PROTON DECAY EXPERIMENTS

D.H. Perkins

CERN, Geneva, Switzerland

and

Department of Nuclear Physics, University of Oxford, England

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1. INTRODUCTION

1.1 Summary and Overview

At the time of writing this review, there is as yet neither convincing evidence for believing that protons (and bound neutrons in nuclei) undergo decay, nor any good reasons for believing that they can live for ever. The situation is a dramatic one. Some of the limits set to the lifetime for particular decay modes are reaching perilously close to the limit of experimental feasibility. Nevertheless, there are circumstantial grounds, based on the absence of any detectable long-range field coupled to the baryon number, and the observed matter-antimatter asymmetry of the Universe, for believing that protons cannot be completely stable. The grand unified theories of the fundamental interactions (GUTs) predict that protons will indeed decay, at a very small but quite possibly measurable rate, determined by the mass $M_X$ of the postulated gauge bosons of the grand unifying symmetry.

One particular form of GUT, incorporating minimal SU(5) as the gauge group, with $M_X \sim 10^{15}$ GeV, makes clear predictions for the lifetime in terms of virtual $X$ boson exchange, and indicates that the mode $p \rightarrow e^+\pi^0$ should dominate. The postulated decay of a proton, containing $u$ and $d$ quarks, to a positron and non-strange meson results from putting together the lightest quarks ($u,d$) and lightest leptons ($e, \nu_e$) into an SU(5) multiplet. The present experimental limit for $\tau(p \rightarrow e^+\pi^0) > 1.5 \times 10^{32}$ yrs is however in clear conflict with the SU(5) prediction of $\tau(p \rightarrow e^+\pi^0) < 10^{31}$ yrs. Other forms of GUT make less definite lifetime predictions but emphasize other decay modes. Some incorporate supersymmetry in which bosons like the Higgs ($H$) have supersymmetric fermion partners ($\tilde{H}$). They suggest that protons decay via fermion ($\tilde{H}, \tilde{W}$) exchanges, and because of the symmetries involved, it turns out that heavier quarks and leptons should be frequent decay products, for example $p \rightarrow \bar{\nu}_\tau K^+$ or $\nu^+ K^0$. Since the only reasonably accurate prediction, that of SU(5), seems excluded, the question of baryon stability, lifetime and decay modes has however become an almost purely empirical matter.

A few major experiments carried out deep underground to reduce cosmic-ray background, have now reported preliminary results. Apart from excluding $p \rightarrow e^+\pi^0$ at the $10^{32}$ yr level, they have found odd events which are apparently difficult to understand in terms of background and
even look tantalisingly like examples of nucleon decay in modes consistent with SUSYGUTs. The mention of lifetimes of $10^{32}$ yrs implies that the detectors must have sensitive masses of 100's to 1000's of tons, i.e. containing $10^{32}$-$10^{33}$ protons, so as to have any chance of finding a signal in a reasonable running time. It is however very difficult to instrument a 1000 ton detector with high resolution, and in fact designs have to be a compromise between precision and baryons per buck. This means that proton decay events will not be individually unique, but have to be distinguished on a statistical basis against the dominant background, that due to interactions of atmospheric neutrinos. The relative rates – baryon decay and neutrino interactions – are equal for a lifetime of order $10^{31}$ yrs. In trying to push lifetime limits to $10^{32}$ or even $10^{33}$ yrs, or hopefully, detecting a signal, an understanding of the neutrino background problem is crucially important and considerable space in this review is devoted to it.

Two principal techniques have been used so far in proton decay searches. Water Cerenkov detectors exploit the fact that Cerenkov light is emitted by relativistic particles in water, and can be detected by photomultipliers placed in or at the surface of, the water volume. They were originally oriented to the search for the SU(5)-favoured decay mode $p \rightarrow e^+ \pi^0$, in which most of the energy appears in the form of relativistic electrons in electromagnetic showers. Large volumes ($10^4$ m$^3$) can be used because pure water is transparent over much of the Cerenkov spectrum, and for a surface array, the phototube cost rises only as the 2/3 power of the water mass.

The second approach uses tracking calorimeters, consisting of a matrix of iron sheets (the target medium) separated by layers of counters (proportional, flash or streamer tubes, or drift chambers) familiar in high energy accelerator experiments. They record the tracks of any charged decay products. The cost per unit mass is 10 times that of the water detectors, and they have disadvantages because of nuclear absorption effects in the iron. On the other hand, decay or interaction vertices can be located with typically 100 times the precision of the water detectors, they can be built in modular form and tested in accelerator beams and, most importantly, they are sensitive to a wider range of possible decay modes, and should be much better at finding the unexpected than are the water Cerenkov devices.
This review starts off by tracing some of the early history of baryon decay, followed by a discussion of the formal problems associated with complete baryon stability (absence of a long range field coupled to baryon number, baryon asymmetry of the universe). The next section deals with theoretical lifetime predictions, and this is followed by an account of the early experimental limits on nucleon lifetime. The problems of cosmic-ray background are then discussed, before entering the main description of the recent experiments and their results.

1.2 History of Baryon Conservation

The apparent stability of matter was first given a concrete formulation in terms of a conservation law in 1929 by Weyl [1]. At that time, the two pairs of components of the Dirac wavefunction were interpreted as the electron and the proton, and the conservation of both was associated by Weyl with a "twofold gauge invariance". In 1938, Stueckelberg [2] postulated a conservation law for "heavy charge" - what we now call baryon number - expressing the fact that transformations of heavy particles (nucleons) to light particles (electrons and neutrinos) were not observed. In 1949 (also 1952) Wigner [3] independently re-stated the conservation law of baryons, drawing an explicit parallel between conservation of electric charge and that of baryon number, associated with stability of the electron and proton respectively. As he said "It will be assumed ..... that the two conservation laws have similar causes and that these have similar consequences".

The experimental limits on nucleon stability were, even in the 50's, known to be formidable long. For example, M. Goldhaber pointed out that the very existence of advanced life forms on Earth implied \( \tau_p > 10^{16} \) yrs. Goldhaber also quoted a limit of \( 10^{21} \) yrs from the non-existence of spontaneous \( \text{Th}^{232} \) fission induced by nucleon decay, [4], a limit that was to increase to \( 10^{23} \) yrs by 1958.

Despite these increasingly stringent limits, the consequences of complete stability of the nucleon and the possibility of nucleon decay were also starting to be discussed more than 20 years ago. Following the extension of the local gauge principle to non-Abelian fields by Yang and Mills [5] in 1954, Lee and Yang [6] pointed out in 1955 that a consequence
of a local gauge symmetry associated with an absolute conservation law for
baryons, would be the existence of a long-range field coupled to baryon
number. There is no evidence for such a field and the matter is discussed
in more detail below. Here it is just worth recalling that, a quarter of
a century earlier, Weyl had also stressed gauge invariance in this context.

In 1959, Yamaguchi [7] in a little-quoted paper noted the
possibility of a "superweak" interaction responsible for nucleon decay.
He stated that "the stronger the interaction, the greater the number of
symmetry properties it possesses" and, by the inverse argument, he
envisioned that the new superweak interaction would be characterized by CP
and possibly CPT violation. Nucleon decay to leptons was assumed to
proceed through 4-fermion type interactions, \( p \to 2e^+ + e^- \) or the K-capture
\( e^- + p \to e^+ + e^- \), and obeyed the selection rule \( AB = AL \). This paper is
interesting not simply as (apparently) the very first detailed theoretical
discussion of nucleon decay via a new interaction on a new energy scale:
it stimulated the first deep underground experiment to search for nucleon
decay, using Cerenkov counters, in 1960 (Backenstoss et al. [8]).

More compelling arguments for nucleon instability were brought
forward by Sakharov [9] in 1966 - in a paper well-known today but also
little noticed at the time. He was the first to point to the importance
of a CP-violating mechanism in accounting for the observed cosmological
baryon-antibaryon asymmetry, if it is produced in the initial stages of
the Hot Big Bang model of the Universe. Sakharov emphasized the
inevitability of proton decay with such a mechanism, and estimated the
lifetime as \( 10^{30} \) yrs or more, using a model in which the mass scale of
the bosons - what he called maximons - mediating the B-violating
interactions was taken as the Planck mass.

From 1973 onwards, proton instability has been postulated from a
different viewpoint, as a consequence of the grand unification of the
strong and electroweak interactions (Pati and Salam [10], Georgi and
Glashow [11], Georgi, Quinn and Weinberg [12], and many others, as
discussed below). Grand unification schemes (GUTs) incorporate leptons
and quarks into the same multiplets of the "leptoquark symmetry" so that
decay of quarks to leptons is, at some level, almost unavoidable.
Complete baryon stability is not excluded, but requires a special "weird" combination of both local and global gauge symmetries [81]. The energy scale determining the nucleon lifetime is set by the unification mass, where the strong and electro-weak couplings $g_s$, $g$ and $g'$ are equal within Clebsch-Gordan coefficients and mixing angles. The effects of these theoretical speculations over the years and particularly the last decade, have been to further stimulate experimentalists to search seriously with large-scale detectors for evidence of proton decay.

2. PROBLEMS FOR BARYON CONSERVATION

As mentioned above, there are two possible difficulties of a formal nature, backed by circumstantial experimental evidence, which might arise if baryon conservation were absolute. First, we expect such conservation to be associated with a long-range field coupled to baryon number, which is however so far unobserved. Secondly, in the framework of the Big Bang model of the Universe, the mechanism postulated for generating a baryon-antibaryon asymmetry is also expected to lead to baryon decay.

At this stage, it is worth reiterating the point made by Goldhaber and Sulak [13] that charge conservation would only allow proton decay if the numerical values of the electric charges of a baryon (proton) and a charged lepton ($e^+$, $\mu^+$) were identical. The limits on the electron-proton charge difference $\Delta Q$ and the neutron charge $\Delta Q_N$ are both $< 10^{-19}|e|$, as obtained by Hughes and his collaborators [14,15] by measuring the deflection of (CsI) molecular beams in an electric field. Indirect methods [16-18] give similar limits. Thus the equivalence of the charges of the electron and proton has been checked with high precision. Their exact equality is of course assumed, by construction, in all grand unified models which incorporate leptons and baryons in multiplets, and where the charge operator is one of the generators of the symmetry.

2.1 Limits on Long Range Field coupled to Baryon Number

Over the last 50 years or so, a succession of experiments of ever-increasing precision have been carried out to test the Einstein Principle of Equivalence. Some of these provide, as a by-product, stringent limits on the strength of any new long-range field coupling to baryon number.
The experiments in question essentially compare the inertial and gravitational masses of bodies using the principle illustrated in fig. 1. A body A at the Earth's surface at latitude $\lambda$ is subject to two forces: the gravitational force $F_G$ along the line AB toward the Earth's centre O, and a centripetal force $F_I$ along AC arising from the Earth's rotation, where

$$F_G = K \frac{M_G M_E}{r^2}$$  \hspace{1cm} (1)

$$F_I = M_I \omega^2 r \cos \lambda$$  \hspace{1cm} (2)

Here, $K$ is the Newtonian constant, $r$ is the earth radius, $\omega$ is the angular velocity of rotation relative to distant stars, $M_E$ is the gravitational mass of the Earth and $M_G$ and $M_I$ are respectively the gravitational and inertial masses of body A. If a body is suspended by a string, this points along the resultant $F_I$ and $F_G$, the angle $\theta$ to the local vertical depending on the ratio $R = M_I/M_E$. According to the Principle of Equivalence, $R$ should be the same for all bodies of whatever material, and for convenience we then define units so that $M = M_I = M_G$ is simply referred to as the mass of the body. This hypothesis has been checked by suspending two bodies of equal masses but different materials from either end of a horizontal beam, itself hanging from a torsion fibre. If $R$ is different for different materials, so will also be the values of $\theta$ and the result is a net couple which changes sign upon rotating the entire apparatus through 180°. In 1922, Eötvös et al. [19] obtained a null result which can be expressed as a limit on

$$\frac{\Delta R}{R} = \frac{2(R_1 - R_2)}{(R_1 + R_2)}$$  \hspace{1cm} (3)

where $R_1$, $R_2$ refer to the two materials.

If we assume the validity of the Equivalence Principle, then the limit $\Delta R/R$ determines the maximum strength of any long-range field coupling to baryon number. In fig. 1, such a field would produce an extra force along AB

$$F_B = K \frac{B B_E}{r^2}$$  \hspace{1cm} (4)
where \( B, B_E \) are the baryon numbers of the body and of the earth, \( K_B \) the coupling of the new field analogous to \( K \). It is assumed that the potential has the form \( 1/r \). For a tensor (vector) field, \( F_B \) will be parallel (antiparallel) to \( F_G \). For the same inertial mass, two bodies will not have the same baryon number because of the dependence of nuclear binding energy on mass number \( A \), the neutron-proton mass difference and variations of the neutron-proton ratio. The atomic mass can be written (neglecting electronic binding)

\[
M = AM_N \left[ 1 - \frac{Z}{A} \frac{M_N - M_H}{M_N} - \frac{W}{AM_N} \right]
\]

where \( W \) is the total nuclear binding energy in MeV, \( M_N \) and \( M_H \) are the neutron and hydrogen atom masses. Then the fractional mass difference of two different elements containing the same number of nucleons will be

\[
\frac{\Delta M}{M} = \left[ 8.3 \frac{\Delta(Z/A)}{A} + 10.6 \frac{\Delta(W/A)}{A} \right] \times 10^{-4}
\]

In the pairs of elements measured, the first term is only about 10\% of the second and can be neglected. For the same mass of the two elements, the fractional difference in baryon number will also be

\[
\frac{\Delta B}{B} = 10^{-3} \frac{\Delta(W/A)}{A}
\]

with a corresponding limit

\[
\frac{K_B}{K} \approx \frac{(\Delta B/R)}{(\Delta B/R)}
\]

Table 1 shows results from some experiments since 1922. The Dicke et al. [20] and Braginsky and Panov [21] experiments achieved high sensitivity by utilizing the gravitational field of the Sun, rather than the Earth, and searching for a 12 h oscillation period of the torsion system, as the magnitude of the centripetal force due to the Earth's rotation changes sign relative to the Sun's gravitational field.

