higher dimensional operators (such as neutron-anti-neutron oscillation, $pp \rightarrow e^+e^+$ decay or $p \rightarrow \ell\ell\ell$ decay) provide important information about physics beyond the standard model which supplement that gained from the study of the B-L conserving decay models discussed earlier. Since such processes become observable if there is new physics in the mass ranges of one to a hundred TeV, in the minimal versions of the GUT theories discussed, such processes would be unobservable. Thus any evidence for them would be an indication of physics at a nearby scale and would be an indication against simple GUT theories. Furthermore, these processes invariably arise from the exchange of either diquark Higgs bosons or leptoquark Higgs bosons of TeV range mass; therefore, any positive evidence for the any of the above processes is an indication of the existence of low mass leptoquarks /or diquarks. It is possible to construct consistent and interesting low mass scale theories [3, 2, 4] where these higher dimensional operators can arise with observable strength for natural values of the parameters.

§3 Experimental Search with IMB

IMB-3 was a large ring imaging water Čerenkov detector with a fiducial mass of 3.3 kton. During a 7.6 kton year exposure, 935 contained events were collected at a rate of approximately one event per day. This sample is largely consistent with the predicted atmospheric neutrino flux and is been used to set preliminary limits on the nucleon decay rate[10].

Unfortunately, there is significant uncertainty in the estimated background due to atmospheric neutrinos. This uncertainty comes in two forms, experimental systematic uncertainties and fundamental theoretical uncertainties. The experimental systematics have been estimated to be ~20%. The fundamental theoretical uncertainties are highlighted by the current discussion of the "missing" muon type events in IMB-3 and Kamiokande[10, 9]. In particular, IMB-3 measures the ratio of muon neutrino type events to electron neutrino type events to be 0.54 ± 0.06 when the expected ratio is 1.04 ± 0.2. This may reflect a fundamental uncertainty in the neutrino flux at the detectors, or some new physical phenomenon like neutrino oscillations.

Since there is a large uncertainty in the neutrino flux at the detector, results are presented for two different assumptions. The first assumption is that the measured muon to electron ratio represents the neutrino flux present at the detector, e.g. due to a mistake in the predicted neutrino flux. The second assumption is that the ratio of muon neutrinos to electron neutrinos present at the detector has been correctly predicted, e.g. the measured ratio is due to some experimental error. Preliminary results are presented in table 1[11]. A careful examination of table 1 shows that for many modes the statistical uncertainty is less that the systematic uncertainty in the background estimate. Unless this situation is resolved, background subtracted searches for nucleon decay will be severely hampered in future nucleon decay detectors.

§4 The Status of Soudan-II Search

The Soudan 2 detector is a calorimeter with 1 meter drift tubes occupying the voids in a stack of corrugated 1 meter square 1.6mm thick steel plates. A proportional wire system measures the charge deposited in the tubes. The detector consists of 224 modules each containing 240 layers of steel and tubes, with a total mass of 963 metric tons. Although the final modules were installed in November of 1993, the partially-completed detector has been acquiring data on throughgoing muons, atmospheric neutrino interactions and nucleon decay since 1989, when 1/4 of the final detector was operational. Approximately 1.7 Kty of exposure has been accumulated to date (July 1994), but only the first 0.5 Kty portion of this has been analyzed for possible nucleon decay signatures.

After the data have been scanned for contained event selection (the basic requirements are that the event come no closer than 20cm to the exterior of the detector and that no in-time shield hit be recorded), the events are sorted into various topological categories. Each distinct topology is then tested against a possible nucleon decay mode. Only three possible combinations of mode and topology have been analyzed thus far:

$$p \rightarrow \nu K^+ (K^+ \rightarrow \nu\mu^+, \mu^+ \rightarrow \nu\nu e^+)$$
$$n \rightarrow e^- K^+ (K^+ \rightarrow as\ above) \text{ and}$$
$$n \rightarrow \mu^- K^+ (K^+ \rightarrow as\ above).$$

(We assume the μ^- is captured before decay.).

The first of these has a 3-"track" topology, while the latter is 4-"track". The full power of the detector in the form of hit counting, track/shower separation and ionization measurement is then used to discriminate between these modes and possible neutrino-induced backgrounds.

