PROSPECTS FOR FUTURE EXPERIMENTS TO SEARCH FOR NUCLEON DECAY

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Summary

We review the status of theoretical expectations and experimental searches for nucleon decay, and predict the sensitivities which could be reached by future experiments. For the immediate future, we concur with the conclusions of the 1982 Summer Workshop on Proton Decay Experiments:[1] all detectors now in operation or construction will be relatively insensitive to some potentially important decay modes. Next-generation experiments must therefore be designed to search for these modes, and should be undertaken whether or not present experiments detect nucleon decay in other modes. These future experiments should be designed to push the lifetime limits on all decay modes to the levels at which irreducible cosmic-ray neutrino-induced backgrounds become important. Since the technology for these next-generation experiments is available now, the timetable for starting work on them will be determined by funding constraints and not by the need for extensive development of detectors. Efforts to develop advanced detector techniques should also be pursued, in order to mount more sensitive searches than can be envisioned using current technology, or to provide the most precise measurements possible of the properties of the nucleon decay interaction if it should occur at a detectable rate.

Theoretical Overview

Much of the current interest in proton decay is motivated by grand unified theories (GUT's)[2,3] of strong and electroweak interactions. Those theories embed the standard SU(3) × SU(2) × U(1) model in simple gauge groups such as SU(5) or SO(10), and thereby necessarily assign quarks and leptons to common irreducible representations. As a result, new interactions are automatically present which transform quarks and leptons into one another. Such interactions violate baryon and lepton number conservation (although B − L is often conserved; see discussion below). The most dramatic consequence of this is proton decay. Of course the proton is known to be rather stable,[4] $\tau_p^{exp} \gtrsim 10^{30}$ yr, so these new interactions must be highly suppressed. In most GUT's, τ_p scales as m_X^4, where m_X is the unification mass scale ($1/m_X$ is the distance at which all interaction strengths become equal). If one assumes the "desert" hypothesis, i.e., that there are no intermediate mass scales between 10^2 GeV and m_X, then one can calculate m_X, which turns out to be in the range 10^{14} to 10^{15} GeV, implying a proton lifetime very close to the present experimental bound.

Cosmology also suggests that baryon and lepton number are not absolutely conserved. The universe is observed to be matter dominated. Within the framework of big-bang cosmology, one can understand this matter-antimatter asymmetry if B, L and CP were violated during the early evolution of the universe. GUT's provide these necessary ingredients and thus offer a natural explanation for the asymmetry.

Why have GUT's become so popular recently? After all, they have been around since 1974.[2] Besides their attractive elegance, this popularity is primarily due to one very successful prediction of the Georgi-Glashow minimal SU(5) model. Using the fine structure constant α and the QCD mass scale parameter $\Lambda_{\overline{MS}}$ as input, one finds in the case of minimal SU(5)[5,6]

$$\sin^2\hat{\theta}_W(m_W) = 0.214 + 0.006\ln(0.16\ \mathrm{GeV}/\Lambda_{\overline{MS}}) \qquad (1a)$$

for the weak mixing angle. Employing the current world average,[7] $\Lambda_{\overline{MS}} = 0.16^{+0.10}_{-0.08}$ GeV, this formula yields the prediction

$$\sin^2\hat{\theta}_W(m_W) = 0.214^{+0.004}_{-0.003}\ , \qquad (1b)$$

which is to be compared with the experimental average (including radiative corrections)[8]

$$\sin^2\hat{\theta}_W(m_W)^{exp} = 0.215 \pm 0.014\quad . \qquad (1c)$$

The excellent agreement between theory and experiment provides impressive support for grand unification and in particular for the minimal SU(5) model.

Grand unification models also predict proton decay (as well as baryon-number violating neutron decay) and the existence of very massive (≈10^{16} GeV) magnetic monopoles. In the minimal SU(5) model, for example, the proton lifetime is predicted to be:[9]

$$\tau_p \simeq 2 \times 10^{29\pm 2}\ \mathrm{yr}\quad , \qquad (2)$$

where the ±2 in the exponent represents a conservative estimate of the uncertainties in $\Lambda_{\overline{MS}}$ ($\tau \propto \Lambda_{\overline{MS}}^4$) and in the proton-decay matrix elements. The central value in eq.(2) is already below the experimental bounds on τ_p, but the uncertainty in the calculations is quite large (a factor of 100!). In addition, by enlarging the Higgs scalar sector of the SU(5) model one could further increase τ_p without significantly modifying $\sin^2\hat{\theta}_W(m_W)$.[9,10] Nevertheless, the ongoing generation of proton decay searches[1], which are sensitive up to $\tau_p \simeq 10^{32}$ yr, should provide an important test of the minimal SU(5) model.