The result of these experiments is the limit

\[
K_B < 10^{-9} K
\]
This limit of course proves nothing directly about the stability of the nucleon. It shows that, if any such long-range field coupled to baryon number exists, the coupling is however extremely weak. Since it is hoped to incorporate the various fundamental interactions into a unified theory, a new interaction with such very weak coupling would clearly make such a task very much more difficult. The alternative is to postulate a unified theory with both global and local symmetries, such that a suitable linear combination of the global and local charges can correspond to an absolutely conserved baryon number [81]. This is arbitrary and rather ugly and involves extra particles with "weird" quantum numbers, and is generally considered to be much less attractive than the unification models in which unstable baryons occur "naturally".

2.2 CP Violation in the Early Universe

The Big Bang theory is at present the most credible model of the evolution of the Universe and has had two notable successes: it is able to account for the 3°K background radiation, as the cooled remnant of the primordial radiation emitted with the Big Bang; and it correctly predicts the observed mass ratio (≈ 0.25) of helium to hydrogen, in terms of nucleosynthesis in the first 100 sec after the Big Bang. However, a major problem is to account for the presently observed ratio of matter density (baryons) to radiation (photons), $n_B/n_\gamma \sim 10^{-9}$, and the preponderance of matter over antimatter ($> 10^9 : 1$ in our Galaxy). These questions have been discussed at length in the recent review of this subject by Kolb and Turner [23] and we only outline a few salient points.

In the initial stage of the Big Bang ($t < 10^{-6}$ s, temperature $T > 1$ GeV), nucleons and antinucleons should have been generated as abundantly as photons and leptons. As the Universe cooled, the creation of baryon-antibaryon pairs by radiation would no longer compensate annihilation of pairs to photons, and the resulting density would fall as

$$n_B/n_\gamma \approx (M/T)^{3/2} \exp(-M/T) \tag{9}$$

where $M$ is the nucleon mass, and $n_B = n_{\bar{B}}$, by symmetry. The annihilation rate per nucleon is given by $R = n_B \sigma v$, where $\sigma$ and $v$ are the annihilation cross section and the relative velocity of nucleon and antinucleon. Thus $R$ falls exponentially as $T$ decreases and must eventually decrease below
the expansion rate $H$, varying as $T^2$. When $R < H$ (in fact for $T < 22$ MeV) nucleons can no longer find antinucleons to annihilate with, and the BB residue becomes "frozen out" with a value, from (9), of $n_B/n_\gamma \sim 10^{-16}$ and $n_B = n_\gamma$ (assuming no initial asymmetry). Thus the model predicts a catastrophically smaller proportion of baryons than is observed and is unable to account for the preponderance of matter over antimatter. An alternative is to postulate a baryon number $n_B/n_\gamma \sim 10^{-9}$ as an initial condition, but this seems extremely artificial and unlikely.

On the other hand, cosmological models incorporating grand unification, while at present unable to predict unambiguously the observed $n_B/n_\gamma$ ratio, do offer a more reasonable and viable scenario, in terms of an initially baryon-symmetric Universe. They appeal to CP violation to generate the eventual asymmetry. Such CP violation is already known to occur in at least one physical situation, that of the $K^0$-$\bar{K}^0$ system.

The first models of a dynamically-generated baryon excess were described by Sakharov [9] and Kuzmin [24], who listed three necessary conditions:

(a) A baryon number non-conserving process.
(b) CP and C violation (so that the rates of production of quarks and antiquarks are unequal).
(c) The baryons and antibaryons should be out of thermal equilibrium. In thermal equilibrium, the baryon density can depend only on the temperature and particle mass, which is the same for particle and antiparticle, by CPT. Hence an "arrow of time" is also necessary, provided by a non-equilibrium expansion.

The generation of baryon number in the context of GUTs was considered by Yoshimura [25], Weinberg [26], Toussaint et al. [27] and others. The heavy gauge bosons $X, \bar{X}$ and the Higgs $H, \bar{H}$ of the GUT are supposed to be created initially (at temperatures $T \sim M_{\text{Planck}}$) in equilibrium with the other fundamental fermions and bosons. The equilibrium abundance of $X$ bosons when $T$ falls below $M_X$ will be given by eq. (9) with $M = M_X$. This
abundance will not be achieved unless the $X$ bosons can stay in equilibrium, and the most important process for decreasing the density $n_X$ is decay ($X, \bar{X}$ annihilation is too slow). The $X$ decay rate $\Gamma \propto M_X^2$, on dimensional grounds, while the expansion rate $H \propto T^2$. For values $T \sim M_X$, whether $\Gamma$ is large or small compared with $H$ depends on the $X$ mass and couplings for decay processes. If $\Gamma \gg H$, $X$ bosons remain in thermal equilibrium and no baryon asymmetry can develop, with CP-violating decays exactly counter-balanced by the inverse decay process. If $\Gamma \ll H$ however, the abundance $n_X$ becomes larger than the equilibrium value and an asymmetry is possible. This condition requires a minimum value for $M_X$, which calculations show is $M_X > 10^{16}$ GeV [28-30]. This condition is not satisfied by the gauge bosons $X, Y$ of the SU(5) model, where $M_X \sim 10^{15}$ GeV. On the other hand, because of their different couplings, the corresponding condition for Higgs bosons is the weaker requirement $M_H > 10^{13}$ GeV, and this is very likely to be fulfilled, since one expects $M_H \sim M_X$.

In the minimal SU(5) model, the predicted baryon asymmetry turns out to be much too small, resulting in $n_B/n_Y \lesssim 10^{-16}$. For non-minimal SU(5), with more complex Higgs structure, it seems possible to account for the observed asymmetry, although the result depends sensitively on the degree of CP violation in the model. In particular, since several CP-violating phases are involved, it is not possible to relate the baryon asymmetry directly, in either magnitude or sign, to the observed CP violation parameters in the neutral kaon system. However, it can at least be claimed that GUTS offer the possibility of accounting numerically, and in a non-artificial way, for the present huge preponderance of matter over anti-matter, in terms of tiny asymmetries in the early stages of the Big Bang.

In the sense that grand unified theories so far seem to offer the only natural way to account for the baryon asymmetry of the Universe, the existence of that asymmetry is tangible if circumstantial evidence in support of grand unification and therefore, of the existence of baryon instability at some level.
3. THEORETICAL PREDICTIONS ON PROTON DECAY

3.1 Proton Decay in SU(5) version of GUTs

A thorough discussion of proton decay in GUTs has been given in the review by Langacker [32], and we shall only discuss here a few salient points.

Although it is possible to construct unified theories in which baryons are absolutely stable — even if they have undesirable features — non-conservation of B is a feature of most GUT models. Estimates of lifetime depend primarily on the type of operators involved in the decay mechanism, and on the mass scale at which it is expected that ∆B interactions will be commonplace. For example, Sakharov [9] had taken the scale as the Planck mass $M_p \approx 2 \times 10^{19}$ GeV and obtained $\tau_p > 10^{30}$ yrs. In GUTs the mass scale is set by that at which the electroweak and strong couplings merge. In the minimal SU(5) version [11] quarks and leptons are placed in SU(5) multiplets, and the scale of the grand unified coupling is $M_X \approx 10^{15}$ GeV, where $M_X$ is the mass of the $X$, $Y$ "leptoquark" bosons, of charge 4/3 and 1/3, mediating quark-lepton and quark-antiquark transitions. Some diagrams — those involving the dominant "dimension 6" operators — for proton decay in this model are shown in fig. 2. Fig. 2(a) shows the 2-quark fusion graph corresponding to the processes

$$p \rightarrow e^+ u\bar{u} \quad \text{or} \quad n \rightarrow e^+ d\bar{u}$$

$$\rightarrow \bar{\nu}_e d\bar{u} \quad \rightarrow \bar{\nu}_e d\bar{d}$$

where the $QQ$ pairs can form $\pi$, $\rho$, $\omega$ ... mesons. Fig. 2(b) shows the process of 3-quark annihilation to a lepton preceded by meson emission, giving the same result as (10) and of comparable amplitude. Other graphs contribute but may be neglected compared with the ones shown. Since the $X$ propagator introduces a factor $M_X^{-4}$ in the decay rate, dimensional arguments suggest that

$$\tau_p = \frac{A M_X^4}{\alpha^2 M_p^2}$$

where $\alpha = 1/40$ is the grand unified coupling and $A$ contains details of hadronic matrix elements, and is of order unity. For $A = 1$, $M_X = 10^{15}$ GeV,
\[ \tau_P = 6 \times 10^{31} \text{ yrs}. \] In principle, decays can also occur via superheavy scalar (Higgs) exchange. However, because the coupling to light fermions is weaker for \( H \) than for \( X, Y \), the contribution from Higgs exchange is small, unless \( M_H \ll M_X \), which appears unnatural. In SU(5), the predominance of \( e^+ \) and \( \bar{\nu}_e \) leptons in the decay products is a consequence of putting the light leptons and the light quarks in the same family, and this is to some extent justified by the limited success of relations between quark and lepton masses.

There are a few selection rules for nucleon decay which are generally applicable. Weinberg [26] showed that a necessary result of baryon non-conservation in leading order is the conservation of (B-L), so that only \( \Delta^+ \) and \( \Delta^- \) should appear among the decay products. The observation of negative electrons or muons, for example, would be quite disastrous for the GUT schemes. Within the context of vector exchange (as in SU(5) or SO(10)) there are two fundamental couplings, whose ratio can be denoted by \( r \). For \( \Delta S = 0 \) processes it can be shown from isospin arguments [31] that, for example

\[
\Gamma(p \to e^+ \pi^0) = (1 + r^2)\Gamma(p \to \pi^+ \pi^-) = (1 + r^2)\Gamma(n \to \pi^0 \nu) \\
\Gamma(p \to e^+ + X_{NS}) = (1 + r^2)\Gamma(n \to \nu + X_{NS}) \geq (1 + r^2)\Gamma(p \to \nu + X_{NS})
\]

and so on, where \( X_{NS} \) is any non-strange hadronic state. In the SU(5) model, \( r = 2 \) while in SO(10) \( r = 0 \).

Estimates of SU(5) branching ratios are given in table 2, after the review by Langacker [32]. We do not list here the numerous theoretical estimates of the lifetime. A dominant factor is the unification mass, \( M_X \), which in terms of the QCD scale parameter \( \Lambda_{\overline{MS}}(\text{GeV}) \) has the value

\[ M_X \approx 2.4 \times 10^{18} [\Lambda_{\overline{MS}}/0.16] \text{ GeV} \]  \hspace{1cm} (13)

In his 1981 review Langacker, using this value of \( M_X \), quotes a "best" value of the lifetime as

\[ \tau_p = 3.2 \times 10^{21.3} [\Lambda_{\overline{MS}}/0.16]^4 \text{ yrs} \]  \hspace{1cm} (14)
The usually quoted value for $A_{ms} = 0.16$ GeV, and this is considered reliable within a factor 2. The main changes to $\tau_p$ calculated recently in SU(5) have come from variations in $A$ in eq. (11). This quantity involves specification of matrix elements relating the fundamental process involving quark decay via $X$ exchange, to the final state hadrons, and the value in (14) comes from non-relativistic SU(6) or bag models. Berezinsky et al. [33] determine $A$ from QCD sumrules and find a value

$$\tau_p / B(p \to e^+ \pi^0) = 1.1 \cdot 10^{29\pm1.3} \frac{[A_{ms}/0.16]^4 \text{ yrs}}{\text{yrs}} \quad (15a)$$

with $B = 0.5$. More recently Brodsky et al. [33] found another way of calculating $A$, relating it to nucleon form-factors and $\psi \to \bar{p}p$ decay rates. These calculations give even shorter lifetime estimates, and they obtain

$$\tau_p / B(p \to e^+ \pi^0) = 1.7 \cdot 10^{29\pm1.3} \frac{[A_{ms}/0.16]^4 \text{ yrs}}{\text{yrs}} \quad (15b)$$

that is a factor 20 shorter than in eq. (14). As we shall see, the IMB observed 90% CL limit $\tau_p / B(p \to e^+ \pi^0) > 1.5 \cdot 10^{32}$ yrs, putting the prediction in eq. (14) in serious trouble and in complete disagreement with that in eq. (15a) or (15b). The SU(5) prediction can be increased by invoking more complex structure than for minimal SU(5). We have already seen that SU(5) also fails to predict the correct cosmological baryon/photon density ratio. Within the restrictions imposed by the need to obtain the correct value of $\sin^2 \theta_w$, there is considerable freedom also in other forms of GUT ($E(6)$, $O(10)$ ... ) to obtain larger values of $\tau_p$.

