An Overview of Current Experiments in Search of Proton Decay

The discussion of the stability of the proton started about 50 years ago. During most of the half-century since Weyl (and later Stückelberg and Wigner) postulated that a conservation law is responsible for the proton's stability,[1] nearly everybody believed in it as an absolute truth. In fact, a quarter of a century passed before physicists realized that it is an experimental question and asked: "Is the proton really stable?" Of course, experimentally we cannot prove absolute stability. But we can at least set a quantitative lower limit on the lifetime or find the actual decay of the proton.

The first results on limits[2] for proton stability were obtained in 1954: two methods were discussed, a nuclear method and a counting method. The nuclear method permits us to obtain a lifetime limit for a nucleon because of the shell structure of the nucleus. Only rarely, if one of the loosely bound nucleons were to decay, would the nucleus be left unexcited. Usually some excitation energy is left in the nucleus, leading to a de-excitation which can be detected in various ways. The mode of de-excitation first considered was induced fission, which would look like spontaneous fission. Since spontaneous fission had been looked for in thorium but not found, a limit for nucleon decay of $\sim 10^{20}$ yr could be established. The best limit for spontaneous fission of ^{232}Th was obtained later by Flerov (see Ref. 1). If we multiply his limit by ~ 200, we get an approximate lower limit on the lifetime of the nucleon of 2×10^{22} yr. With a high degree of confidence we can believe this limit nearly independent of the nucleon decay modes. For instance, if a neutron were to decay into three neutrinos, which could be described as "disappearance without a trace," it would still leave a hole behind. Since this is equivalent to a high state of nuclear excitation, it would normally lead to fission.

The nuclear method was extended by Rosen,[3] who proposed the use of

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more versatile radiochemical methods. Essentially one uses the fact that an excited nucleus resulting from proton decay can emit 0, 1, 2, or more, nucleons, and one can calculate the relative probabilities roughly from the shell model. For instance, in ^{130}Te the decay of a neutron, if it does not leave the nucleus too highly excited, will lead to ^{129}Te which decays into ^{129}I and ultimately into ^{129}Xe. Typically the early experimental information was derived from work done for other reasons. In this case a search was made for double β decay by looking for ^{132}Xe from the isotope ^{132}Te. Limits for ^{129}Xe were also obtained. From this Evans and Steinberg[4] deduced a proton lifetime limit of 1.6×10^{25} yr, again essentially independent of the decay mode. Then Fireman[5] and Steinberg and Evans[5] in 1977 did a specially designed or "dedicated" experiment. They had a large amount of potassium where the ^{39}K can, after the decay of one nucleon and the loss of another one, ultimately end up as ^{37}Ar (for which there are very sensitive methods of detection developed by Ray Davis). They obtained a limit for nucleon decay of $>2.2 \times 10^{26}$ yr.

Bennett has developed a nuclear technique[6] which extends the limit of the nuclear method to $\sim 2 \times 10^{27}$ yr. Samples of mica are taken from a deep mine (>2 miles depth) so that they have not been exposed to too many cosmic rays. If a nucleon were to decay, π mesons would be emitted and absorbed in a nucleus, leading to spallation. The spallation gives short (1–2 μ), heavy tracks which etching brings out. These etched tracks can be counted. The sensitivity of this method is limited to the above value by the inherent background. It arises from tracks produced by the spontaneous fission of the natural ^{238}U in the minerals (typically at ~1 ppm). Although these tracks are normally 20 μ long, they can anneal at several intermediate locations along their length, creating spurious short tracks. It is interesting that methods which are essentially independent of decay mode have gone pretty far.

The direct counting methods rely on the production of certain charged particles of some minimum energy. If Weyl had asked himself how can a proton decay, he would not have been able to write down a single equation conserving charge, energy, spin and momentum because he speculated on proton decay before the positron was discovered. But now the particle spectrum contains an embarrassment of riches. In principle the nucleon could decay in many ways, involving at least one fermion to conserve spin, and one or more other particles. Some decay modes may directly or eventually through π decay lead to muons. A direct counting technique looking for these muons was originally pursued by Reines and his collaborators. With an exposure of 67 ton years, they reached $\sim 10^{30}$ yr as a limit for nucleon decay for those decay modes resulting in a muon.[7]

Of course, proton decay could only happen if the charges of, say, the proton and the e^+ were exactly equal. Otherwise, charge conservation alone would stop it.[8] On the other hand, if we ever found nucleon decay, we could conclude that the charges are equal. The present limit on the difference between the charges of the e^+ and the proton, for instance, is the impressively small value of $\sim 10^{-19}$ of an electron charge[9] (see also Ref. 8).