Although the minimal SU(5) model has scored an impressive success in correctly predicting the now measured value of $\sin^2\hat{\theta}_W(m_W)$, a large class of GUT's can accommodate a similar weak mixing angle. Therefore, in analyzing the goals and prospects for nucleon decay experiments, it is desirable to use as general and model-independent a theoretical framework as possible. Present upper bounds on the nucleon decay rate require that such a decay be mediated by particles with masses much greater than m_N or indeed m_W. Hence, as well as the presumably exact SU(3) color and U(1) electromagnetic symmetries, weak SU(2) is an extremely good symmetry at this mass scale. Based on this fact alone, one can carry out a far-reaching analysis of the types of operators which can contribute to nucleon decay.[11] First, one observes that the operators which are responsible for such a decay are SU(3) × SU(2) × U(1) invariant. Now, in order for an operator to be a color singlet and mediate nucleon decay, it must involve three quark fields. Further, in order for it to be Lorentz invariant, it must be a product of a minimum of four fermion fields, of which the fourth must be a lepton. Such an operator has dimension d = 6 in mass units. Operators of higher dimension are suppressed by powers of the nucleon mass over the much larger mass characterizing the decay interaction. In particular, if one assumes that there are only two mass scales in the theory, namely the low-energy scale of 1-100 GeV and the high energy unification scale of $\sim 10^{14}$ GeV, then higher dimension operators are completely negligible. If one allows the possibility of intermediate mass scales,[12] then the situation becomes more complicated; this matter is discussed further below and in the report on $n \leftrightarrow \bar{n}$ transitions in these Proceedings.

There are then six dominant SU(3) × SU(2) × U(1)-invariant, Lorentz-invariant, four-fermion operators relevant for baryon decay; these are (assuming no ν_R fields):

$$O_1 = \varepsilon_{\alpha\beta\gamma}\,[u^{T\alpha}_{Rg_1}\ C\ u^{\beta}_{Rg_2}][d^{T\gamma}_{Rg_3}\ C\ e_{Rg_4}] \tag{3a}$$

$$O_2 = \varepsilon_{\alpha\beta\gamma}\,[u^{T\alpha}_{Rg_1}\ C\ d^{\beta}_{Rg_2}][u^{T\gamma}_{Rg_3}\ C\ e_{Rg_4}] \tag{3b}$$

$$O_3 = \varepsilon_{\alpha\beta\gamma}\,\varepsilon_{ij}\,[q^{Ti\alpha}_{Lg_1}\ C\ q^{j\beta}_{Lg_2}][u^{T\gamma}_{Rg_3}\ C\ e_{Rg_4}] \tag{3c}$$

$$O_4 = \varepsilon_{\alpha\beta\gamma}\,\varepsilon_{ij}\,[u^{T}_{Rg_1}\ C\ d_{Rg_2}][q^{Ti\gamma}_{Lg_3}\ C\ \ell^{j}_{Lg_4}] \tag{3d}$$

$$O_5 = \varepsilon_{\alpha\beta\gamma}\,\varepsilon_{ij}\,\varepsilon_{km}\,[q^{Ti\alpha}_{Lg_1}\ C\ q^{j\beta}_{Lg_2}][q^{Tk\gamma}_{Lg_3}\ C\ \ell^{m}_{Lg_4}] \tag{3e}$$

$$O_6 = \varepsilon_{\alpha\beta\gamma}\,(\varepsilon_{ik}\varepsilon_{jm} + \varepsilon_{im}\varepsilon_{jk})[q^{Ti\alpha}_{Lg_1}\ C\ q^{j\beta}_{Lg_2}][q^{Tk\gamma}_{Lg_3}\ C\ \ell^{m}_{Lg_4}] \tag{3f}$$

where α, β, and γ are SU(3) color indices; i,j, etc. are weak SU(2) indices; g_i are generation indices (e.g., $e_1 = e$, $e_2 = \mu, \ldots$); u_R, d_R, and e_R are the right-handed components of the up-quark, down-quark, and charged-lepton fields; $q_L = (u_L, d_L)$ and $\ell_L = (\nu_L, e_L)$ are the left-handed quark and lepton doublets; and $\varepsilon_{\alpha\beta\gamma}$ and ε_{ij} are the totally antisymmetric SU(3) and SU(2) tensors, respectively. If one neglects small mixing effects, then only first generation operators contribute to nucleon decay. In this one-generation case the operators O_1 and O_6 vanish. The six operators given in eq.(3) are listed in order of increasing complexity with regard to the SU(2) factor group. This order differs from that used by Weinberg[11]: the correspondence is $\{O_1, O_2, \ldots, O_6\}$ used here = $\{O_6, O_5, O_2, O_1, O_3, O_4\}$ used by Weinberg.

Which operators among the total set of six do contribute depends on the presence in the theory of various kinds of particles which can mediate baryon decay. Again, one can classify these particles on the basis of their transformation properties under the standard SU(3) × SU(2) × U(1) theory without having to delve into model-dependent features of specific grand unified theories. The resulting correlations are given in Table I. For example, in the standard minimal SU(5) GUT, assuming vector-boson (X,Y) mediated nucleon decay, the only column which applies is that for $X_V(-1/3,-4/3)$, and the only operators which contribute are O_3 and O_4.

There are several important selection rules which follow from this analysis and are subject to experimental test:[11]

1. $\Delta(B-L) = 0$, so that, for example, the decay $p \to e^+\pi^o$ is allowed, as is $n \to e^+\pi^-$, whereas the modes $p \to e^-\pi^+\pi^+$ and $n \to e^-\pi^+$ are forbidden. One can evade this rule and break the B-L symmetry by introducing one or more intermediate mass scales (associated with Higgs particles which can mediate (B-L)-violating decays and $n \leftrightarrow \bar{n}$ transitions) and using six-fermion operators. Thus, it is very important for experiments to search for (B-L)-violating nucleon decays as a test of the desert hypothesis.