3.2 Proton Decay in Supersymmetric GUTs

In supersymmetry, each fermion (boson) is duplicated by a boson (fermion) partner. These extra particles slow down the logarithmic $q$ dependence of the running coupling constants so that the unification mass grows to $M_X \gtrsim 10^{17}$ GeV, and the predicted proton lifetime may become very long. However, as pointed out by Weinberg [35] and Sakai and Yanagida [36], in this case "dimension 5" operators could contribute, corresponding to the supersymmetric Higgs ($\tilde{H}$) exchange as in fig. 2(c). Since $\tilde{H}$ is a fermion, the lifetime varies only as $M^2_H$. Further, the mass $M_H$ can be very different from $M_X$ or $M_H$, so that a lifetime similar to that in
minimal SU(5) is easily possible. Indeed, extra symmetries are invoked to suppress some of the operators and avoid short lifetimes, with the result that decays to quarks and leptons in other generations than that of \((u, d, e, \nu_e)\) are strongly favoured, for example [34]

\[
p \rightarrow \bar{\nu}_e K^+, \quad n \rightarrow \bar{\nu}_\tau K^0
\]

with

\[
p \rightarrow \mu^+ K^0, \quad n \rightarrow \bar{\nu}_\mu \pi^-
\]

less probable. Decay \(N \rightarrow e\pi, \mu\pi\) is suppressed in these models [37–39].

3.3 Consequences for Proton Decay Experiments

The SU(5) model predicts that 2-body decay modes into positron and meson will dominate. Since \(\pi, \rho, n, \omega\) also give high energy \(\gamma\)'s among the decay products, double electron-photon showers with a "back-to-back" configuration will be prominent, and it was on this basis that the large water Cerenkov detectors were built, since:

(a) they are very good detectors of electron-photon showers separated in space by large angles, as in 2-body decay,

(b) in the most favoured SU(5) decay modes, nearly all the energy appears in relativistic charged particles, and the total Cerenkov signal is a simple and fairly precise indicator of the total energy in the decay,

(c) the momenta of the individual decay products can be measured, since Cerenkov light indicates the direction of motion of the particle producing it and this, together with the energy measurement, is an essential kinematic constraint in combatting the neutrino background.

In GUTs incorporating supersymmetry, on the other hand, the lepton is frequently a neutrino, and strange hadrons are favoured. Topologically, such events are much more difficult to identify. For example, the decay \(\n \rightarrow \bar{\nu}_K^0, K^0 \rightarrow 2\pi^0 \rightarrow 4\gamma\) provides an adequate Cerenkov pulse of well-defined energy (if we neglect Fermi motion) but there is no "back-to-back" configuration, because the \(K^0\) has low velocity, and the Cerenkov light is almost isotropic in direction. Generally speaking, multiprong decays, involving charged particles with a decay sequence, as in \(p \rightarrow \mu^+ K^0, K^0 \rightarrow \pi^+ \pi^-, \) or \(p \rightarrow \bar{\nu}_K^+, K^+ \rightarrow \mu^+ + \nu,\) should be more easily distinguished by means of fine-grained tracking calorimeters with good (≤ 1 cm) vertex resolution.
4. **EARLY RESULTS ON NUCLEON STABILITY**

4.1 **Decay-Mode Independent Methods (Geochemical and Radiochemical)**

The first useful limits on nucleon lifetime were obtained using nuclear methods, the principle being that, when a nucleon is removed from a nucleus, it may be left in an excited state, undergoing radioactive decay or fission, which can be detected radiochemically. Alternatively, a rare isotope may be formed as a result of decay of a common nuclide, and can be detected by geochemical techniques. Both methods have been discussed by Rosen [46].

Table 3 summarizes the results obtained. The Goldhaber [4] and Flerov [40] limits from Th$^{232}$ have already been mentioned. Evans and Steinberg [41] used the measured Xe$^{129}$ abundance [42,43] in telluride ores to set a limit on nucleon decay in Te$^{130}$.

The most precise geochemical limit is that of Bennett [44] who used etched mica samples from a deep (10,000 mwe) mine to measure short nuclear spallation tracks which could have followed nuclear absorption of hadrons from nucleon decay. From the rate of such etch-pits he found $\tau > 2 \times 10^{27}$ yrs.

Fireman [47] used a 1.7 ton sample of potassium acetate to measure the rate of production of radioactive Ar$^{37}$ from nucleon decay, followed by nucleon emission in K$^{39}$. In this technique, locating the sample at great depth is an essential and crucial feature in reducing the background.

4.2 **Summary of Early Searches for Nucleon Decay by Direct Methods**

In this section, we describe briefly the results of early searches [48] for nucleon decay by direct detection of decay products. The detectors were not primarily designed for this purpose, and in particular could not fully contain the charged particles, electrons or $\gamma$-rays from such decays inside the detector volume. The list of experiments is given in table 4.
Reines, Cowan and Goldhaber [4] recorded charged particles of kinetic energy above 100 MeV in 300 \% of liquid scintillator under 100 ft of rock, setting a limit $\tau > 10^{22}$ yrs determined by crossing cosmic ray background. In 1958, Reines, Cowan and Kruse [49] improved this limit to $\tau > 4 \cdot 10^{13}$ yrs by using a 170 kg target of heavy water containing CdCl$_2$, and requiring a delayed pulse (within 20 \(\mu\)s of the initial pulse) from moderation and capture of the neutron produced in the reaction $d \rightarrow n +$ (proton decay products).

The first deep underground experiment was undertaken by the CERN group of Backenstoss et al. [8] in 1960 in the Lötschberg railway tunnel (2400 mwe). A 50 \% liquid Cerenkov counter recorded upward-travelling relativistic charged particles (for example, from proton decay in the surrounding rock). Giamati and Reines [50] and Kropp and Reines [51] carried out experiments in 1962–65 at the Fairport Harbor Salt Mine, Ohio (1760 mwe), using 200 \% of liquid scintillator plus a Cerenkov anticoincidence shield to veto crossing cosmic rays.

Gurr, Kropp, Reines and Meyer [52] and Reines and Crouch [53] made deep underground observations in a S. African gold mine (8000 mwe), using a large (20 ton) scintillator hodoscope, intended originally to record secondary muons from neutrino reactions in the surrounding rock. On the basis of the muon rate at wide zenith angle (thus excluding atmospheric muons), Gurr et al. found $\tau > 2 \cdot 10^{20}$ yrs, while Reines and Crouch based their estimate on muons stopping and decaying in the scintillator. Five events were observed, which could be accounted for in terms of neutrino origin, but if ascribed to nucleon decay, gave $\tau > 2 \cdot 10^{20}$ yrs.

In the same year (1974) Bergamesco and Picchi [54] operated with 500 \% liquid scintillator detector plus anticoincidence shield in the Mont Blanc tunnel (4270 mwe). On the basis of the rate of secondaries with pulseheights exceeding 10 MeV, both originating and ending in the scintillator (i.e. with range < 130 gm cm$^{-2}$) they found $\tau > 1.3 \cdot 10^{29}$ yrs. This seems to have been the first experiment actually requiring that a charged particle should be totally confined in the detector, but of course it would reject 2-body decays in which charged decay products could obtain up to 500 MeV energy.
The last two experiments in the list are those of Learned et al. [55] and Cherry et al. [56]. Learned et al. (1979) re-evaluated the Reines-Crouch data, while Cherry et al. (1981) operated 150 tons of water Cerenkov detectors (in several tanks of 2 m³ volume) in the Homestake Mine (4200 mwe). They observed 3 decays of upward or horizontal muons, contained in the tanks and involving a prompt pulse of 50-600 MeV equivalent energy. Taking account of the surrounding veto counter efficiency, they concluded τ > 1.5 × 10³⁰ yrs.

All the limits we have listed depend on assumptions about decay modes, and in this sense are partial lifetime limits. The requirement of a muon decay, for example, assumes pions or muons among the decay products. Such limits are irrelevant if the dominant decays are p → e⁺ + 2ν or n → e⁺ + e⁻ + ν, for example. Nevertheless, since most theories of nucleon decay involve at least one meson secondary, with at least a 25% probability of escaping nuclear absorption and of producing a muon via the decay chain, it is true to say that these early experiments set limits on the nucleon lifetime of order 10³⁰ yrs.

5. BACKGROUND IN PROTON DECAY EXPERIMENTS

There are several potential sources of background in proton decay experiments. In calorimeter experiments in which decay products are to be tracked through a large array of gas counters (which might total a million in a one kiloton array), radioactivity is not negligible, producing a singles rate of about 1 Hz in a counter of 1 cm² cross section and 1 m in length. This means that a basic trigger requirement is that counters from several contiguous or nearly contiguous layers must fire simultaneously in order to be accepted as an "event", so that a threshold energy release of perhaps 100 MeV in the calorimeter is involved.

Crossing cosmic ray muons cannot be confused with decay events, but they are a nuisance which can be kept down to reasonable levels by trigger requirements, by use of anticoincidence shields and by going deep underground (see fig. 5 for the muon flux as a function of depth). The muons also generate neutral hadrons in the surrounding rock, and they are a potential source of background; but not, fortunately, an important one, as discussed in section 5.5 below.
The dominant background to proton decay experiments is that due to atmospheric neutrinos, which are distributed nearly isotropically in space angle and are the ultimate limiting factor determining the sensitivity to long proton lifetimes. It has become abundantly clear from the experiments now under way, that a proper understanding of this background is at least 90% of the battle to discover a proton decay signal.

5.1 Atmospheric Neutrino Fluxes

There have been several calculations of atmospheric neutrino fluxes over the past 20 yrs, with two broadly different approaches to the problem. The procedure in the earlier calculations was to deduce an empirical production spectrum of pions (and kaons) in the atmosphere, on the basis of the muon fluxes measured at sea-level or at high altitudes. The original object of these calculations was to compare expected and observed neutrino event rates deep underground, to obtain information about neutrino cross sections above the then available energy range of accelerator beams, i.e. $E_{\nu} \gg 1 \text{ GeV}$. They made power-law approximations to production spectra which are not necessarily relevant in the calculation of low energy neutrino fluxes ($E_{\nu} < 1 \text{ GeV}$). It is precisely these however which are important for nucleon decay background.

More recently calculations have started from the measured primary spectrum of protons and $\alpha$-particles, and used a Monte-Carlo cascade program to propagate these through the atmosphere, employing accelerator data on pion and kaon production to derive absolute muon and neutrino fluxes at sea-level or elsewhere. These calculations have the advantage that they provide neutrino spectra at low as well as high energy, and that geomagnetic and solar modulations of the primary spectrum are easily incorporated. The precision of the predicted neutrino fluxes is however limited, because the pion and kaon yield data from accelerators exists for only a limited range of incident energy, and of secondary angle and momentum, so that interpolations are necessary. In all the flux calculations, normalization is made to the sea-level muon spectrum, measured using magnetic spectrometers [57,58].
A few general remarks can be made before discussing the detailed results. The primary cosmic-ray protons generate secondary mesons with interaction length \( \lambda = 100 \text{ gm cm}^{-2} \), small in comparison with the total atmospheric depth \( X \approx 1000 \text{ gm cm}^{-2} \). The pions and kaons can either be absorbed by nuclear interaction, with absorption length \( \lambda \), or decay in flight. Integrating over the source distribution, the fraction of mesons of energy \( E \) which have decayed by sea-level is [59]

\[
P_{\pi, K}^{\text{decay}} = \frac{q \sec \theta}{(1 + q \sec \theta)}
\]  

where

\[
q = H/\gamma \beta c \tau = A/E(\text{GeV})
\]

Here, \( \gamma = E/mc^2 \) and \( \tau \) are the Lorentz factor and proper lifetime of the meson, \( \theta \) is the zenith angle, \( H = RT/Mg = 6.5 \text{ km} \) is the scale height of the (isothermal) atmosphere. At large zenith angles, the flux is enhanced by the \( \sec \theta \) factor, expressing the larger decay probability for inclined particles. The values of \( A \) for pions and kaons are:

\[
\begin{align*}
A(\text{GeV}) & \quad \pi^+ & \quad K^+ & \quad K_L^0 \\
& 110 & 200 & 200
\end{align*}
\]

For values of \( E \ll A \), which is the energy region relevant to neutrino background to proton decay, we see that essentially all parents decay before interacting (\( P = 1 \)). Thus, if the primary spectrum follows a power law and we assume Feynman scaling, the muons and neutrinos will follow the same power law (For \( E \gg A \) however, it is clear that the \( \mu, \nu \) spectra will have an index one unit steeper than the primaries).

Muons also contribute to the neutrino fluxes (\( \nu_e \) and \( \nu_\mu \)). If we crudely assume all muons are generated in a thin layer of atmosphere at depth \( x_o \) (or \( x_o/\sec \theta \) for inclined primaries) the proportion which decay by sea-level (depth \( X \text{ gm cm}^{-2} \)), neglecting ionization loss in the atmosphere, will be

\[
P_{\mu}^{\text{decay}} = 1 - \exp[-q \sec \theta \ln(X \sec \theta/x_o)]
\]

where for muons, \( q = 1.03/E(\text{GeV}) \). With \( x_o \approx 100 \text{ gm cm}^{-2} \), \( X \approx 1000 \text{ gm cm}^{-2} \), one finds that for \( E_\mu < 1 \text{ GeV} \), nearly all muons decay before sea-level
whereas at higher energy ($E \cos \theta > 10 \text{ GeV}$) the decay probability varies as $E^{-1}_\mu$. The sea-level muon spectrum is affected by ionization loss in the atmosphere, which is of order $2 \text{ sec} \theta \text{ GeV}$. Thus nearly all muons recorded at sea-level originate from pions with energy above $3 \text{ GeV}$, whereas the bulk of neutrinos of low energy, especially $E_\nu < 0.5 \text{ GeV}$, come from decay of pions of energy below $3 \text{ GeV}$. The sea-level muon spectrum is therefore a good monitor for high energy neutrino fluxes, but is not relevant at low $E_\nu$. For this reason, muon flux measurements at high altitudes are important (but unfortunately, very meagre). The important sources of neutrinos and antineutrinos, the branching ratios and average fractional energies which they receive from the parents in the relativistic limit are as shown in table 5.