Initially each event is rejected or accepted for further analysis based on a total hit requirement, a requirement that each track/shower assignment be appropriate, and that each real track direction is consistent with the mode. Further analyses then involve the measured kaon range and ionization, the muon range and ionization, the decay-electron's shower size, and the reconstructed momentum flow at both the K-mu and mu-e vertices. Four algorithms that utilize this information have been investigated: simple cuts (any failure rejects the candidate), a 7-dimensional nearest-neighbor analysis, a combined liklihood analysis and a neural-net determination. All of these lead to rejection conditions which can be eased (to improve the acceptance) or tightened (to reject more background). While all methods of analysis are comparable, the neural net technique is slightly superior to its rivals, and is the basis of the current (preliminary) limits (which have been set to reject background at the 1 event/5 Kty level): (1) $p \rightarrow \nu K^+$ with lifetime limit $> 4.5 \times 10^{30} yr$ and 0.10 events background, (2) $n \rightarrow e^- K^+$ with lifetime limit $> 7.5 \times 10^{30} yr$ and 0.03 events background, and (3)$n \rightarrow \mu^- K^+$ with lifetime limit $> 6.5 \times 10^{30} yr$ and 0.04 events background.

§5 Kamiokande Results and the Future: SuperKamiokande

Kamiokande is a ring imaging water Cherenkov detector that is still in operation. Its fiducial volume for nucleon decay analysis is 1,040 ton. A total of 948 20" PMT are attached inside the inner detector. The total detector exposure of $3.62kt - yr$ of KAMIOKANDE-II data are analyzed for $(B - L)$ violating nucleon decay processes. A total of 325 fully contained events were observed.

We analyzed 13 nucleon decay channels using total invariant mass, momentum imbalance and shape of momentum distributions. No statistically significant evidence of nucleon decay were obtained. Therefore, we set 90 % confidence level lower limits as shown in Table 2. We obtained 90 % C.L. life time limits as 3.3×10^{32} years $(p \rightarrow e^+\pi^0)$ and 1.3×10^{32} years $(p \rightarrow \overline{\nu}K^+)$ based on KAMIOKANDE-I+II $4.92kt - yr$ data on the $\Delta(B - L) = 0$ decay modes.

Presently the total detector exposure of Kamiokande is $7.7kt - yr$. Unfortunately, we don't have statistically significant evidence of nucleon decay and we will have at most only to 8.0 or $8.5kt - yr$ of data for the nucleon decay analysis.

Therefore, we are constructing SuperKamiokande. SuperKamiokande is a 50,000 ton water Cherenkov detector with 11,200 20" PMT. It is essentially just a scaled up version of Kamiokande. The inner detector volume is 32,000 ton, and 40% of the surface of the inner detector is covered by PMTs. The fiducial volume will be 22,000ton. SuperKamiokande will be accumulate events at 22 times rate of the present Kamiokande (and about 7 times that of IMB). We will start data taking in April 1996, and will have $100kt - yr$ of data at 2002.

The decay modes such as $e^+\gamma\gamma$... or $\mu^+\gamma\gamma$... will be background free in SuperKamiokande owing to its good momentum and position resolution. If we assume that ϵBm is same as KAM-II and neutrino B.G. is 0, the detector sensitivities on each decay mode are 10^{33-34} years. We will have to generate and analyze at least $1Mton \cdot yr$ or $10Mton \cdot yr$ of M.C. for these modes.

The nucleon decay mode, $p \rightarrow \overline{\nu}K^+$, is background limited mode in Kamiokande. However, this mode can be background free utilizing the 6.3MeV gamma coming from the decay of the daughter ^{15}N. The characteristics of this mode is 6.3MeV gamma and a delayed signal of 236 MeV μ^+. If we can distinguish γ from μ^+ with 10n sec time difference, the detector sensitivity will be 10^{33} years. There are a lot of possibilities to improve on detecting nucleon decay signal, such as $K_S(\pi^+, \pi^-)$, K_L with regeneration or charge exchange.

In conclusion, we will have $100kt-yr$ of data at the beginning of the next century, and will be accessible to 10^{34} years for $p \rightarrow e^{+}\pi^{0}$, and 10^{33} years for $p \rightarrow \overline{\nu}K^{+}$ with SuperKamiokande.