2. $\Delta S/\Delta B \le 0$, so that, for example, $p \to e^+K^o$, but not $p \to e^+\bar{K}^o$ or $n \to e^+K^-$.

3. $\Delta I = 1/2$, which leads to relations between various decay rates, such as

$$\Gamma(p \to \ell^+_R\,\pi^o) = \frac{1}{2}\,\Gamma(n \to \ell^+_R\,\pi^-) \tag{4}$$

and

$$\Gamma(p \to \ell^+_L\,\pi^o) = \frac{1}{2}\,\Gamma(n \to \ell^+_L\,\pi^-) \quad . \tag{5}$$

Table I

Classification of operators that result from the the set of fields which can mediate nucleon decay. The numbers at the top are the (SU_3,SU_2) representations, while the numbers in parentheses are the electric charges of the fields. Operators O_1 and O_6 vanish for the case of one generation. The symbol Y (yes) indicates that the operator would result if the given mediating field were present in the GUT.

(SU_3,SU_2) representation:	(3,2)		(3,1)		(3,3)
Mediating Field:	$X_V(-\frac{1}{3}, -\frac{4}{3})$	$X'_V(\frac{1}{3}, -\frac{2}{3})$	$X_S(-\frac{1}{3})$	$X'_S(-\frac{4}{3})$	$X''_S(\frac{2}{3}, -\frac{1}{3}, -\frac{4}{3})$
Operator					
O_1				Y	
O_2			Y		
O_3	Y		Y		
O_4	Y	Y	Y		
O_5			Y		
O_6					Y

In the case $\ell = \mu$, if one can measure the μ helicity, one could test these relations. More simply, one can test the implied relation

$$\Gamma(p \rightarrow \ell^{+}\pi^{o}) = \frac{1}{2}\,\Gamma(n \rightarrow \ell^{+}\pi^{-}) \quad . \qquad (6)$$

There are also other relations involving decay modes with (anti)neutrinos in the final state, but one anticipates that these would be much more difficult to test experimentally, since the usual criteria $E_{tot} = m_N$ and $\vec{p}_{tot} = 0 \pm O$(Fermi motion corrections) cannot be effectively applied.

4. Lepton polarizations. If, indeed, nucleon decay is dominantly mediated by vector bosons rather than scalar bosons (which is plausible if the latter have strengths suppressed by small Yukawa couplings), then the lepton polarizations are definitely predicted for $\Delta S = 0$ and for $\Delta S = 1$ modes, in terms of the coefficients of the operators O_3 and O_4.

From this discussion it is clear that an important goal for future nucleon decay experiments should be to perform tests to elucidate the fundamental composition of the operators contributing to the process, as well as, for example, determining actual branching ratios for specific decay modes. As is well known, there have been many different attempts to calculate these exclusive branching ratios with a rather large scatter of results.

An additional exciting issue pertains to the possibility that nature is well described by a supersymmetric GUT at sufficiently high energy and, as a consequence, the branching ratios for baryon decays may be significantly different from those in an ordinary GUT (with the caveat that even in the latter case these can only be estimated with rough accuracy). For example,[13] in one class of supersymmetric GUT's, the decay mode $p \rightarrow \bar{\nu}_{\tau}K^{+}$ would have a branching ratio much larger than that for the usual decay $p \rightarrow e^{+}\pi^{o}$. Of course, this has obvious implications for present water Cerenkov detectors, which are not very sensitive to the kaon decay mode. As before, this underlines the importance of well-instrumented, fine-grained, massive detectors for the next generations of nucleon decay experiments.

The Present Experimental Situation

Worldwide, there are currently eight experiments, either in operation or under construction, which have been designed specifically to search for proton decay. We refer to these as the "first generation" of proton decay experiments, and distinguish them from earlier, completed experiments which obtained limits on the proton lifetime only as byproducts from underground detectors which were designed to study cosmic-ray physics. It is likely that in a few years time, the first generation experiments will have achieved a considerably improved sensitivity to proton decay, so it is important to understand what their capabilities will be before commitments are made to the "second generation" of proton decay experiments. This question was considered in depth at the 1982 Summer Workshop on Proton Decay Experiments,[1] so we will only summarize the most important points here.

The sensitivity of a given detector to proton decay is determined both by the total number of nucleons monitored times the observation time and by the background rejection capabilities. Typically, the sensitivity of a particular experiment is quite dependent on decay mode, and different detectors may have very different sensitivities to a given decay mode. Maximum sensitivity requires that decays be separable from background on an event-by-event basis, and that no important background subtraction is needed. This is particularly true in the present situation, where the first priority must be to establish either convincing evidence for the existence of proton decay, or the most restrictive lower limits on the lifetime for each decay mode.