Until recently most counting experiments were parasitic to neutrino experiments. To detect neutrinos with their small cross sections, very massive counters have been built. The size of these counters made them also useful in searching for the very long lifetimes expected in proton decay. As an illustration, a one hundred ton detector, say, has roughly 10^{32} nucleons. So if the lifetime of the nucleon were 10^{31} yr, about ten nucleons would decay inside the detector per year.

At present there are about ten "dedicated" attempts to measure the proton lifetime. Why do we all make such an effort at this time? Indeed, only recently have compelling physics reasons appeared that doubt the permanence of the proton. Speculation on the possible demise of the nucleon was absent until Sakharov's work[10] in 1966, where he argued that the baryon excess in the universe implied that the proton is unstable. An independent line of reasoning, based on a desire to unify the theories of the strong force and the electroweak force, has inspired several authors[11] (Pati and Salam; Georgi and Glashow; Georgi, Quinn, and Weinberg) to include both quarks and leptons in the same multiplets. The virtual transitions of diquarks into leptons plus antiquarks within these multiplets, albeit slow, naturally give rise within grand unified theories (GUTS) to nucleon instability. Thus, while the older generation of theoretical physicists felt it in their bones that the proton was stable, the younger generation has a visceral feeling that it decays!

The lifetimes which are predicted by the grand unified theories ($10^{31\pm1}$ yr) are seductively close to the old experimental limit; it looks as if just a little extra effort should bring us to the promised land. Therefore, many groups are now in the process of preparing or proposing experiments. Instead of being parasitic to neutrino experiments these experiments are dedicated to proton decay studies. By being dedicated they generally emphasize a technique different from that most useful in neutrino research. (But of course the situation is immediately turned around: as soon as one builds very large counters, there are new neutrino ideas which can be tested with them.[12] In a real sense, proton decay experiments and cosmic ray neutrino experiments have often become symbiotic.)

The new detectors fall into two classes: totally active water Čerenkov detectors with light collected by phototubes, and sampling calorimeters with particle ionization tracked by gas tube arrays. We will treat one of each of these detectors in detail, point out the features of other detectors in the same class, and compare them all in Tables I and II.

But first let us say a word about the depth of the detector locations. The greater the shielding above an experiment, the lower the cosmic ray muon rate, and the slower the electronics and data acquisition system. On the other hand, the detectors at the greatest depths are generally forced for practical reasons (by the limited size of the cavities available there) to have a source material with a high density to achieve a given minimum detector mass. Another depth dependent consideration is the necessity of distinguishing cosmic ray muon induced background from potential proton decay events. At the relatively shallow depth of three of the mine experiments in the U.S., typically 10^7–10^8 muons traverse a detector per year. This places a burden on pattern recognition if one is to eventually see a few proton decay events per year. In the deep Alpine tunnels of Europe, and the still deeper Kolar gold fields in India, muon-induced background is no problem. On the other hand, monitoring the minute by minute integrity of the detector is helped by frequent muon traversals.

We start our overview of counter experiments with the one with which we are best acquainted (the one in which we are both collaborators), the Irvine–Michigan–Brookhaven (IMB) experiment.[13] Because we wanted to test definitively the predictions for the proton lifetime based on SU(5) and some higher groups containing SU(5), we tried to find an underground location where it would not be too expensive to dig a very large hole, ($\sim$21 m)^3. We wanted to build a detector massive enough to do an experiment which could reach a limit of 10^{33} yr, covering the theoretical predictions. This size of the detector, 10 kilotons, is also natural for another reason. Namely, the inherent neutrino-induced background becomes dominant above this level of sensitivity. The location we chose had been used by Reines and collaborators for a long time. It is the Morton salt mine in Fairport Harbor, Ohio, not far from Cleveland.

Since we wanted a very large amount of material at a reasonable cost, and, simultaneously, desired a totally active device with information on particle directionality, water was a natural choice. If a proton were to decay in water, energetic, charged secondaries would produce Čerenkov radiation. By detecting the time and intensity of the radiation efficiently, one could reconstruct the decay event. Although the Čerenkov spectrum increases as the frequency squared, ultraviolet light is very rapidly absorbed in water, leaving a peak in the deep blue part of the spectrum. The IMB group chose to use this portion of the Čerenkov radiation.