Regarding contributions to the neutrino fluxes, it is found that the rapidly falling primary spectrum combines with the rapid increase of neutrino yield with proton energy $E_p$ [61], to give a peak in the proton energy contributing to the neutrino flux for $E_\nu \approx 1 \text{ GeV}$, in the region $E_p \sim 10 \text{ GeV}$. The relevant $K^+/\pi^+$ and $K^-/\pi^-$ ratios are of order 0.07 and 0.03 respectively, considerably below the value 0.20 for $K^+/\pi^+$ used in early flux calculations [60]. We also note that despite the larger energy fractions involved, the lower decay branching ratios and production cross sections of kaons as compared with pions means the $\nu_\mu$ flux contribution from kaons is almost an order of magnitude smaller than for pions, at least for $E_\nu \leq 1 \text{ GeV}$. Muons and pions therefore emerge as the dominant and roughly equal sources of both $\nu_e$ and $\nu_\mu$, until one reaches energies $E_\nu > 5 \text{ GeV}$, when the $1/E$ decay probability for muons cuts down their contribution.

For electron neutrinos, the flux is totally dominated by $\mu$-decay. Taking account of branching ratios and energy fractions, the $\nu_e$ contribution from $K$ decay is negligible in comparison. The $\nu_e$ flux from $\mu$-decay is slightly less than the $\nu_\mu$ flux from the same source, because of the smaller energy fraction in the decay.

In summary, $\nu_e$ fluxes in the 1 GeV energy region are dominated by muon decay, and $\nu_\mu$ fluxes have their main (and roughly equal) contributions from both pion and muon decay. The $\nu_e$ flux is about one half the $\nu_\mu$ flux,
for vertical incidence. At large zenith angles, the secθ factor enhances the muon-produced neutrino flux. At $E_\nu \sim 1$ GeV, the horizontal fluxes of $\nu_e$ and $\nu_\mu$ from muon decay are about twice those at vertical incidence. On the other hand, eqs (17)-(19) tell us that the horizontal and vertical fluxes of $\nu_\mu$ from pion (or kaon) decay are nearly equal.

The relative fluxes of neutrinos and antineutrinos are of great interest, since both neutral and charged current cross sections are so different for the two, and this affects total rates. The sea-level $\mu^+/\mu^-$ ratio has been extensively measured, is practically energy-independent and has a value $R = 1.25-1.30$ [58,62]. This means the same value for the effective $\pi^+/\pi^-$ ratio as well as $(\bar{\nu}_\mu/\nu_\mu)$ from pion decay. From muon decay however, $(\nu/\bar{\nu}_\mu) = 1/R = 0.8$. In the GeV region, pion and muon contributions to the $\nu_\mu$ flux are about equal, so the overall $\nu_\mu/\bar{\nu}_\mu$ flux ratio should be close to unity. On the other hand, electron neutrinos originate almost entirely from muon decay, so that the ratio $(\nu_e/\bar{\nu}_e) = R = 1.25$.

5.2 Results of Flux Calculations

Early estimates of atmospheric neutrino fluxes from pion decays were made in 1961 by Markov and Zheleznyk [63], to be followed by calculations by Zatsepin and Kuz'min [64] who included the contribution from muon decay. They assumed a power law energy spectrum for the pions and included ionization loss of muons in the atmosphere. In 1965, Osborne et al. [60] made similar calculations but included also the various decay chains of kaons. Their results are included in figs 3 and 4, showing the vertical $(\nu_\mu + \bar{\nu}_\mu)$ spectrum, the ratio $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu)$ and the ratio of vertical to horizontal fluxes. All the above calculations applied to $E_\nu > 1$ GeV.

Tam and Young [65] extended the Osborne et al. flux calculations down to $E_\nu = 0.2$ GeV. As explained above, high altitude muon fluxes are required to provide information on the low energy part of the pion source spectrum, and the daughter neutrinos. Tam and Young employed the pion spectrum deduced by Olbert [66] using the technique of Ascoli [69], and based on the altitude dependence of low energy ($\sim 300$ MeV/c) muons measured.
in aircraft flights by Conversi [67] and Sands [68]. It is not clear if Tam and Young included effects of kaon production or not. More recently (1980), fresh calculations of neutrino flux were made by Volkova [70], using the most recent accelerator data for K/π ratios, and presenting the zenith angle and energy dependence of the flux in empirical analytical forms. The results of Tam and Young and of Volkova are included in figs 3 and 4.

The alternative approach to the problem, that starting out from the primary flux, and employing a Monte-Carlo program to trace the hadronic cascade through the atmosphere to determine the source spectrum of neutrinos (and muons), has been taken by Gaisser et al. [61]. As input they used primary flux data on protons and heavier nuclei [71] and accelerator yield data on pion and kaon production as a function of energy and angle, for proton-light nucleus collisions [71(a)]. Their calculated fluxes extend down to $E_\nu = 0.3$ GeV and are included in figs 3 and 4.

Comparing the vertical ($\nu_\mu + \bar{\nu}_\mu$) fluxes at $\lambda = 50^\circ$ in fig. 3, it is seen that for $E_\nu > 2$ GeV the Osborne et al., Volkova and Gaisser et al. results are in good agreement. This is not surprising, since they are normalized to the sea-level muon spectrum and the only differences can be in the K/π ratio. For $E_\nu < 2$ GeV, substantial discrepancies are apparent. The Volkova flux at $E_\nu = 1$ GeV is 60% larger than that of Osborne et al., despite their higher K/π ratio. The Gaisser et al. fluxes are 30% larger than those of Osborne et al. at 1 GeV, and a factor 2 larger than those of Tam and Young at 0.3 GeV. These discrepancies are probably a fair reflection of the present uncertainties in absolute neutrino flux in the low energy region.

The relative intensities of $\nu_e$ and $\nu_\mu$ flux and of horizontal and vertical fluxes are shown in fig. 4, and for such ratios there is good agreement between the various calculations.
Battistoni et al. [97] exposed a module similar to that in the calorimeter they employed to search for proton decay, to an accelerator beam from the CERN PS. The accelerator and atmospheric neutrino energy spectra were closely similar. About 400 events were recorded, with the plane of the plates at 90° and 45° to the neutrino beam. Disregarding differences at the two angles, they obtained measurements of background in a few specific channels, applying of course to the particular granularity and steel thickness (1 cm) employed. They considered the modes:

(a) \( p \rightarrow \mu^+ \pi^- \) and \( n \rightarrow \mu^+ \pi^- \),
(b) \( n \rightarrow \bar{\nu}K^o, K^o \rightarrow \pi^+ \pi^- \),
(c) \( p \rightarrow \mu^+ \pi^0, K^o \rightarrow \pi^+ \pi^- \).

From a Monte-Carlo calculation they estimated that in 50% of genuine decays of type (a), the lepton and pion would have opening angle \( \Theta > 120° \) (in the remainder, the pion is scattered or absorbed inside the iron nucleus). Among the 400 neutrino events, 7 were 2-prong events compatible with \( \mu \pi^- \), energy \( 940 \pm 210 \) MeV and \( \Theta > 120° \), while only one simulated \( p \rightarrow \mu \pi^0 \). Thus, 1.7% of neutrino events simulate \( n \rightarrow \mu^+ \pi^- \) and about 0.3%, \( p \rightarrow \mu^+ \pi^- \).

Battistoni et al. tried to fit 2-prong neutrino events to the \( n \rightarrow \bar{\nu}K^o \) hypothesis (b), and found 9 events out of 400 doing so, that is a 2.5% background. Finally hypothesis (c) \( p \rightarrow \mu^+ K^o \) will produce 3-prong events. In the accelerator data, only two events had 3 prongs, total energy below 1.2 GeV, and with angles between pions and muon in the correct region to mimic \( p \rightarrow \mu^+ K^o \) decay. So, this background is at the level of 0.5% of the total neutrino events.

Although the number of neutrino events examined by Battistoni et al. was not very large, their work is unique in the sense that they can directly compare, in similar modules, underground events with neutrino events. All other experiments have had to rely on Monte-Carlo calculations to estimate background, or use accelerator neutrino data from a completely different detector.
5.5 Neutron Background

The cosmic ray muon flux is shown as a function of depth in fig. 5, after Menon [75]. At the depths of nucleon decay experiments, the mean muon energy is 200–400 GeV. Such muons can generate nucleon cascades in inelastic scattering in the rock, and isolated neutrons from them may enter the detector and conceivably simulate nucleon decay events.

Upper limits [76] on neutron rates have been deduced from stopping muon rates. At great depth, these muons result mostly from decay of pions and thus reflect hadron production by energetic muons. The actual number of isolated neutrons has been estimated by Grant [77] from a Monte-Carlo cascade program. Grant considered neutrons of kinetic energy Te > 0.7 GeV; actually, neutrons of at least 3 GeV are required to produce pions with high probability, and to mimic nucleon decay, so the Grant estimates should be reduced by a factor ≥ 30. We deduce that, for a 10 x 10 x 10 m cubic detector at h = 1600 mwe depth (that of the IMB experiment), there are ≪ 10 isolated neutron interactions of E_n > 3 GeV per year. At h = 5000 mwe (Mont-Blanc tunnel) this would be reduced to ≪ 1 event per year. For a detector of unit density (i.e. of 1 kiloton), the neutrino rate would be ~ 150 events per year.

These calculations indicate that neutron background is ≪ 10% of neutrino background at all depths exceeding 1600 mwe. Because of the short interaction length, neutrons can in any case be vetoed by a fiducial volume cut. The practical situation is that, in the NUSEX (Mont-Blanc) experiment, to be discussed below, no high energy (≥ 1 GeV) neutral hadrons accompanying crossing muons were observed, among 10 neutrino interactions. Thus isolated neutron background, calculated to be at least an order of magnitude smaller than that accompanied by muons through the detector, must be less than a few per cent of neutrino background.

In summary, neutron background in proton decay experiments is at a low level relative to neutrino background, and in comparison with it, may be disregarded.
Battistoni et al. [97] exposed a module similar to that in the calorimeter they employed to search for proton decay, to an accelerator beam from the CERN PS. The accelerator and atmospheric neutrino energy spectra were closely similar. About 400 events were recorded, with the plane of the plates at 90° and 45° to the neutrino beam. Disregarding differences at the two angles, they obtained measurements of background in a few specific channels, applying of course to the particular granularity and steel thickness (1 cm) employed. They considered the modes:

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These calculations indicate that neutron background is $<< 10\%$ of neutrino background at all depths exceeding 1600 mwe. Because of the short interaction length, neutrons can in any case be vetoed by a fiducial volume cut. The practical situation is that, in the NUSEX (Mont-Blanc) experiment, to be discussed below, no high energy ($\geq 1$ GeV) neutral hadrons accompanying crossing muons were observed, among 10 neutrino interactions. Thus isolated neutron background, calculated to be at least an order of magnitude smaller than that accompanied by muons through the detector, must be less than a few percent of neutrino background.

In summary, neutron background in proton decay experiments is at a low level relative to neutrino background, and in comparison with it, may be disregarded.
6. **PROTON DECAY EXPERIMENTS - RESULTS**

As indicated in the Introduction, two main types of detector are in use to study proton decay; water Cerenkov detectors and tracking calorimeters.

6.1 **Water Cerenkov Detectors**

The water Cerenkov method relies on the fact that Cerenkov light is emitted along the surface of a cone of half-angle $41^\circ = \cos^{-1} 1/n$ about the trajectory of a relativistic charged particle of $\beta > 1/n = 0.75$. It is therefore suitable for recording secondary electrons and photons, using photomultipliers to sample the Cerenkov light, and indeed such detectors were proposed largely because $p + e^+ \rightarrow \gamma$ was the favoured decay mode in SU(5). The Cerenkov cone from a track in the water will intersect the water surface in an elliptical ring, as shown in figs 6 and 8. The ring width depends on the track length, and the relative times of firing of the photomultipliers allow the direction in space of the track to be determined. The identification of multi-track events depends on reconstruction of several Cerenkov cones. For 2-track "back-to-back" events, as might be obtained in 2-body proton decay, the cones are well separated in space and should be easily identified, while for multitrack events the pattern can be complicated and difficult to analyze.

Among the advantages of the Cerenkov technique are:

(a) The water medium responds uniformly, and track directions are unambiguous.

(b) Muon decays are detectable as delayed (2 µs) pulses.

(c) Very large volumes of water can be employed. For very pure water, the absorption length in the blue region is as large as 40 m. Because of the large dimensions, proton decay events are easily contained inside the volume (radiation length in water $X_o = 40$ cm).

(d) A fraction of the nucleons (11%) are free protons.

(e) Nuclear absorption of hadronic decay products in a parent oxygen nucleus can take place, but this is a smaller effect than in calorimeters employing an iron medium.
Table 9 gives a list of water Čerenkov detectors now in operation, their characteristics and the expected photoelectron yields for different decay modes.

6.2 The IMB Experiment

This experiment has been mounted in the Morton Salt Mine, Cleveland, Ohio (Bionta et al. [78,79]). The volume of water has a total mass (fiducial mass) of 7000 (3300) tons. It is almost cubical in shape and the 2048 5" photomultipliers are mounted over the surface on a 1 m grid (see fig. 7). Crossing cosmic ray muons provide the absolute energy calibration, with an error of ±15%. The relative timing and pulseheights of the phototubes are calibrated using a pulsed light source of variable intensity, placed inside the water. Examples of the Čerenkov signals from a crossing and stopping muon are given in fig. 8. The Čerenkov light from a muon decay is detected as a delayed pulse, with efficiency 60 ± 10%.