The most important backgrounds to nucleon decay result from the interactions of cosmic-ray muons and neutrinos (produced in the earth's atmosphere), both in the detector itself and in the surrounding rock. All experiments plan to reject the muon-induced background to a very low level by some combination of passive shielding (depth) and active shielding (particle detectors surrounding the experiment). Typically, the outer part of the detector itself is used as an element of the active shield: decay candidate events must be totally contained within the detector, and the vertex must not be too close to an edge. Cosmic-ray muons and charged particles from muon interactions are easily rejected by all detectors. The most important muon-induced background comes from showers in the rock; these can send unaccompanied neutral particles into the detector, which then interact within the fiducial mass to produce contained events which resemble nucleon decay.[14] The rate of such events can be reduced to an arbitrarily low level by attenuation of the incident muon flux (depth) and by placing the active shield close to the rock in order to detect charged particles from showers in the rock. These techniques seem to be capable of achieving adequate background rejection at depths greater than about 1500 meters of water equivalent, with more elaborate active shields needed at the shallower depths. The criterion for adequate rejection of muon-induced backgrounds is simply that the residual background to proton decay be much less than that from neutrino interactions, which is independent of both depth and active shield efficiency.

The atmospheric-neutrino-induced background sets the ultimate limits to the sensitivity to proton decay, since at some lifetime level neutrino interactions will be indistinguishable from decay events. This problem is exacerbated by the fact that all detectors use nuclear matter as the primary source of nucleons, and the Fermi motion of individual nucleons limits the usefulness of good energy and angular resolution in distinguishing decays from neutrino background events. Typically, the neutrino background will be indistinguishable from decays at nucleon lifetimes in the range of 10^{30} years to 10^{33} years, depending strongly on the decay mode and on the detection technique. Detectors must have good energy and angular resolution, particle identification, multi-track reconstruction capability, and the ability to determine the direction of motion of particles if they are to achieve the best rejection of neutrino backgrounds. As detectors are made larger in order to be sensitive to longer nucleon lifetimes, they must also achieve better background rejection by providing more detailed information about each event.

Three types of detectors are currently being employed in the search for proton decay: very large water Cerenkov counters, totally active calorimeters (typically using liquid scintillator), and fine-grained sampling calorimeters (typically using gas track chambers in an iron matrix). The parameters of the eight "first generation" experiments[4,15-21] are summarized in Table II. These experiments differ signficantly in their ability to reject background and in the number of nucleons monitored for decays. Most of them have had little or no operating experience. The ultimate sensitivity for many decay modes will be determined by the background rejection, which is as

Table II

Summary of the Parameters of the First Generation Proton Decay Experiments

Detector Location	Material	Total Mass (fiducial mass)	Technique	$\sigma_{E/E}$ ($e^+\pi^o$)	Direction of Motion?	Muon Decay?	Status
Homestake I,[4] South Dakota	water	300 tons (150 tons)	Cerenkov light, μ decay	---	yes (timing)	yes	Completed
Soudan 1,[15] Minnesota	Fe-concrete	30 tons (16 tons)	gas proportional tubes	25%	yes (dE/dx)	yes (μ^+)	Operating (Oct.'81)
IMB,[16] Ohio	water	7000 tons (3000 tons)	water Cerenkov	10%	yes (Cerenkov, timing)	yes	Operating (July '82)
HPW,[17] Utah	water	800 tons (600 tons)	water Cerenkov	10%	yes (Cerenkov, timing)	yes	Operating (July '82)
Kamioka,[18] Japan	water	3000 tons (1000 tons)	water Cerenkov	5%	yes (Cerenkov)	yes	Constr. (Jan.'83)
KGF,[19] India	iron	140 tons (100 tons)	gas proportional tubes	30%	topology only	yes (μ^+)	Operating (Nov.'80)
NUSEX,[20] Italy	iron	150 tons (100 tons)	streamer tubes	20%	topology only	yes (μ^+)	Operating (June'82)
Frejus,[21] France	iron	1500 tons (1000 tons)	flash chambers, Geiger tubes	15%	topology only	no	Constr. (1984)

yet unmeasured. In fact, kiloton-scale experiments have never before been operated deep underground, so the background processes themselves have not yet been directly measured at the level relevant for nucleon decay experiments.

These uncertainties in the nature of the backgrounds and in detector performance lead to considerable uncertainty in any predictions of the level of sensitivity to the various decay modes. We have nevertheless tried to indicate in Fig. 1 our best guesses, both for the first generation detectors and for future experiments. Despite the uncertainties, it is clear that some decay modes will be very poorly studied by the first generation detectors, due to confusion with background processes. The best example is the mode predicted to dominate by some supersymmetric theories, $p \rightarrow \bar{\nu}_\tau K^+$, $K^+ \rightarrow \mu^+\nu_\mu$. Such decays will usually appear as "Vee's", which will be easily confused with neutrino interactions unless the directions of motion of the K^+ and μ^+ are known. Identification of the K^+ and the μ^+ (either by ionization or by decay time), and measurement of their energies will also be essential for the best rejection of neutrino-induced background. Of the first generation experiments, only Frejus has the potential for detecting this mode efficiently, but it is severely hampered by the lack of information on ionization, track direction, and muon decay. Thus, it is conceivable that if protons decay entirely into $\bar{\nu}_\tau K^+$ with a lifetime of 10^{31} years, proton decay could be missed by first generation experiments. This conclusion was one important reason that the 1982 Proton Decay Workshop[1] recommended that work on a second generation of fine-grained detectors should be started as soon as possible. Similar "blind spots" occur in other decay modes as well (e.g. in most modes containing a neutrino in the final state), and are symptomatic of the shortcomings of the first generation experiments.