§7 The Future at ICARUS

The search for proton decay must continue. This being one of the few ways to probe the 10^{16} GeV energy scale. The ICARUS detector is partially designed as a dedicated proton decay detector.

ICARUS is ideally suited to take up such a challenge by providing both a large sensitive mass (5,000 tons of liquid argon per module) and a new detector technique which can best be thought of as a modern version of the bubble chamber. As will be described in detail below, a proton decay will provide unambiguous, background-free, spectacular, metre-long tracks easy to reconstruct with superb particle identification. The proton decay search will be carried out in many exclusive channels simultaneously. A clear advantage of the ICARUS technique is that discovery will be possible down to a single event, while any other existing or proposed experiment will have to rely on statistical background subtraction to eventually show the existence of a signal.

In view of the importance of the scientific issue at stake and armed with a technological breakthrough in experimental technique now to hand, the ICARUS collaboration considers the search for the proton decay as the priority of the experiment.

There exist classes of supergravity models which will obviously be tested by a combination of LEP and ICARUS, since they predict that either $\tau(\mathrm{p} \rightarrow \overline{\nu}\mathrm{K}^{+})$ will be smaller than 1.5 x 10^{33} years (which is well within ICARUS range) or that one of the gauginos or one of the Higgs particles will be discovered at LEP200.

Particle identification benefits greatly from the ability to measure the ionization loss (dE/dx). In particular, using dE/dx versus range only, an excellent separation is obtained between pions and kaons. The separation between kaons and pions is obvious even here where we make use of the dE/dx information only. If one takes into account that, in addition, energy and topology information are also available, it is easy to understand that the proton decays can clearly be identified event per event, and, for most channels, it is not necessary to relay on statistical methods to eventually extract a signal.

In the absence of background, the limit on the nucleon lifetime reachable in T years of observation is given by the simple formulae:

$\tau_P > 1.2\mathrm{x}M\mathrm{x}T\mathrm{x}\eta(10^{32}\mathrm{year})$ (90% C.L.) for the proton

$\tau_n > 1.4\mathrm{x}M\mathrm{x}T\mathrm{x}\eta(10^{32}\mathrm{year})$ (90% C.L.) for the neutron

where M is the detector mass in kton and η is the overall detection efficiency. Proton decay events are characterized by a definite value of the total energy and by the fact that the total momentum of the decay products must be zero. These features, which are true for a free nucleon, are also approximately verified for a nucleon bound in a nucleus, provided the decay products do not rescatter before escaping the nucleus. As a consequence, we also include in our definition of detection efficiency $\eta = \epsilon_D \hat{\epsilon}$ the probability ϵ that the decay products do not interact with the nucleus in which they were produced, and the reconstruction efficiency ϵ_D. These nuclear effects, the distortions of the energy and momentum distributions due to the nucleon Fermi motion, and the reinteraction of decay particles with the nucleus have been studied by Monte Carlo simulation methods.

For example, for the decay mode $p \to \bar{\nu}K^+$ we obtain $\epsilon = 0.85$ and a corresponding lifetime limit $\tau_p > 4.7\mathrm{x}10^{32}$ (90% C.L.) years for one year of data-taking. This would increase the present limit by about two orders of magnitude. For this decay mode in particular (as for many others) we don't expect to have any significant background. Kaon production by atmospheric neutrinos is very rare. The probability that a charged-current neutrino interaction with emission of a proton from the argon nucleus can simulate a $p \to \bar{\nu}K^+$ decay is also expected to be negligible, because we can either distinguish the direction of motion of the charged hadron due to the increase of ionization at the end of the range, or directly recognize the kaon from the dE/dx and range measurements. However, since for this particular channel the discovery requires only one event, because of the negligible background, a lifetime of 10^{34} years is in fact reachable.

We have performed a complete study of only some of the proton decay modes of interest. Similar studies are under way. However, our detailed study of three characteristic decay modes indicates, that, except for channels such as $p \to e^+\nu\nu$ for which the topology is identical to that of atmospheric ν_e charged-current events, the background corresponding to a data-taking period of one year is negligible. It is interesting to note here that the availability of a CERN neutrino beam aimed at the Gran Sasso Laboratory would offer the possibility to directly simulate, if needed, some of the nucleon decay backgrounds.