The trigger for event selection requires more than 12 PMT's to fire within 50 ns, or that more than 3 PMT's in any 2 of 32 groups of 64 fire within 150 ns. Any PMT signal within 7.5 µs of the initial trigger is also recorded. The time resolution was 11 ns (FWHM) resulting in a "vertex" resolution (as judged by the pulsed point light source) for single tracks of ± 1 m and for p + e⁺ν of ± 0.6 m. Two-track events are recognizable if each track fires > 40 PMT's and the opening angle exceeds 100°.

The trigger rate is 2.3 . 10⁴ per day, due mostly to crossing muons. These events are subject to an energy selection (40–300 PMT's) corresponding to an energy loss for a relativistic particle of 250–1700 MeV, plus the requirement that the reconstructed vertex position is more than 2 m from the detector surface (for short tracks from neutrino reactions or proton decay, it is a good approximation to treat the light as from a point source). This selection reduces the event rate by a factor 1000, to 230 per day, and these are analysed by three independent methods. They are mostly due to short entering and stopping muon tracks and corner-clipping muons. Based on the points on the surface where the earliest tubes fixed, and using a fitting procedure, all the muons can be rejected and one is left with "contained" events inside the fiducial
volume, at the rate of 3 per day with > 40 PMT's firing. These candidates are examined visually using a graphics system, and about 1 per day is retained. Monte-Carlo simulations show that 75% of neutrino interactions and 90% of proton decays should be retained by the filtering procedure. The selected events are due primarily to single track neutrino interactions.

NEUTRINO INTERACTIONS After a live time of 132 days (or 4.10^{32} "proton years" of exposure), 112 neutrino events were observed [78]. They are uniformly distributed through the detector volume, and allowing for the detection efficiency, correspond to a rate of 125 ± 12 events per kton yr, in reasonable agreement with expectations (see tables 11, 7 and 8). Fig. 9 shows the estimated true energy spectrum of neutrino events, after adding 230 MeV to the "Cerenkov energy" to allow for the muon mass and the fact that for part of the range, the muon is below Cerenkov threshold. The dashed curve shows the expected distribution.

The up-down ratio in the events is 0.88 ± 0.17, consistent with the prediction U/D = 0.86 in Table 6. It is however, to be emphasized that the typical angle of emission of the muon relative to the neutrino at energies below 1 GeV is large and therefore, the U/D ratio of the muons will be closer to unity than for the neutrinos. The observed fraction of events with muon decays is 25%. This is consistent with the \( \nu / (\nu + \nu_e) \) flux ratios (Table 7), the muon detection efficiency (60%) and the higher sensitivity of the Cerenkov detector to electrons than to muons.

THE DECAY MODES \( p \to e^+ \pi^0, p \to \mu^+ \pi^0 \) All except 3 of the 112 events described above fitted the "one-track hypothesis", that is, they are single or multi-track events in which the Cerenkov light is mainly concentrated in one hemisphere, with fewer than 40 PMT's firing in the backward hemisphere. The 3 events are "wide angle two-track events", that is, with a back-to-back configuration of Cerenkov cones, and are potential candidates for decay \( p \to e^+ \pi^0 \) (although \( \pi^0 \to 2 \) photons, the value of \( E_{\pi}/m_\pi \approx 3.55 \) so that the average angle \( \bar{\theta} \) between the photons is smaller than the Cerenkov angle of 41°. This fact, together with the disparity between photon energies for \( \bar{\theta} > \bar{\theta} \), means the \( \pi^0 \) signal will appear as a single cone). The 3 events have opening angles between the cones of \( \theta = 115-135^\circ \). They are
however not acceptable as \( p \rightarrow e^+ \pi^0 \) decays because (a) two have a muon decay signal (b) one event triggers 340 PMT's and has total energy 1.7 GeV (c) for this event \( \theta = 115^\circ \), which is outside the range expected for decay of a free or bound proton, taking account of Fermi motion in the parent nucleus. It is expected that \( \theta > 140^\circ \) in the majority of genuine decays.

The 3 "2-track" events with \( \theta > 100^\circ \) are attributed to inelastic neutrino reactions of the form \( \nu N \rightarrow \mu \pi N \), or \( \nu N \rightarrow e \pi N \). The characteristics have been estimated from the configuration of events in the Gargamelle heavy liquid chamber exposed to a neutrino beam at the CERN PS (Deden et al. [80]). The opening angle between \( \mu \) and \( \pi \) is plotted in fig. 10 against the energy ratio \( (E_1 - E_2)/(E_1 + E_2) \) where \( E_1 \) is the energy of the higher energy particle. \( p \rightarrow e^+ \pi^0 \) events should occur in the circular quadrant, while the points are simulated neutrino data, equivalent to what would be obtained from the atmospheric neutrino flux in a 1.75 year run. We note that \( \sim 20 \) events have \( \theta > 115^\circ \) so that in a 132-day exposure, 3 or 4 neutrino events would be expected.

On the basis that no events attributable to \( p \rightarrow e^+ \pi^0 \) are observed in a more extended 250 day run, Bionta et al. [79,98] place the following 90% CL limit

\[
\tau/B(p \rightarrow e^+ \pi^0) > N f \frac{\epsilon}{n} \frac{\tau t}{2.3} = 1.5 \times 10^{32} \text{ yr} \tag{22}
\]

where \( N = 2 \times 10^{33} \) is the number of nucleons, \( f = 10/18 \) is the proton fraction, \( \epsilon = 0.68 \) is the computed \( \pi^0 \) nuclear survival probability, \( \epsilon = 0.9 \) is the detection efficiency, and \( T \) the time. The IBM group also quote a similar limit for

\[
\tau/B(p \rightarrow \mu^+ \pi^0) > 1.5 \times 10^{32} \text{ yr} \tag{23}
\]

THE DECAY MODES \( p \rightarrow \mu^+ K^0, n \rightarrow \nu K^0 \) The first method employed to search for the decay \( p \rightarrow \mu^+ K^0 \) is based on the decay \( K_s \rightarrow 2\pi^0 \), giving 4 \( \gamma \)'s with a nearly isotropic distribution in angle (the Lorentz factor of the \( K^0 \) is only 1.2). The Cerenkov rings from 4 isotropically distributed showers are not easily separable. Bionta et al. calculate a quantity called the isotropy, \( I \), for the event, which is the vector sum of unit vectors from the vertex to each PMT, divided by the number of PMT hits. For a single track, \( I = \cos 42^\circ = 0.7 \), while for an isotropic light source, or a
"back-to-back" 2-track event such as \( p \to e^+\pi^- \), \( I \approx 0 \). Fig. 11 shows the scatter plot for 109 events with Cerenkov energy 500 < \( E_c \) < 850 MeV. 90% of \( p \to \mu^+K^0 \) events are expected to fall within the dashed curve, and 3 events are found there. One is excluded on the basis of too high an energy on one track, while the vertex of a second can be adjusted so that all the light is contained in one hemisphere. The one remaining candidate yields a 90% CL limit

\[
\frac{\tau}{B(p \to \mu^+K^0)} > 1.8 \cdot 10^{31} \text{ yr (for } K^0 \to 2\pi^0) \tag{24}
\]

after inserting the appropriate branching ratio for \( K^0 \to 2\pi^0 \) including a contribution from \( K_L^0 \) interactions. A search has also been made for the decay \( p \to \mu^+K^0 \) via the mode \( K^0 \to \pi^+\pi^- \), with the two subsequent decays \( \pi^+ \to \mu^+ \to e^+ \). From 2 events within the required pulse height range, each with 2 muon decays, one is rejected because it again contains a single track of too high an energy, and the remaining candidate gives

\[
\frac{\tau}{B(p \to \mu^+K^0)} > 1.3 \cdot 10^{31} \text{ yrs (} K^0 \to \pi^+\pi^- \). \tag{25}
\]

The results in eqs (24) and (25) can be combined to give

\[
\frac{\tau}{B(p \to \mu^+K^0)} > 2.6 \cdot 10^{31} \text{ yrs} \tag{26}
\]

The above methods have also been applied to the decay \( n \to \nu K^0 \), \( K^0 \to 2\pi^0 \). The 90% contour for such events in fig. 11 is shown by the full curve. Of the 5 events in this region, only 3 survive after rejecting one event with a muon decay and one with too much energy in one track, leading to the limit

\[
\frac{\tau}{B(n \to \nu K^0)} > 0.8 \cdot 10^{31} \text{ yrs} \tag{27}
\]

Other limits [79,98] obtained by the IMB group are given in Table 13. In summary, this experiment has given by far the most stringent limits on lifetime for a variety of decay modes of the nucleon. It is clear that, with increased statistics, the limit for the decay \( p \to \mu^+\pi^- \) or \( e^+\pi^- \) can be pushed proportionately further, possibly by another order of magnitude. On the other hand, the multiprong decays such as \( p \to \mu^+K^0 \), or those without a clear back-to-back signature such as \( n \to \nu K^0 \), are more difficult to differentiate from background, and the results (24-27) can most likely not be improved by a large factor.
6.3 The HPW Experiment

The water detector employed by the HPW Collaboration [82] in a mine at Park City, Utah, is in the form of a cylindrical tank of diameter 12 m and depth 7.3 m. The 700 5" PMT's are mounted on a 1 m grid through the water volume. The inside of the tank is covered with an aluminium reflector to increase light output and a veto shield of proportional wire chambers surrounds the tank. Operational since early 1983, the equipment has been checked by measuring muon angular distributions and the stopping muon lifetime. Pattern recognition in the volume array, with reflection of light by the walls, is clearly more difficult than for the IMB surface array. No proton lifetime limits have yet been reported.

6.4 The Kamiokande Experiment

Constructed by groups from Tokyo, Kek, Niigata and Tsukuba [99], this detector is again a cylindrical water tank, of diameter 15.6 m and height 16 m, with (fiducial) mass of 3000 (1000) tons. 20" diameter photo-multipliers are mounted on a surface grid inset 1.5 m from the tank walls. The photocathodes cover 20% of the surface area, that is about 10 times that of the IMB detector.

On the basis of 98 days of running, 29 events, presumably of neutrino origin, have been observed in the fiducial volume, corresponding to a rate of 123 ± 23 per kton yr, in good agreement with expectations (see Table 11). The energy spectrum of a sample of single-track neutrino reactions is included in fig. 9. Limits have been set on the decay modes discussed for the IMB experiment (see Table 13). They are about one order of magnitude smaller, because of the smaller fiducial mass and running time to date. In principle, this device is sensitive to decay modes which would be below the trigger threshold of the IMB experiment. Furthermore with a tenfold larger fractional area covered by photocathode, it should be able to identify multi-track events and make more rigorous cuts on background, for example on the basis of coplanarity.
6.5 Tracking Calorimeter Detectors

The water Cerenkov detectors described above possess a sensitivity to nucleon decay, in terms at least of the mass of active medium, which it is hard to match by other methods. Nevertheless, although they have given by far the most stringent limits on 2-body decay modes, such as $p \rightarrow e^+\pi^0$, $\mu^+\pi^0$, they have some disadvantages when dealing with events of higher multiplicity or with non-relativistic secondaries, and the ability to discover unexpected decay modes. Tracking calorimeters were developed in parallel with the water Cerenkovs, because they depended on well-proven techniques at a time when the true potentiality of the water Cerenkov method was unknown (see Table 10). The advantages of an iron calorimeter instrumented with layers of gas counters are the following:

(a) Because of the high density and high mass number of the medium, proton decay products can be confined within a volume of dimensions one order of magnitude smaller than for water detectors. Even for arrays of order 100 tons only, most of the mass can be useful for containing events.

(b) Vertices can be reconstructed with a precision of order 1 cm, compared with 1 m, and this enormously aids pattern recognition.

(c) Tracks can be followed in detail only limited by the sampling frequency, and particle direction inferred from scattering (or, if it is measured, ionization), or existence of muon decays.

(d) The detector can be easily built in modular form, is transportable and can be tested with accelerator beams.

6.6 The Soudan I Detector

This calorimeter consists of an array of 3456 proportional tubes, each of 4.5 cm diameter, embedded in an iron/concrete matrix. The dimensions are 2.9 x 2.9 x 1.9 m and the total mass, 31.5 tons. It has been built and operated by a Minnesota-ANL Collaboration (Bartelt et al. [92]), and is located at a depth of 1800 mwe at the Soudan mine, N. Minnesota. In 0.38 yrs of operation, one contained event has been reported. It is interpreted as a neutrino reaction and the expected rate (Table 7) is consistent with this. The experiment places a lower limit on the proton lifetime $\tau > 10^{30}$ yrs.
6.7 The KGF Calorimeter

The first iron calorimeter specifically designed to search for nucleon decay was built by the Tata-Osaka-Tokyo Collaboration (Krishnaswamy et al. [85,86]), and installed since 1980 in a mine at the Kolar Gold Fields (KGF), S. India. At a depth of 7600 mwe, it is by far the deepest detector in operation. The detector consists of a rectangular box of dimensions $6 \times 4 \times 4$ m consisting of 1.2 cm thick iron plates separated by 34 horizontal layers of proportional counters, each counter being of $10 \times 10$ cm cross section. Alternate layers of counters are mounted at right angles to give 3 dimensional track coordinates. The total mass is 140 tons and the mean density 1.5. Because of the low density, many events originating in the detector are unconfined. The basic trigger is a 5-fold coincidence of pulses among any successive 11 layers.