If nucleon decays are actually detected by these experiments, it will be important to measure the branching ratios into as many modes as possible, and here again, the potential capabilities of second generation experiments will be important. None of the large experiments (IMB, Kamioka, Frejus) will be able to distinguish μ^+ from μ^-, and only Frejus can tell π^+ from π^-. The lack of dE/dx ionization measurements and of muon-decay detection are serious shortcomings of the Frejus experiment which could be rectified in second generation experiments using existing techniques.

Second Generation Experiments

Second generation proton decay experiments must necessarily be able to identify those nucleon decay modes which are not unambiguously detected by the first generation experiments. If the first generation experiments discover nucleon decay, it is likely to be in a mode which is detectable with good efficiency such as $p \rightarrow e^+\pi^o$. The second generation will then be needed to determine the exact structure of the grand unified theory through a measurement of branching fractions into other decay modes. It may also happen that the first generation experiments will not observe nucleon decay. In that case, a second generation of experiments will be necessary to search for decays in modes to which the first generation is less sensitive. It is possible that the dominant decay modes, even within the framework of SU(5), can only be found by a detector with wider capabilities than those of the first generation. The history of physics provides many examples of experiments which should have been sensitive to a rare but fundamental signal, but did not make the discovery. For example, "second generation" experiments were needed, sometimes being mounted many years after initial null results, in the discoveries of parity violation, neutral currents, $K \rightarrow \mu\mu$, ψ/J, and atomic parity violation.

For all possible results of the first generation of experiments, including observation of a signal which cannot be unambiguously separated from background, a second generation of nucleon decay experiments will be necessary. Furthermore, the design criteria for such experiments will be the same no matter what the outcome of the first generation. Details of this argument are given by the report of the Langacker group at the 1982 Proton Decay Workshop.[1] In order to detect all of the possible nucleon decay modes, such as those predicted by the theories outlined in Table III, a second-generation nucleon decay detector should be a tracking calorimeter with a fiducial mass greater than 1 kiloton, and should be expandable to about 10 kilotons in stages. This detector should measure the energies and directions of all tracks, identify particles from their tracks, determine the charges of particles, and have good multitrack reconstruction ability. At least three proposals exist for such second-generation proton decay detectors.[22-24] Table IV compares the properties of the proposed detectors among themselves and with a hypothetical water Cerenkov experiment with 20-inch diameter phototubes. (Table IV is an expanded version of a table from the report of the Grant group at the 1982 Proton Decay Workshop.[1]) Both the active liquid-scintillator type of detector and the fine-grained sampling calorimeter fulfill all the requirements of a second generation experiment.

Since the design of the second generation experiments is independent of the results of the experiments now in operation or under construction, and since adequate designs exist for such detectors using well understood technology, at least one second generation experiment should be constructed immediately, to begin operation about 1984. The cost of such an experiment is expected to be between $5M and $10M per fiducial kiloton.[1] Thus, the cost for a 5 to 10 kiloton detector is on the order of that for a major accelerator detector facility, but is substantially less than the cost for a significant improvement of an existing accelerator. The impact of such experiments on our understanding of particle physics may well be as great as that resulting from the construction of a new higher energy accelerator at many times the cost. In addition, the results from nucleon decay experiments will allow a first look at physics in an energy range well beyond that achievable by any currently conceivable accelerator.

Beyond the Second Generation

If the second generation detectors observe nucleon decay, they will also be able to investigate most of the proposed decay modes. These detectors would of course be expanded (or replicated at other sites) to perform the detailed measurements demanded by theorists. The precision measurements of branching modes and the investigation of rare decay modes of the nucleon would become an industry comparable to the present-day experimental program at an accelerator laboratory. Nucleon decay spectroscopy will probe