In summary, many nucleon decay modes can be searched for simultaneously and, after only one year of data taking, ICARUS will reach or exceed most present limits. The equivalent of five years of data will take us to the unexplored region between 10^{33} and 10^{34} years for some of the most relevant channels.

§7 An Aside: n-$\overline{n}$ Oscillations

Baryon number violating processes mediated by higher dimensional operators (such as neutron-antineutron oscillation) provide important information about physics beyond the standard model that supplement that gained from the study of proton decay. Such processes become observable if there is new physics in the mass range of one to a thousand TeV; at higher mass scales, n-$\overline{n}$ oscillations are unobservable. Thus evidence for neutron-antineutron oscillations would be an indication of physics near the TeV scale. Furthermore, neutron-antineutron oscillations invariably arise from the exchange of either diquark Higgs bosons or leptoquark Higgs bosons of TeV range mass; therefore, any positive evidence for neutron-antineutron oscillations is an indication of the existence of low mass leptoquarks or diquarks.

The search for n-$\overline{n}$oscillations has been carried out to date using both a beam of free neutrons from the ILL reactor and using neutrons bound in either oxygen or iron nuclei. The best limit on the n-$\overline{n}$ oscillation time using free neutrons is $1x10^7$ sec; it is thought this can be extended to about 10^8 sec in the future. The current limit on the bound neutron's oscillation time is $1.2x10^8$ sec, from the Japanese Kamiokande water-Cherenkov (bound lifetime limit $> 4.3x10^{31}$ years) and Frejus iron calorimeter (bound lifetime limit $> 6.5x10^{31}$ years) proton decay detectors.

The signature for a bound n-$\overline{n}$ conversion event is the subsequent annihilation of the antineutron in the nucleus (on either another neutron or on a proton). Such an event has a distinct signature because it is annihilation essentially at rest. Several pions are created and they carry away the nearly 2 GeV of energy produced in the annihilation. This search can be continued into the future.

The first step could be to take advantage of the 7.7 kt-yr of data that now exists (on tape) from IMB-3. These data can extend the n-$\overline{n}$ oscillation time in oxygen to 6x10^{32} years, corresponding to a free lifetime of about 4x10^8 sec. SuperKamiokande will have a total mass of 50 kt and a fiducial mass of 20 kt, about a factor of 7 larger than IMB. Data collected from SuperK can be used to set the world's most stringent limit on the bound n-$\overline{n}$ oscillation time in oxygen to 4x10^{33} years, corresponding to a free lifeimt of about 10^9 sec, from 2 years of SuperKamiokande data.

There is the concern that the effect on the n-$\overline{n}$ oscillation time due to the neutrons being bound in the oxygen nucleus has been poorly estimated. The deuteron is the most weakly bound nucleus so such effects should be more reliable. The SNO detector, the world's only underground heavy water-Cherenkov detector, can search for bound n-$\overline{n}$ oscillations in deuterium to a bound lifetime sensitivity of 4x10^{31} years, corresponding to a free lifetime of about 2x10^8 sec, using 2 years of SNO data.

§8 Summary

Observation of nucleon decay (or another baryon number violating process) would revolutionize our view of particle physics by providing evidence for the unification of the forces. It would also establish a deep connection between quarks and leptons, providing insight into a (presently unknown) deep symmetry that connects them. Unfortunately, progress over the last decade has only been in extending the limits on the proton lifetime by one or more orders of magnitude. The next decade will see the sensitivity of the experiments extended by at least another order of magnitude, with progress beyond that difficult to predict.

Progress beyond the current experiments is hard to foresee due to the sheer size of the detectors needed to extend the sensitivity by another order of magnitude. These detectors will need to be 100 to 1,000 kilotons in size. A 1,000 kiloton detector will observe about 250 atmospheric neutrino events per day (100,000 per year). Clearly excellent detector resolution will be required to reject the atmospheric neutrino backgrounds. However, at this rate, understanding the neutrino backgrounds will be of utmost importance, perhaps even ultimately limiting the sensitivity of the search for nucleon decay.