After 2.2 yrs operation (as of July '83) a total of 17 events have been observed with a vertex inside the detector. This tally includes five single track events. Since the detector has no directional information, elastic neutrino events, consisting of a single exiting muon, are indistinguishable from muons entering and stopping in the detector. The number of muons generated by neutrinos outside the detector, and stopping in it, must be equal to the number of muons generated inside and leaving. Using this principle, and up/down equality of the fluxes, the 5 single tracks entering or leaving the bottom represent a fair estimate for the total of 1-prong neutrino events. Making an allowance for trigger efficiency, this provides a gross event rate of $72 \pm 17$ per kton yr, compatible with the charged current neutrino rate at $\lambda = 0^\circ$ magnetic, of 107/kton yr calculated by Gaisser and Stanev [84].

The number of totally confined events is 7 (the detector is 26 radiation lengths deep, and $v_e$, $\bar{v}_e$ interactions are expected to form 30% of the total neutrino rate).

In the list of events published by the KGF Collaboration, 3 are claimed to be nucleon decay candidates with all tracks fully contained in the detector – and a further 3 as partially confined nucleon decay candidates. Fig. 12 shows 2 confined candidates. Notice that because of the large ($10 \times 10$ cm cross section) gas counters, spatial resolution is
poor and the number of hits per track per stereo view is very small (2-3 on average). This means that track and vertex reconstruction is extremely difficult. Event 587, containing 3 or 4 prongs is interpreted as $p \rightarrow e^+\pi^0$ because of the scatter of hits, implying electromagnetic origin. Event 867 is interpreted as a 2-prong event with a back-to-back configuration; on the basis of the criteria of Battistoni et al. described previously, it is also unlikely as a neutrino interaction. This and the third event are interpreted as $p \rightarrow \nu\pi^+$ or $\nuK^+$, and $p \rightarrow \nuK^0$ or $n \rightarrow e^+\pi^-$ respectively. If the reconstruction of these events is accepted, there is no doubt that they are unlikely to be of neutrino origin.

What are the KGF events? Are they nucleon decays, as the authors claim, or simply background? I believe the answer is not just in trying to reconstruct tracks in these events, and showing that they have unacceptable topologies as neutrino interactions, because the very reconstruction of tracks and vertices must be highly subjective and therefore suspect. For example, secondary hadrons undergo Coulomb and nuclear scattering (and absorption) in iron, at a rate critically dependent on particle momentum. There is no way one can take this into account with a coarse-grain detector, and on an event-by-event basis, because the information level is too low. Rather one must expose the detector to an accelerator beam, to observe a sample of neutrino reactions directly for comparison, and on a statistical basis; or, failing that, generate neutrino events by a Monte-Carlo program using as input actual data (e.g. from bubble chamber accelerator neutrino events), and propagating such Monte-Carlo events through the detector. Unless some additional input of this kind is fed in, it seems impossible to reach positive conclusions about the KGF events.

In making these criticisms, it should however be emphasized that the KGF detector was, by a long way, the first in the field, and that if the proton lifetime had been a factor 100 shorter than the present limit, this group would have discovered proton decay, just from the gross even rate. Their great contribution in the field was to be there first with a large detector which could contain decay events, and to stimulate the building of larger and more finely-grained detectors.
6.8 The NUSEX Calorimeter

This device consists of a 3.5 x 3.5 x 3.5 m cube of mass 150 tons built from 136 layers of 1 cm thick iron plates separated by layers of 1 x 1 cm plastic streamer tubes. The experiment is being carried out by a collaboration of Frascati, Milano, Torino and CERN (89–91) in the Mont-Blanc tunnel, at 5000 mwe depth. Each one of the 4300 tubes can provide a 3-dimensional track coordinate via read-out from anode wires and cathode pick-up strips orthogonal to the anodes (fig. 13). The mean density is 3.6 gcm⁻³ and the radiation length X₀ = 4.5 cm. The event trigger requires a coincidence of any four adjacent planes of counters, or of 3 adjacent planes plus 2 other adjacent planes elsewhere in the array.

NEUTRINO EVENTS After a live time of 0.87 yrs (130 ton yrs total, 113 yrs fiducial) the collaboration have observed 10 contained events [97]. The gross event rate of 118 ± 37 per kton yr is compatible with that expected from neutrino background (see Table 11). The identified neutrino events (fig. 14) include 6 elastic and up to 4 inelastic events and 2 due to νₑ, νₑ̄. In bins of visible energy, the sample of 10 events is consistent with rates expected in Table 8, with 5 events below 1 GeV and 5 above (see also fig. 9).

PROTON DECAY CANDIDATE Among the 10 events in the NUSEX calorimeter is one stated to be incompatible with a neutrino interpretation [90]. It is shown in fig. 15(a). If the event were to be ascribed to a reaction of the form νW → μW, then the pion would have to undergo a large angle scatter as shown (fig. 15(b)), and the total energy and momentum would then be E_{vis} = 0.84 ± 0.20 GeV, \( p_{vis} = 0.81 ± 0.20 \) GeV/c. The probability that a neutrino interaction could have such a topology is found directly from the accelerator data in the same calorimeter, discussed in sect. 5.4, to be 2/400. Hence the expected number of neutrino events of this type is 0.05. An alternative interpretation, in fig. 15(c), is of the decay \( p → μ^+K^0, K^0 → π^+π^- \). In that case, the visible energy and momentum are \( E_{vis} = 1.0 ± 0.2 \) GeV, \( p_{vis} = 0.4 ± 0.2 \) GeV/c. A finite momentum is permitted for proton decay when allowance is made for nuclear Fermi motion. If it is so interpreted, then, after correcting for efficiency and probability of observing \( K^0 \) if it decays in the \( K^0_L \) mode instead of \( K^0_S → π^+π^- , π^0π^0 \), the NUSEX group find a 90% CL limit
\[ \tau/B(p \to \mu^+K^0) > 0.9 \cdot 10^{31} \text{ yrs} \] (28)

Other interpretations in terms of alternative decay modes \( p \to 3\mu, \ p \to K^0\nu\bar{\nu} \) are also possible for this event.

6.9 The FREJUS Experiment

This device is located in the Frejus tunnel near Modane (4400 mwe), and consists of an array of 3 mm steel plates separated by layers of 0.5 x 0.5 cm polypropylene flash chambers. There are 500 flash tube planes (a total of \( 10^6 \) tubes), and 124 planes of Geiger tubes for triggering, with 10.5 cm between trigger planes. The experiment is being carried out by a collaboration of Aachen, Orsay, Palaiseau, Saclay and Wuppertal, and the full detector mass will be 1 kton [103].

The detector has three times finer granularity than the NUSEX detector and its expected energy resolution for electrons and photons is 15\%, and for pions, 12-20\%. The full device should be operating in mid 1984.

7. LIMITS ON MONOPOLE CATALYSIS OF PROTON DECAY

Several of the proton decay experiments have set limits on fluxes of magnetic monopoles. Emphasis is on the proposed superheavy GUT monopoles of mass \( \sim 10^{16} \) GeV, which were supposedly created in the early stages of the Universe, and which are likely to have present velocities in range \( 10^{-4} < \beta < 10^{-2} \). These could certainly penetrate deeply into the Earth and be recorded in proton decay detectors.

Flux limits have been set by the Soudan I Collaboration (Bartelt et al. [93]), the NUSEX Collaboration (Battistoni et al. [91]) and the KGF Collaboration (Krishnaswamy et al. [101]), by assuming that monopoles produce sufficient ionization to leave tracks, and utilizing a trigger which ensures that the particle velocity is in the above range. No events with the required linearity in traversal time through successive layers of detector have been observed in any of these experiments. The corresponding flux limits, of order \( F_m < 10^{-13} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \), are given in table 12.
Rubakov [94] and Callan [95] have argued that GUT monopoles \( M \) may catalyse nucleon decay via a strong interaction process of the type

\[
M + p + M + e^+ + \text{mesons}
\]

with a cross section

\[
\sigma_c = \frac{\sigma_0}{\beta_r} \tag{29}
\]

where \( \sigma_0 \sim 0.1 \text{ GeV}^{-2} = 0.1 \text{ mb} \) and the catalysis cross section \( \sigma_c \) is expected to follow the \( 1/\beta_r \) dependence typical of an exothermic capture reaction. Here, \( \beta_r \) is the relative velocity of monopole and proton. In a nucleus, for slow monopoles, \( \beta_r \approx 0.1 \), the velocity of Fermi motion. If \( \sigma_c \) is large enough, so that the interaction mean free path \( \lambda \left( = 1/N\sigma_c \right) \) where \( N \) is the nucleon density) is comparable with or smaller than the detector dimensions, multiple proton decays should be observed. The question of whether such decays can be recognized will depend on the monopole velocity, \( \beta \), and the sensitive time or dead time of the detector, following the first proton decay event.

Limits have been set on such a process by the IMB Collaboration (Errede et al. [96]), and by the NUSEX Collaboration (Battistoni et al. [91]). Errede et al. observe no multiple events inside an 8 \( \mu \)s time slot (corresponding to \( \beta > 10^{-4} \)), in a 100 day run. The corresponding limit on flux of monopoles is \( F_m < 7 \cdot 10^{-15} \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) for large values of \( \sigma_c \geq 10 \text{ mb} \), and for \( 10^{-4} < \beta < 10^{-1} \), where the efficiency for detecting multiple events would have been essentially 100\%. For smaller values of \( \sigma_c \) the limit is less stringent (see table 12). Battistoni et al. also observe no double interactions, but in this case, they would have to occur either within a 5 \( \mu \)s time slot, or after a recovery interval of 20 ms. They find for \( \sigma_c \geq 5 \text{ mb} \), \( F_m < 2 \cdot 10^{-14} \text{ cm}^{-2} \text{sr}^{-1} \text{s}^{-1} \).

If the catalysis cross section \( \sigma_c \ll 1 \text{ mb} \), multiple proton decays would be infrequent in any of these detectors, since \( \lambda \) is larger than the detector size (\( \sigma_c = 1 \text{ mb} \) corresponds to 16 m water). Nevertheless, a flux limit can be set from the frequency of single interactions. Errede et al. [96] argue that because of the "brick-wall" kinematics between a nucleon and massive monopole, a monopole-catalysed nucleon decay should
not have zero net momentum for the decay products, and can indeed look like any neutrino reaction of energy below 2 GeV. They therefore conservatively assign all 66 neutrino events in 100 days run time to monopole-induced proton decays. The flux limit in this case is $F_m < 2 \cdot 10^{-12} \text{ cm}^{-2} \text{sr}^{-1} \text{sec}^{-1}$ for $\sigma_c = 1 \text{ mb}$, rising to $F_m < 10^{-11}$ for $\sigma_c = 0.1 \text{ mb}$. Battistoni et al. use their single proton decay candidate to set a limit on monopole flux of $F_m < 10^{-13}$ for $\sigma_c = 1 \text{ mb}$, rising to three times this limit for $\sigma_c = 0.1 \text{ mb}$.

In summary, no experiments have direct evidence for GUT monopoles in the form of tracks due to slow particles, and limit the flux to the level $F_m < 10^{-12}$ to $10^{-13} \text{ cm}^{-2} \text{sr}^{-1} \text{sec}^{-1}$, for velocities in the range $\beta = 10^{-4}$ to $10^{-2}$. These limits depend on assumptions about monopole velocity and ionization in gases which are still the subject of debate. There is no evidence either for proton decay catalyzed by monopoles. The flux limits also depend on the monopole velocities and of course on the catalysis cross sections, but are in the region $F_m < 10^{-14}$ to $10^{-12} \text{ cm}^{-2} \text{sr}^{-1} \text{sec}^{-1}$. None of these limits yet reaches inside the Parker bound [104] of $F_m < 10^{-15} \text{ cm}^{-2} \text{sr}^{-1} \text{sec}^{-1}$, which is the maximum flux which could be tolerated without destroying the galactic magnetic field, of order 3 $\mu$G.

8. COMPARISON OF RESULTS, FUTURE POSSIBILITIES AND CONCLUSIONS

8.1 Present Results

All experiments described find events attributable to neutrino interactions. If we assign all events in this way, the total rates observed at different locations (Table 11) are in agreement with expectations based on calculated fluxes. Further, the energy spectrum of events (fig. 9), the relative numbers due to upwards and downwards neutrinos, and the relative numbers attributed to $\nu_e$ and $\nu_\mu$, respectively, are all in accord with predictions. In particular, there are no peaks in energy spectra or anomalies in prong distributions which might suggest another major source of events.
Table 13 summarizes the proton lifetime limits from different detectors and for various decay modes. Regarding the decay mode $p \to e^+ \pi^0$, IMB set a limit $\tau/B(p \to e^+ \pi^0) > 1.5 \cdot 10^{32}$ yr, while the KGF Collaboration claim one event as a serious candidate, with negligible background. The corresponding lifetime is $\sim 2 \cdot 10^{31}$ yrs. The joint probability that these two experiments are statistically compatible has a maximum value of 2.2%, and in view of the remarks in a previous section, the KGF claim has to be rejected. For the decay mode $p \to \mu^+ K^0$, the limits are less severe. On the basis of one possible candidate each, IMB give a limit $\tau/B(p \to \mu^+ K^0) > 2.6 \cdot 10^{31}$ yrs while NUHES quote $0.6 \cdot 10^{31}$ yrs, with neutrino background at the 7% level. These two results are compatible, with a joint probability of 15% (for $\tau/B(p \to \mu^+ K^0) \sim 7. 10^{31}$ yrs).