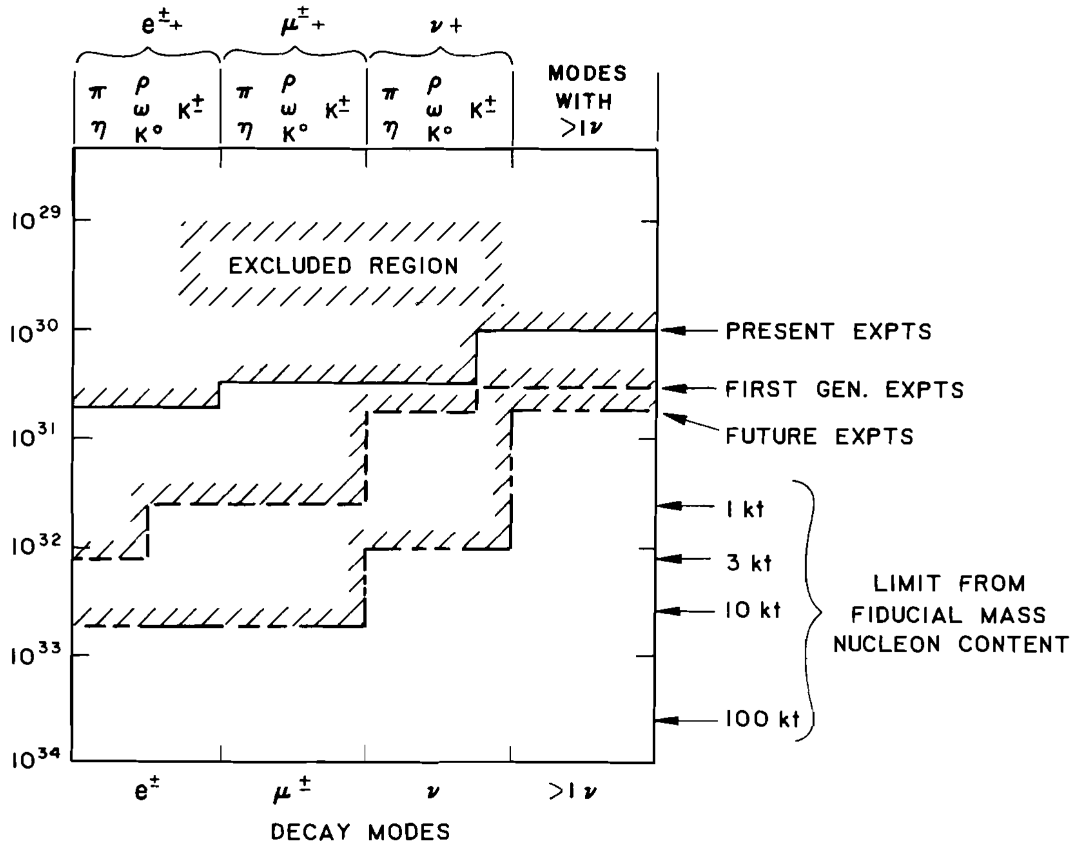

Fig. 1. Approximate expectations for present and future experimental limits on the nucleon lifetime for various decay modes. The limits shown would result from either (1) fewer than five decay events per year or (2) fewer decay events than neutrino background events, assuming 100% of the decays go into the given channel. Detectors are assumed to have a 33% detection efficiency for decay events, after cuts to remove the neutrino background events. The curve labeled "Present Expts" is for experiments which have been in operation for some time, and are characterized by minimal rejection of the neutrino-induced background (assumed to consist of $\nu_\mu : \nu_e = 2:1$). The curve labeled "First Generation Expts" refers to the expected results from the water Cerenkov experiments and the Frejus tunnel calorimeter. The "Future Expts" curve refers to expectations from fine-grained detectors with $\gtrsim$ 10 kton fiducial mass and 100 times better background rejection for the electron and muon modes than present experiments. The fiducial-mass limits indicated show what could be achieved with a one-year exposure on the basis of the nucleon content of a detector alone.

Table III

Theoretical Significance and Experimental Signatures of Some Nucleon Decay Modes

Decay Modes	Significance	Signature (unless previously described)
$N \to e^+X_n$ $X_n = \pi, \rho, \eta, \omega$, nonresonant $\pi\pi$	All standard gauge-mediated theories predict the same relative branching ratios among these modes.	Visible energy ~ 1 GeV. Visible momentum conserved. Hadron state never has positive charge. Hadrons visible either as tracks or electromagnetic showers. At least one electromagnetic shower.
$N \to \bar{\nu} X_n$ $N \to e^+X_n$	$\bar{\nu}/e^+$ ratio distinguishes between standard gauge-mediated theories.	Visible energy < 1 GeV for ν modes.* Visible momentum not conserved for ν modes. Monochromatic hadron state (except for nonresonant $\pi\pi$). Hadron state never positive for e^+X_n modes. Hadrons visible either as tracks or electromagnetic showers.
$N \to \mu^+ X_s$ $N \to e^+ X_n$ $X_s = K, K^*$	$(\Delta S=1)/(\Delta S=0)$ ratio gives information on the gauge group, symmetry-breaking pattern, and mixing angles in standard gauge-mediated theories. A large μ^+X_s rate implies Higgs mediation or a supersymmetric GUT.	Visible energy ~ 1 GeV. Visible momentum conserved. Noninteracting μ track. $\mu^+ \to e^+$ decay after μ^+ stops. K^+ decay after stopping: $K^+ \to \mu^+$ track (67%), stopped $\mu^+ \to e^+$; or $K^+ \to \pi^+\pi^o$ (21%), $\pi^o \to$ electromagnetic showers, π^+ track, stopped $\pi^+ \to \mu^+ \to e^+$.
$N \to \mu^+ X_s$ $N \to \bar{\nu} X_s$	These modes dominate for some supersymmetric GUT's.	Visible energy < 1 GeV for ν modes.* Visible momentum not conserved for ν modes. $K^o \to \pi^+\pi^-$ (69%), $\pi^o\pi^o$ (31%). $K^+ \to \mu^+ \to e^+$ (67%), $\pi^+\pi^o$ (21%).
$n \to e^-X_n$ $n \to e^-X_s$	Can occur in low-mass-scale (~ 10^{10} GeV) models described by an effective Lagrangian of dimension d = 7. $(\Delta S=1)/(\Delta S=0)$ ratio gives the structure of operator.	Visible energy ~ 1 GeV. Visible momentum conserved. Hadron state always has positive charge. Hadron tracks. $K^+ \to \pi^+\pi^o$, $K^+ \to \mu^+ \to e^+$. At least one electromagnetic shower.
$n \to e^- \nu\nu X_n$ $n \to e^- \nu\nu X_s$	Low-mass-scale (~ 10^4 GeV) models with d = 10 operators.	Visible energy < 1 GeV.* Visible momentum not conserved. Hadron state always positive. At least one electromagnetic shower. Only identifiable if decay rate > ν interaction rate.
$p \to e^+ \bar{\nu}\bar{\nu}$	Low-mass-scale (~ 10^4 GeV) models with d = 11 operators.	Visible energy < 1 GeV.* Visible momentum not conserved. All observable energy in one electromagnetic shower. Only identifiable if decay rate > ν interaction rate.
$pn \to \pi$'s $nn \to \pi$'s $(n \leftrightarrow \bar{n})$	Low-mass-scale (~ 10^5 GeV) models with d = 9 operators. Neutron oscillations.	Visible energy ~ 2 GeV. Visible momentum conserved. Mean π multiplicity = 4 to 5. $\pi^o \to$ electromagnetic shower. π^+ track stops. No leptons.
$pp \to e^+e^+$ $(H \leftrightarrow \bar{H})$	Low-mass-scales (> 10^{2-3} GeV) models with d = 12 operators. Hydrogen oscillations.	Visible energy ~ 2 GeV. Visible momentum conserved. Only two electromagnetic showers.