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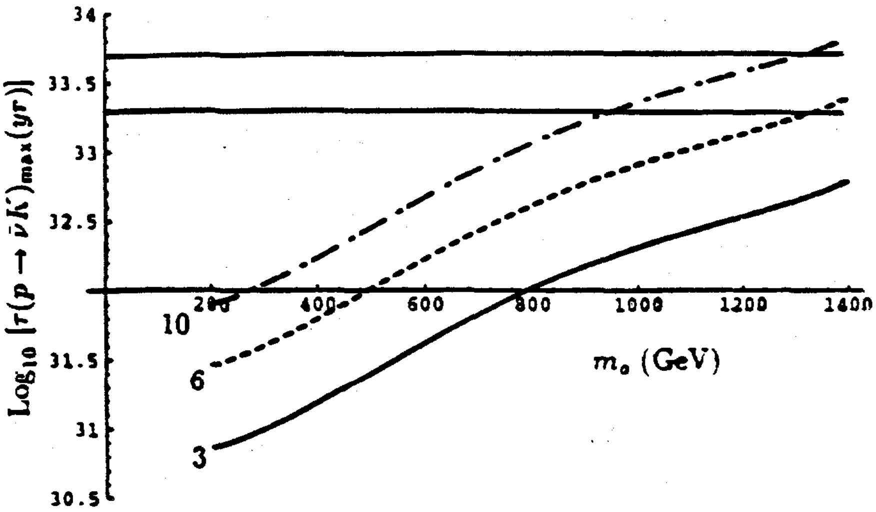

Figure 1: Dependence of the proton lifetime on the chargino mass in a SUSY-SU(5) model, for a top mass of 150 GeV. The lines represent the model predictions for different model parameters; the horizontal lines are the expected experimental sensitivities of SuperKamiokande and ICARUS.

Decay Mode	Recovery Efficiency	Candidates	Background assuming $\frac{\nu_\mu}{\nu_e} = 0.54$	Lifetime Limit	Background assuming $\frac{\nu_\mu}{\nu_e} = 1.04$	Lifetime Limit
$n \rightarrow e^+ e^- \nu$	0.57	5	7.5	518	9.3	518
$n \rightarrow e^+ K^-$	0.14	35	29.4	20	26.4	17
$n \rightarrow e^+ \pi^-$	0.30	3	5.0	270	4.8	270
$n \rightarrow e^+ \pi^- \pi^0$	0.44	38	34.2	67	30.6	53
$n \rightarrow e^+ \rho^-$	0.49	4	4.8	293	6.5	446
$n \rightarrow \mu^+ e^- \nu$	0.42	25	29.4	219	34.1	378
$n \rightarrow \mu^+ K^-$	0.10	20	28.4	90	34.0	90
$n \rightarrow \mu^+ \mu^- \nu$	0.81	100	145.0	734	188.9	734
$n \rightarrow \mu^+ \pi^-$	0.14	1	1.9	122	3.7	122
$n \rightarrow \mu^+ \pi^- \pi^0$	0.29	17	20.8	173	25.2	266
$n \rightarrow \mu^+ \rho^-$	0.36	3	9.5	324	11.5	324
$n \rightarrow \nu \eta^0$	0.17	0	1.2	158	1.1	158
$n \rightarrow \nu \gamma$	0.80	163	144.7	44	123.6	28
$n \rightarrow \nu \gamma \gamma$	0.49	5	7.5	441	9.3	441
$n \rightarrow \nu K^0$	0.21	34	34.1	48	30.6	35
$n \rightarrow \nu K^{*0}$	0.51	40	50.0	455	56.4	455
$n \rightarrow \nu \omega^0$	0.28	12	22.5	252	26.7	252
$n \rightarrow \nu \pi^0$	0.30	6	6.6	149	7.5	186
$p \rightarrow e^- \pi^+ K^+$	0.46	81	127.2	518	160.3	518
$p \rightarrow e^+ \eta^0$	0.28	0	0.2	315	0.2	315
$p \rightarrow e^+ e^+ e^-$	0.71	0	0.5	799	0.9	799
$p \rightarrow e^+ \gamma$	0.60	0	0.1	675	0.1	675
$p \rightarrow e^+ K^0$	0.12	23	25.2	55	26.4	68
$p \rightarrow e^+ K^{*0}$	0.39	38	52.0	433	61.1	433
$p \rightarrow e^+ \mu^+ \mu^-$	0.47	1	0.9	396	1.2	429
$p \rightarrow e^+ \nu \nu$	0.32	152	153.7	49	138.7	26
$p \rightarrow e^+ \omega^0$	0.21	7	10.8	236	13.5	236
$p \rightarrow e^+ \pi^0$	0.48	0	0.2	540	0.2	540
$p \rightarrow e^+ \pi^0 \pi^0$	0.26	2	0.8	147	0.7	143
$p \rightarrow e^+ \pi^+ \pi^-$	0.23	16	23.1	253	27.2	253
$p \rightarrow \mu^- \pi^+ K^+$	0.40	3	4.0	349	5.6	444
$p \rightarrow \mu^+ \eta^0$	0.23	3	2.8	144	2.8	145
$p \rightarrow \mu^+ e^+ e^-$	0.47	0	1.0	529	1.1	529
$p \rightarrow \mu^+ \gamma$	0.42	0	0.1	478	0.2	478
$p \rightarrow \mu^+ K^0$	0.19	4	7.2	214	9.5	214
$p \rightarrow \mu^+ \mu^+ \mu^-$	0.60	0	0.3	675	0.4	675
$p \rightarrow \mu^+ \omega^0$	0.33	11	12.1	171	21.5	371
$p \rightarrow \mu^+ \pi^0$	0.42	0	0.6	473	0.6	473
$p \rightarrow \mu^+ \pi^0 \pi^0$	0.20	3	1.6	103	1.7	103
$p \rightarrow \mu^+ \pi^+ \pi^-$	0.44	25	38.0	495	45.1	495
$p \rightarrow \nu K^+$	0.41	15	21.4	461	29.5	461
$p \rightarrow \nu K^{*+}$	0.11	7	9.1	92	11.3	124
$p \rightarrow \nu \pi^+$	0.03	15	20.3	34	23.5	34
$p \rightarrow \nu \rho^+$	0.54	18	21.7	385	25.1	608