8.2 Future Experiments

For the decay mode $p \to e^+ \pi^0$, the water detectors have little background and in time, the existing IMB experiment should push the limit to around $10^{33}$ yrs. On the other hand, there does not appear to be much prospect of pushing the limits on the modes $p \to \mu^+ K^0$, $n \to \bar{\nu} K^0$ by more than a factor 3 or so, because of the branching ratio $K^0 \to 2\pi^0$ and the absence of clean kinematic handles, as in $p \to e^+ \pi^0$. For these decay modes, large (kiloton) tracking calorimeters are probably more suitable. The new Frejus calorimeter should be able to attain a limit for $N \to \mu K, \bar{\nu} K$ of $10^{32}$ yrs or beyond.

Our discussions have concerned results from existing detectors. New projects are also proposed, including Soudan II, a 1 kiloton calorimeter instrumented with drift chambers, to be located in N. Minnesota, intended to provide information on particle direction from track ionization; a multi-kiloton calorimeter equipped with flash chambers, with track direction from timing, to be located in the Gran Sasso tunnel; and various "second generation" projects, for example using liquid argon as the calorimeter medium.
8.3 Conclusions

At present, there is simply no evidence that protons decay. The IMB limit on $p \rightarrow e^+ \pi^0$ definitely excludes the minimal SU(5) version of GUTs, but a signal in other modes, such as $\mu \pi^0$ or $\nu \kappa^0$ is by no means excluded at a level which should be detectable in the future ($10^{32}$ yrs or even longer) and compatible with other versions of GUT. I may quote here from my assessment at the Paris Conference (July 1982), since what I said then [102] is still true today: "Nucleon decay, if it is ever discovered, will have to be based on unimpeachable evidence from several independent experiments using different techniques. We are a long, long way from such a goal". The fact that there are physicists actively engaged on the search is mute testimony to the baryon asymmetry of the Universe, and by inference, that protons do decay at some level. It is important to find such a process, not least because its existence would be a unique test of our ideas of grand unification, and the observed decay modes would give us an important handle on the nature of the mechanisms and gauge groups involved.
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REFERENCES (Cont'd)


REFERENCES (Cont'd)


REFERENCES (Cont'd)


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J. Gaidos, private communication, November 1983.


### TABLE 1

**Experiments leading to limits on a new interaction coupled to baryon number**

<table>
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<tr>
<th>Authors</th>
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<th>$\Delta B/B$</th>
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<th>$K_B/K$</th>
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<td>$7 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>Braginsky and Panov 1972 [21]</td>
<td>Pt, Al</td>
<td>$4 \cdot 10^{-4}$</td>
<td>$1 \cdot 10^{-12}$</td>
<td>$2 \cdot 10^{-9}$</td>
</tr>
</tbody>
</table>

$\Delta B/B$ = fractional difference in baryon number per unit mass.

$\Delta R/R$ = fractional difference in ratio of inertial to gravitational mass.

$K_B/K$ = ratio of baryon coupling to gravitational coupling.
TABLE 2

Nucleon decay branching ratios predicted in SU(5). Average values from review by Langacker [32]

<table>
<thead>
<tr>
<th>Mode</th>
<th>BR (%)</th>
<th>Mode</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \to e^+\pi^0$</td>
<td>30</td>
<td>$n \to e^+\pi^-$</td>
<td>54</td>
</tr>
<tr>
<td>$e^+\rho^0$</td>
<td>14</td>
<td>$e^+\rho^-$</td>
<td>23</td>
</tr>
<tr>
<td>$e^+\eta$</td>
<td>4</td>
<td>$\bar{\nu}_e\eta$</td>
<td>~ 1</td>
</tr>
<tr>
<td>$e^+\omega$</td>
<td>30</td>
<td>$\bar{\nu}_e\omega$</td>
<td>7</td>
</tr>
<tr>
<td>$\bar{\nu}_e\pi$</td>
<td>11</td>
<td>$\bar{\nu}_e\pi^0$</td>
<td>7</td>
</tr>
<tr>
<td>$\bar{\nu}_e\rho$</td>
<td>4</td>
<td>$\bar{\nu}_e\rho^0$</td>
<td>4</td>
</tr>
<tr>
<td>$\nu_eK^0$</td>
<td>7</td>
<td>$\bar{\nu}_\mu K^0$</td>
<td>4</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>&lt; 1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 3

Geochemical and radiochemical limits on nucleon lifetime

<table>
<thead>
<tr>
<th>Authors</th>
<th>Experiment</th>
<th>Depth (mwe)</th>
<th>$\tau_{\text{min}}$ (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goldhaber [4]</td>
<td>$^{232}$Th fission</td>
<td></td>
<td>$10^{21}$</td>
</tr>
<tr>
<td>Flerov et al. [40]</td>
<td>$^{232}$Th fission</td>
<td></td>
<td>$10^{23}$</td>
</tr>
<tr>
<td>Evans and Steinberg [41]</td>
<td>$^{120}$Te $\to$ $^{129}$Xe</td>
<td>~ 400</td>
<td>$1.6 \cdot 10^{25}$</td>
</tr>
<tr>
<td>Bennett [44]</td>
<td>Mica spallation</td>
<td>10,000</td>
<td>$2 \cdot 10^{27}$</td>
</tr>
<tr>
<td>Fireman [47]</td>
<td>$K^{39} \to Ar^{37}$</td>
<td>4,400</td>
<td>$2 \cdot 10^{26}$</td>
</tr>
</tbody>
</table>
TABLE 4
Early limits on nucleon lifetime by direct methods

<table>
<thead>
<tr>
<th>Authors</th>
<th>Experiment</th>
<th>Decay mode</th>
<th>Depth (mwe)</th>
<th>$\tau_{\text{min}}$ (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reines, Cowan, and Goldhaber 1954 [4]</td>
<td>300 l liquid scint.</td>
<td>All (E_ch &gt; 100 MeV)</td>
<td>200</td>
<td>$10^{22}$</td>
</tr>
<tr>
<td>Reines, Cowan and Kruse 1958 [49]</td>
<td>As above, with delayed neutron pulse</td>
<td>All</td>
<td>200</td>
<td>$4 \cdot 10^{23}$</td>
</tr>
<tr>
<td>Backenstoss et al. 1960 [8]</td>
<td>50 l liquid Cerenkov, upward rel. sec.</td>
<td>At least one secondary of &gt; 250 MeV</td>
<td>2400</td>
<td>$3 \cdot 10^{26}$</td>
</tr>
<tr>
<td>Giamati and Reines 1962 [50]</td>
<td>200 l liquid scint.</td>
<td>All</td>
<td>1760</td>
<td>$6 \cdot 10^{27}$</td>
</tr>
<tr>
<td>Kropp and Reines 1965 [51]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gurr et al. 1967 [52]</td>
<td>Scint. hodoscope</td>
<td>All</td>
<td>8000</td>
<td>$2 \cdot 10^{28}$</td>
</tr>
<tr>
<td>Reines and Crouch 1974 [53]</td>
<td>Scint. hodoscope + $\mu$ decay</td>
<td>Muon</td>
<td>8000</td>
<td>$3 \cdot 10^{29}$</td>
</tr>
<tr>
<td>Bergamesco and Picchi 1974 [54]</td>
<td>500 l liquid scint.</td>
<td>All</td>
<td>4270</td>
<td>$1.3 \cdot 10^{29}$</td>
</tr>
<tr>
<td>Learned, Reines and Soni 1979 [55]</td>
<td>Liquid scint.</td>
<td>Muon</td>
<td>8000</td>
<td>$10^{30}$</td>
</tr>
<tr>
<td>Cherry et al. 1981 [56]</td>
<td>150 ton H 0 Cerenkov + $\mu$ decay</td>
<td>Muon</td>
<td>4400</td>
<td>$1.5 \cdot 10^{30}$</td>
</tr>
</tbody>
</table>
### TABLE 5

Sources of atmospheric neutrinos

<table>
<thead>
<tr>
<th>Neutrino flavour</th>
<th>Source</th>
<th>Branching fraction</th>
<th>Mean energy $E_\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$, $\bar{\nu}_\mu$</td>
<td>$\pi^+ \to \mu^+ + \nu_\mu$</td>
<td>1</td>
<td>$0.21 E_\pi$</td>
</tr>
<tr>
<td></td>
<td>$K^+ \to \mu^+ + \nu_\mu$</td>
<td>0.64</td>
<td>$0.48 E_K$</td>
</tr>
<tr>
<td></td>
<td>$K^- \to \mu^- + \mu^+ + \nu_\mu$</td>
<td>0.13</td>
<td>$0.30 E_K$</td>
</tr>
<tr>
<td></td>
<td>$\mu^- \to e^- + \bar{\nu}<em>e + \nu</em>\mu$</td>
<td>1</td>
<td>$0.35 E_\mu (= 0.28 E_\pi)$</td>
</tr>
<tr>
<td>$\nu_e$, $\bar{\nu}_e$</td>
<td>$K^+ \to \pi^0 + e^+ + \nu_e$</td>
<td>0.05</td>
<td>$0.30 E_K$</td>
</tr>
<tr>
<td></td>
<td>$K^- \to \pi^- + e^+ + \nu_e$</td>
<td>0.20</td>
<td>$0.30 E_K$</td>
</tr>
<tr>
<td></td>
<td>$\mu^+ \to e^+ + \nu_e + \bar{\nu}_e$</td>
<td>1</td>
<td>$0.30 E_\mu (= 0.24 E_\pi)$</td>
</tr>
</tbody>
</table>

### TABLE 6

Dependence of $(\nu_\mu + \bar{\nu}_\mu)$ flux $\phi$ on latitude

(a) Latitude Ratio $\phi(\lambda = 0^\circ)/\phi(\lambda = 50^\circ)$ for downward neutrinos

<table>
<thead>
<tr>
<th>Authors</th>
<th>$E_\nu$ (GeV)</th>
<th>0.2</th>
<th>0.5</th>
<th>1.0</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tam and Young [65]</td>
<td></td>
<td>0.58</td>
<td>0.62</td>
<td>0.79</td>
<td>0.84</td>
</tr>
<tr>
<td>Gaisser et al. [61]</td>
<td></td>
<td>0.58</td>
<td>0.58</td>
<td>(E &gt; 0.6)</td>
<td>-</td>
</tr>
<tr>
<td>Dar [73]</td>
<td></td>
<td>0.13</td>
<td>0.20</td>
<td>0.31</td>
<td>0.70</td>
</tr>
</tbody>
</table>

(b) Up/Down flux ratio (Gaisser et al. [61]; $E_\nu > 0.6$ GeV, $E_{\nu_e} > 0.4$ GeV)

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Up-Down Rates/Kton yr Solar max.</th>
<th>Solar min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>52° (IMB)</td>
<td>51.4/59.7 = 0.86</td>
<td>59/73 = 0.81</td>
</tr>
<tr>
<td>27° (Kamioka)</td>
<td>46.3/43.4 = 1.07</td>
<td>53/46 = 1.15</td>
</tr>
<tr>
<td>2° (KGF)</td>
<td>44.3/33.0 = 1.34</td>
<td>50/35 = 1.43</td>
</tr>
</tbody>
</table>
### TABLE 7

Neutrino event rates, per kton yr, $\lambda = 50^\circ$ (Battistoni et al. [98])

<table>
<thead>
<tr>
<th>$E_\nu$ (or $E_{\nu_{vis}}$) (GeV)</th>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
<th>$\nu_\mu + \bar{\nu}_\mu$</th>
<th>$\nu_e + \bar{\nu}_e$</th>
<th>El.</th>
<th>Inel.</th>
<th>Total CC</th>
<th>El.</th>
<th>Inel.</th>
<th>Total CC</th>
<th>NC</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 - 0.4</td>
<td>6.8</td>
<td>1.2</td>
<td>2.5</td>
<td>-</td>
<td>10.5</td>
<td>5.3</td>
<td>1.0</td>
<td>16.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.4 - 0.6</td>
<td>9.6</td>
<td>3.6</td>
<td>3.7</td>
<td>1.3</td>
<td>18.2</td>
<td>9.1</td>
<td>1.8</td>
<td>29.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6 - 0.8</td>
<td>6.3</td>
<td>3.7</td>
<td>2.3</td>
<td>1.3</td>
<td>13.6</td>
<td>6.3</td>
<td>1.2</td>
<td>21.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8 - 1.0</td>
<td>4.2</td>
<td>2.0</td>
<td>1.3</td>
<td>0.9</td>
<td>9.4</td>
<td>4.9</td>
<td>1.3</td>
<td>15.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 - 2</td>
<td>7.9</td>
<td>10.3</td>
<td>3.2</td>
<td>2.6</td>
<td>24.0</td>
<td>11.4</td>
<td>3.7</td>
<td>39.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 - 5</td>
<td>4.1</td>
<td>14.1</td>
<td>2.2</td>
<td>3.2</td>
<td>23.6</td>
<td>11.4</td>
<td>0.9</td>
<td>35.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>157</td>
</tr>
</tbody>
</table>

### TABLE 8

Comparison of predicted event rates per Kton year, $\lambda = 50^\circ$, $E_\nu = 0.3 - 5$ GeV

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu + \bar{\nu}_\mu$</th>
<th>$\nu_e + \bar{\nu}_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>El.</td>
<td>Inel.</td>
</tr>
<tr>
<td>Battistoni et al. [98]</td>
<td>54.1</td>
<td>44.2</td>
</tr>
<tr>
<td>Krishnaswamy et al. [85]</td>
<td>68.4</td>
<td>27.8</td>
</tr>
<tr>
<td>Gaisser et al. [61] Solar max. Solar min.</td>
<td>67.8</td>
<td>43.3</td>
</tr>
</tbody>
</table>
### TABLE 9
Water Cerenkov Detectors