*For decay modes yielding neutrinos, the total-energy and momentum-balance constraints cannot be applied. Separation from background and sensitivity for these decay modes will therefore be worse than for non-neutrino modes.

Table IV

Comparison of Single Track Measurements in Different Detector Types

Detector type:	New Water Cerenkov (20" PMT)	Fréjus type	Active Liquid Scintillator (without/with tracking)	Soudan 2 type
$\langle\rho\rangle$(g/cm^3)	1.0	2.2	0.9/0.6	2.0
cost/kton ($M)	0.9	4.6	5/10	6.6
Electrons				
Method	ring (#pe/#PM)	visual shower	fluctuations (dE/dx)	visual shower
Direction	yes	yes	yes	yes
σ_E/E at 1 GeV	4%	15%	4%/15%	20%
e/γ separation	no	poor	no/poor	poor
Muons < 300 MeV/c				
Method	ring (if > C_{thr})	clear track, noninteracting	min. ionizing	clear track, noninteracting
Direction	yes	no	yes (TOF, dE/dx)	yes (dE/dx)
Sign	no	no	no	fair (50%)
π/μ separation	bad	good	poor/good	good
Pions$^\pm$				
Method	ring (if > C_{thr})	interaction	> min. ionizing	interaction
Direction	yes	no	yes (dE/dx)	fair (67%, dE/dx)
Sign	yes (60%)	no	yes (π^- star)	fair ($\pi \to \mu \to e$)
π/e separation	yes	yes	yes	yes
Kaons				
Detection	no	yes (decay)	yes (time delay)	yes (decay)
Direction	--	no	yes (dE/dx)	yes (dE/dx)

fundamental physics at the shortest distances possible in the forseeable future. If the nucleon lifetime happens to lie within the narrow window accessible to current experiments, this will be a most fortuitous match to present technology and budget constraints.

It is also possible that the second generation experiments will rule out nucleon decay into any mode at lifetime limits similar to those shown in Fig. 1. The impetus for nucleon decay searches will then diminish for two reasons. First, no current theory will give any firm prediction for the nucleon lifetime if it is experimentally found to be longer than 10^{33} years. Although most classes of theories do predict nucleon decay at some level, those which would survive an experimental limit at 10^{33} years would find any long but finite lifetime acceptable. Nucleon decay experiments would then be in a class of physics problems which includes the searches for Higgs, for supersymmetric particles or for technicolor particles: important discoveries which may be just around the corner or may be completely inaccessible with current technology. This class of physics is worthy of experiments if they are inexpensive, but cannot justify the expense of a major experimental effort on the scale proposed for second generation nucleon decay experiments.

The second reason is experimental. At about the 10^{33} year level, the atmospheric neutrino background becomes a problem even for easily identified modes such as $p \to e^+\pi^0$. Detectors would have to distinguish between, for example, the charged-current reaction $\nu N \to e N^*$, $N^* \to \pi^0 N$ and $p \to e^+\pi^0$. Better resolution (at a higher cost per kiloton) than the proposed second generation detectors would be of limited use. Since the resolution of the second generation detectors will be matched to the background-rejection limits imposed by nuclear Fermi motion, third generation detectors would probably need to observe light nuclei, ideally hydrogen, to achieve better rejection of the neutrino background. New technology will clearly be needed to increase the nucleon lifetime limit, for a reasonable cost, if the second generation experiments fail to find nucleon decay. These much larger, third-generation, detectors would obviously be less expensive if they could operate on the surface instead of in deep mines. This is not entirely inconceivable: the cosmic-ray muon rate of $\sim 10^7$/sec through a detector, with much smaller rates through each detector element, is not very different from that which is handled routinely by high-rate accelerator experiments. These surface experiments would require active shielding such as proportional tubes or limited-discharge chambers which could efficiently veto through-going muons. The absence of material near the detector (mine walls) would also reduce the number of neutral secondaries entering the detector from muon interactions, although neutral hadron shielding would still be necessary. The same detector might also be used as a very large neutrino detector at an accelerator.