Table 1: Nucleon decay limits determined using the IMB-3 Detector. The estimated background and limits are presented for two situations; the ratio of muon neutrinos to electron neutrinos at the detector is the measured value of $\frac{\nu_\mu}{\nu_e} = 0.54$, or the ratio is the predicted value of $\frac{\nu_\mu}{\nu_e} = 1.04$

Table 2: Summary of result of each nucleon decay mode from Kamiokande.

decay mode	# of ev	ν M.C.	$\epsilon \cdot B_m$	τ/B sub. ($10^{31} yr$)	τ/B unsub. ($10^{31} yr$)
$n \rightarrow e^-\pi^+$	0	<0.2	0.28	12	12
$n \rightarrow \mu^-\pi^+$	0	<0.2	0.18	7.5	7.5
$n \rightarrow e^+e^-\nu$	3	1.0	0.68	12	9.8
$n \rightarrow \mu^+\mu^-\nu$	0	1.8	0.50	20	20
$n \rightarrow e^-\mu^+\nu$	3	4.0	0.58	14	8.4
$p \rightarrow e^+\nu\nu$	81	76(46)(1)	0.91	2.3	1.2
$p \rightarrow \mu^+\nu\nu$	39	82(49)(1)	0.78	13	1.9
$p \rightarrow e^-\pi^+\pi^+$	1	1.4	0.27	11	8.4
$p \rightarrow \mu^-\pi^+\pi^+$	0	0.5	0.29	15	15
$n \rightarrow e^-\pi^+\pi^0$	0	<0.2	0.06	3.3	3.3
$n \rightarrow \mu^-\pi^+\pi^0$	0	0.5	0.17	7.9	7.9
$n \rightarrow e^-K^+(\mu^+\nu)$	0	0.5	0.34	15	15
$(\pi^+\pi^0)$	0	0.5	0.02		
$n \rightarrow \mu^-K^+(\mu^+\nu)$	0	0.2	0.35	17	17
$(\pi^+\pi^0)$	0	<0.2	0.05		

(1) A number in parenthesis is multiplied by a factor 0.6 for the conservative estimate of the neutrino background.