<table>
<thead>
<tr>
<th>Experiment</th>
<th>IMB</th>
<th>HPW</th>
<th>KAMIOKANDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Cleveland, Ohio</td>
<td>Park City, Utah</td>
<td>Kamioka, Japan</td>
</tr>
<tr>
<td>Depth mwe</td>
<td>1570</td>
<td>1500</td>
<td>2700</td>
</tr>
<tr>
<td>Shape and dimensions (m)</td>
<td>Rectangular 23 x 18 x 17</td>
<td>Cylindrical 7.3 x 12(φ)</td>
<td>Cylindrical 16 x 15.6 (φ)</td>
</tr>
<tr>
<td>Mass in tons (fiducial mass)</td>
<td>7000 (3300)</td>
<td>780 (560)</td>
<td>3000 (880)</td>
</tr>
<tr>
<td>Number of PMTs % surface</td>
<td>2048 5&quot; 2%</td>
<td>704 5&quot; volume</td>
<td>1000 20&quot; 20%</td>
</tr>
</tbody>
</table>

**Expected photo-electron yield for:**
- \( p \rightarrow e^+ \nu \)
- \( \mu^+ \rightarrow \pi^0 \nu \)
- \( \mu^+ \rightarrow 2\pi^0 \)

<table>
<thead>
<tr>
<th></th>
<th>IMB</th>
<th>HPW</th>
<th>KAMIOKANDE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>170</td>
<td>600</td>
<td>3560</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td></td>
<td>2670</td>
</tr>
<tr>
<td></td>
<td></td>
<td>410</td>
<td>2670</td>
</tr>
</tbody>
</table>

### TABLE 10
Tracking Calorimeter Detectors

<table>
<thead>
<tr>
<th>Experiment</th>
<th>KGF</th>
<th>NU1SEX</th>
<th>FREJUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Kolar Gold Fields, S. India</td>
<td>Mt. Blanc tunnel</td>
<td>Frejus tunnel</td>
</tr>
<tr>
<td>Depth mwe</td>
<td>7600</td>
<td>5000</td>
<td>4400</td>
</tr>
<tr>
<td>Dimensions (m)</td>
<td>6 x 4 x 4</td>
<td>3.5 x 3.5 x 3.5</td>
<td>6 x 6 x 13</td>
</tr>
<tr>
<td>Mass, tons</td>
<td>140</td>
<td>150</td>
<td>1000</td>
</tr>
<tr>
<td>Steel thickness</td>
<td>1.2 cm</td>
<td>1 cm</td>
<td>0.3 cm</td>
</tr>
<tr>
<td>Counters, dimensions</td>
<td>10 x 10 cm proportional counters</td>
<td>1 x 1 cm resistive streamer tubes</td>
<td>0.5 x 0.5 cm flash tubes</td>
</tr>
<tr>
<td>Year operational</td>
<td>1980</td>
<td>1982</td>
<td>1984</td>
</tr>
</tbody>
</table>
### TABLE 11
Event rates observed

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>2°</td>
<td>27°</td>
<td>50°</td>
<td>50°</td>
</tr>
<tr>
<td>No. of (neutrino) events</td>
<td>~17(^{(a)})</td>
<td>29</td>
<td>112</td>
<td>10</td>
</tr>
<tr>
<td>Kiloton yrs (FV)</td>
<td>0.22</td>
<td>0.27</td>
<td>1.20</td>
<td>0.113</td>
</tr>
<tr>
<td>Rate/kton yr (corrected for efficiency)</td>
<td>77 ± 19</td>
<td>123 ± 23</td>
<td>125 ± 12</td>
<td>118 ± 37(^{(b)})</td>
</tr>
<tr>
<td>Prediction [61] solar minimum (see Table 6(b))</td>
<td>85</td>
<td>99</td>
<td>132</td>
<td>132</td>
</tr>
</tbody>
</table>

(a) Total vertex rate.
(b) Assumes 75% containment efficiency.
### Table 12

**Monopole flux limits in proton decay detectors**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Range of $\beta$</th>
<th>$F_m \text{ cm}^{-2} \text{ sr}^{-1} \text{s}^{-1}$ (90% CL upper limit)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time of flight</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bartelt et al. [93]</td>
<td>$10^{-3}$ to $10^{-2}$</td>
<td>4. $10^{-13}$</td>
</tr>
<tr>
<td>Battistoni et al. [91]</td>
<td>$10^{-4}$ to $10^{-2}$</td>
<td>4. $10^{-12}$</td>
</tr>
<tr>
<td>Krishnaswamy et al. [102]</td>
<td>$10^{-3}$ to $10^{-2}$</td>
<td>1. $10^{-13}$</td>
</tr>
<tr>
<td><strong>Monopole-induced p-decay</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Absence of double events:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battistoni et al. [91]</td>
<td>$10^{-4}$ to $10^{-1}$</td>
<td>2. $10^{-14}$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_c \geq 5 \text{ mb}$</td>
<td></td>
</tr>
<tr>
<td>Errede et al. [96]</td>
<td>$10^{-4}$ to $10^{-1}$</td>
<td>7. $10^{-15}$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_c \geq 10 \text{ mb}$</td>
<td></td>
</tr>
<tr>
<td>(b) Single candidate rate:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battistoni et al.</td>
<td>$\sigma_c = 1 \text{ mb}$</td>
<td>10$^{-13}$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_c = 0.1 \text{ mb}$</td>
<td>3. $10^{-13}$</td>
</tr>
<tr>
<td>Errede et al.</td>
<td>$\sigma_c = 1 \text{ mb}$</td>
<td>2. $10^{-12}$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_c = 0.1 \text{ mb}$</td>
<td>10$^{-11}$</td>
</tr>
</tbody>
</table>
TABLE 13

Recent limits on proton lifetime

In units of $10^{31}$ yrs x branching ratio. 90% CL lower limits, unless
indicates signal claimed. Number of candidates, if any, given in
brackets.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>KGF</th>
<th>NUSEX</th>
<th>KAMIOKA</th>
<th>IMB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>[102]</td>
<td>[91]</td>
<td>[100]</td>
<td>[79]</td>
</tr>
<tr>
<td>$p \rightarrow e^+ \pi^0$</td>
<td>$\sim 2 (1)$</td>
<td>1.5</td>
<td>2.0</td>
<td>15</td>
</tr>
<tr>
<td>$\rightarrow \mu^+ \pi^0$</td>
<td>$\sim 2 (1)$</td>
<td>1.0</td>
<td>2.0</td>
<td>15</td>
</tr>
<tr>
<td>$\rightarrow e^+ \rho^0$</td>
<td>-</td>
<td>-</td>
<td>2.5</td>
<td>-</td>
</tr>
<tr>
<td>$\rightarrow \mu^+ K^0$</td>
<td>$\sim 2 (1)$</td>
<td>0.6 (1)</td>
<td>0.8 (1)</td>
<td>2.6 (1)</td>
</tr>
<tr>
<td>$\rightarrow \mu^+ \eta^0$</td>
<td>-</td>
<td>-</td>
<td>0.4 (1)</td>
<td>5.0</td>
</tr>
<tr>
<td>$\rightarrow e^+ K^0$</td>
<td>-</td>
<td>-</td>
<td>0.9</td>
<td>3.1</td>
</tr>
<tr>
<td>$\rightarrow \nu K^+$</td>
<td>$\sim 2 (1)$</td>
<td>0.2</td>
<td>0.5 (2)</td>
<td>-</td>
</tr>
<tr>
<td>$\rightarrow \nu \pi^+$</td>
<td>-</td>
<td>0.2 (≤ 3)</td>
<td>0.3 (2)</td>
<td>-</td>
</tr>
<tr>
<td>$n \rightarrow e^+ \pi^-$</td>
<td>$\sim 2 (1)$</td>
<td>1.5</td>
<td>1.2</td>
<td>-</td>
</tr>
<tr>
<td>$\rightarrow \nu \pi^0$</td>
<td>-</td>
<td>0.7</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>$\rightarrow \nu K^0$</td>
<td>-</td>
<td>0.5</td>
<td>0.3</td>
<td>0.8 (3)</td>
</tr>
</tbody>
</table>
FIGURE CAPTIONS

Fig. 1  The force on a body A at latitude \( \lambda \) at sea-level is the resultant, \( AD \), of the gravitational force, \( F_g \), proportional to the gravitational mass, \( m_g \), and the centripetal force, \( F_c \), proportional to the inertial mass, \( m_i \).

Fig. 2  Diagrams describing proton decay, \( p \to \text{lepton} + \text{meson} \). (a) and (b) show, respectively, decay by 2-quark fusion, and that via 3-quark fusion preceded by meson emission, in the SU(5) model. These are the dominant diagrams involving X-boson exchange, and have comparable amplitudes. (c) shows decay via exchange of supersymmetric Higgsino and charged Wino, in which heavy mesons and leptons (i.e. \( \nu_t, K, \mu K \)) are the dominant decay products.

Fig. 3  Vertical fluxes of muon neutrinos and antineutrinos at \( \lambda = 50^\circ \) magnetic, calculated by various authors, as detailed in the text. The contributions from muon (\( \mu \)) and pion (\( \pi \)) decay are shown separately. The sea-level muon flux is shown for comparison.

Fig. 4  The flux ratios of electron to muon neutrinos and antineutrinos, in the vertical (top curve) and horizontal (middle curve) directions. The lower curve shows the vertical/horizontal flux ratio for muon neutrinos. For references, see text.

Fig. 5  The underground muon flux as a function of depth in metres of water equivalent, after Menon [75].

Fig. 6  Principle of the water Cerenkov detector. Light is emitted on the surface of a cone of half-angle 42° with axis along the track, A or B. The light hits the water surface in an elliptical ring (see also fig. 8). Directions and relative distances of tracks are determined by the time of firing of photomultipliers placed at the water surface.

Fig. 7  Sketch of the surface array of photomultipliers in the IMB experiment.
FIGURE CAPTIONS (Cont'd)

Fig. 8 Photomultiplier pulses recorded for (left) a muon crossing the IMB detector, and (right) a muon stopping in the water, leaving an open Cerenkov ring. The number of crossing lines at each point indicates the PMT pulse-height.

Fig. 9 Energy spectra of (neutrino) events as measured in proton-decay detectors. For the IMB and Kamiokande experiments, the equivalent Cerenkov energy is corrected for the fact that muon secondaries are below Cerenkov threshold at low energy. The dashed curve is the expected distribution for the IMB experiment.

Fig. 10 Plot of $\mu-\pi$ angle versus the energy ratio $(E_1-E_2)/(E_1+E_2)$ for simulated neutrino interactions, $\nu + N \rightarrow \mu + \pi + N$, in water. $E_1$, $E_2$ are the energies of the particles, where $E_1 > E_2$. For proton decay, $p \rightarrow e^+\pi^0$ in water, 80% of $e$, $\pi$ energies and angle should lie within the circular quadrant (after Foster [99]).

Fig. 11 Cerenkov energy, $E_c$, from IMB events plotted against isotropy, I, defined as the sum of the unit vectors from the vertex to the hit PMTs, divided by the number of hit PMTs. For single tracks, $I \sim \cos \Theta$ (Cerenkov angle) $\sim 0.7$, while for decays such as $p \rightarrow e^+\pi^0$, $p \rightarrow \nu K^0$ or $p \rightarrow \mu^+ K^0$, one expects $I < 0.5$. The dashed and full curves indicate the allowed region for decays $p \rightarrow \mu^+ K^0$, $K^0 \rightarrow 2\pi^0$ and $n \rightarrow \nu K^0$, $K^0 \rightarrow 2\pi^0$, respectively.

Fig. 12 Events in the KGF detector, showing, in the two orthogonal views, the proportional tubes which fire. Event 587 is ascribed to the decay $p \rightarrow e^+\pi^0$ (on the basis of energy and scatter of hit tubes indicating electromagnetic origin). Event 877 is ascribed to the decay $n \rightarrow e^+\pi^-$, or $p \rightarrow \mu^+ K^0$, $K^0 \rightarrow \pi^+\pi^-$. 

Fig. 13 Configuration of steel plates and resistive plastic streamer tubes in the NUSEX detector. Readout of the streamer coordinates is by pick-up on orthogonal $(x, y)$ cathode strips.
FIGURE CAPTIONS (Cont'd)

Fig. 14  Examples of interactions of atmospheric neutrinos in the NUSEX detector. Only a small section of the detector is displayed in each case. The x and y coordinate "views" are shown, side by side.

Fig. 15  (a) The orthogonal views of a NUSEX event which is a candidate for proton decay.

(b) Interpretation of event in terms of a neutrino interaction $\nu N \rightarrow \mu \pi N$, with large-angle scattering of the pion.

(c) Interpretation according to the decay $p \rightarrow \mu^+ K^0_S$, $K^0_S \rightarrow \pi^+ \pi^-$. 
Fig. 2
Fig. 3
TOTAL MUON FLUX PER 10 x 10 x 10 m CUBE PER YEAR

1 per sec

x750 IBM (1570)

Kamioka (2700)

Homestake (4400)

Frejus

Mont Blanc (5000)

Muon flux

Rock depth, 1000's mwe

Fig. 5
Event No. 10  $\nu_\mu N \rightarrow \mu \pi^+ N$

Event No. 9  $\nu_\mu N \rightarrow \mu N$

Fig. 14
(a) NUSEX PROTON DECAY CANDIDATE

Plane

60
65
70
75

X-View

Y-View

(b) $\nu N \rightarrow \mu \pi N$

(c) $p \rightarrow \mu^+ K^0 \rightarrow \pi^+ \pi^-$

Fig. 15