Another solution to the neutrino background problem would be to locate the detector in outer space or on the moon. Such an experiment could be much simpler than one on the earth, since neutrino-interaction rejection would no longer be required. Clearly the development of advanced detector techniques is needed if we are to proceed beyond the presently foreseeable sensitivity limit of $\sim 10^{33}$ years. With current technology, both experimental and theoretical, it makes little sense at this time to build a nucleon decay detector larger than a few tens of kilotons unless decays have already been seen in a smaller detector.

Other Physics with Nucleon Decay Detectors

The prediction by grand unified theories that proton decay may occur at a detectable rate has provided compelling motivation for the construction of underground experiments of unprecedented size and sensitivity. As the several types of detectors come into operation in low-background underground laboratories, the situation is somewhat analogous to one which has historically occurred at accelerators. When a new type of detector first begins operation in a new accelerator particle beam with significantly enhanced energy, intensity, or purity, the probability for the observation of new phenomena is high. Whether or not the new underground experiments find evidence for proton decay, there is a good likelihood that other important physics results will emerge. The results may be of some completely unanticipated nature, or may relate to phenomena which have been predicted, but as yet have not been able to justify dedicated experiments on the scale of those now planned for nucleon decay. Some examples of physics which could be done with nucleon decay detectors are:

1. Neutron-antineutron oscillations. As discussed elsewhere in these proceedings, despite the severe suppression of neutron-to-antineutron transitions in nuclear matter, the sensitivity of large nucleon decay experiments to this phenomenon may well exceed that of experiments using free neutrons.[12] Since the experimental signature for $n \to \bar{n}$ oscillations is the appearance of annihilation products with ~2 GeV of energy, the design criteria for an experiment using nuclear matter are identical to those for a proton decay search.

2. Neutrino oscillations using cosmic-ray neutrinos. Low-energy neutrinos generated in the spherical shell of the earth's atmosphere by cosmic-ray interactions allow a search for neutrino oscillations over distances on the order of the earth's diameter. As discussed elsewhere in these proceedings, sensitivities to $\delta m^2 \sim 10^{-4}\,\mathrm{eV}^2$ and $\sin^2 2\alpha \sim 0.1$ are achievable in a 10 kton proton decay detector.[25] Since the neutrino interactions involved are an important background to proton decay, they will be studied and understood by the new experiments in any case.

3. Cosmic-ray physics. Even before the recent surge of interest in proton decay, underground observations of cosmic-ray muons by large particle detectors were providing useful data relating to the nuclear composition of the primary cosmic-ray spectrum.[26] The fine granularity and large size of proton decay searches already in operation have made significant contributions to this field,[27] and the larger detectors now coming into operation can be expected to have an even more significant impact. In addition to studying high-energy muons, some proton decay detectors may also be sensitive to few-MeV neutrinos of solar or astrophysical origin.[28,29]

4. Searches for GUT magnetic monopoles. As discussed elsewhere in these proceedings, proton decay detectors will provide good sensitivity to a possible flux of superheavy magnetic monopoles.[30] In addition to detection through their ionization in matter (which requires monopole velocities $>10^{-4}c$), proton-decay detectors could also find evidence for monopoles through their catalysis of proton decay.[31,32] A careful measurement of branching ratios would be needed to distinguish monopole-induced decays from SU(5) decays.[32]

These examples illustrate that proton decay experiments have a built-in sensitivity to a variety of interesting physical phenomena. In some cases a proton decay experiment is not optimized in the same way that a dedicated experiment would be, but the results obtained are essentially free. In other cases, a modest increase in detector cost can provide enhanced sensitivity to a particular phenomenon. It may well be that the new generation of proton decay searches will lead us in entirely unanticipated directions, and produce discoveries which are as important as those which motivated these experiments initially.

Conclusions

A new generation of proton decay experiments will be needed to investigate decay modes to which those detectors now in operation or under construction will be relatively insensitive. The experimental limits on the decay rates into various modes should be pushed to levels where neutrino backgrounds dominate. The lifetime where neutrino background becomes important depends strongly on decay mode, but is in the range of 10^{30} to 10^{33} years. Currently available technology is adequate for this task, so this next generation should be started as soon as funds are available. Of course, if proton decay is actually observed in the near future, there will be even stronger motivation to search for it in all possible modes with the new generation of experiments. Proton decay experiments will also be quite sensitive to other very interesting physical phenomena. Even if proton decay does not occur at a detectable rate, the discovery of $n\bar{n}$ or neutrino oscillations, magnetic monopoles, or some totally unexpected phenomenon could justify a large investment in the next generation of experiments.

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