(An alternative Čerenkov technique is used by a group from the University of Pennsylvania.[14] They dissolve a waveshifting dye in the water, which

TABLE I

Status of nucleon lifetime experiments—Čerenkov technique (August 1981)

Collaborative institutions	University of Cal/Irvine University of Michigan Brookhaven National Lab	Harvard University Purdue University University of Wisconsin	University of Pennsylvania Brookhaven National Lab
Location	Morton Salt Mine, Painesville, Ohio	Silver King Mine, Park City, Utah	Homestake Gold Mine, Lead, South Dakota
Depth (km water equivalent)	1.7 kmwe	1.7 kmwe	4.4 kmwe
Detector mass (kilotons)	10 KT total $\sim$5 KT fiducial	0.8 KT water, surrounded by mirrors and lead/gas tube shower counter	0.3 KT total 0.15 KT fiducial
Cosmic muon flux	3 μ/sec 10^8 μ/year	$\sim$1 μ/sec $\sim 3 \times 10^7$ μ/year	$\sim 3 \times 10^5$ μ/year
Nucleon source	cube of high transparency water	cylinder of water	water
Detection method	2,048 5 in. PM's on 1.2 m surface grid	800 5 in. PM's on 1 m $\sim$cubic lattice waveshifter (both with and without)	144 5 in. PM's, 4 each in 4 m^3 optically segmented units; waveshifted; separate cosmic veto on top face
Ultimate lifetime sensitivity	$\sim 10^{33}$ years	$\sim 10^{32}$ years	$\sim 10^{31}$ years
Present status	Cubical reservoir completed Operational $\sim$Winter 1981	Cylindrical tub completed Operational $\sim$Fall 1981	Current result: $\tau > 2.4 \times 10^{31}\, B_\mu$ yr For $B_\mu = 5.1\%$ $\tau > 1.2 \times 10^{30}$ yr
Reference	13	16	14

TABLE II

Status of nucleon lifetime experiments—Sampling calorimeter technique (August 1981)

Collaborative Institutions	Tata Institute, Bombay Osaka City University University of Tokyo	CERN INFN Frascati University of Milan University of Turin	University of Minnesota Argonne National Lab Oxford University	Orsay École Polytechnique Saclay
Location	Kolar Gold Fields, South India	Mont Blanc Auto Tunnel (Garage 17) Franco-Italian Border	Soudan Iron Mine, Vermillion, Minnesota	Fréjus Auto Tunnel Franco-Italian Border
Depth (km water equivalent)	7.6 kmwe	5.0 kmwe	1.8 kmwe	4.5 kmwe
Detector Mass (kilotons)	0.14 KT total $\sim$0.10 KT fiducial	0.15 KT total	30 ton total (prototype)	1.5 KT total 1.0 KT fiducial
Cosmic muon flux	2 μ/day 700 μ/year	$\sim$6 μ/day 2×10^3 μ/year	$\sim 3 \times 10^6$ μ/year	1 μ/min. 5×10^5 μ/year
Nucleon source	34 1.2 cm × 4 m × 6 m horizontal Fe plates	134 1 cm × 3.5 m × 3.5 m horizontal Fe plates	48 horizontal slabs taconite (Iron Ore) concrete Average density = 1.85	1500 3 mm vertical Fe plates
Detection method	1600 proportional gas tubes $(10\text{ cm})^2 \times \sim 5$ m long	47,000 limited streamer tubes $(1\text{ cm})^2 \times 3.5$ m long	3456 proportional gas tubes 1 in. diameter × 3 m long	1500 plastic $(0.5\text{ cm})^2$ flash tube planes 200 Geiger tube $(1.5\text{ cm})^2$ planes
Ultimate lifetime sensitivity	$\sim 3 \times 10^{31}$ years	$\sim 4 \times 10^{31}$ years	$\sim 2 \times 10^{30}$ years	$\sim 10^{32}$ years
Present status	Operational for 205 days Current results: $\tau > 3.5 \times 10^{30}$ years at 95% CL	Calibrated in CERN beams Detector Operational $\sim$Winter 1981	Operational since April 1981	Calibrated in CERN beams Staging area excavated in tunnel Proposal submitted October 1980
Reference	17	18	19	20

shifts the ultraviolet part of the spectrum to the visible before it is absorbed appreciably. Although one can gain a factor of 3 or 4 in detected photons this way, the price paid is twofold. First, the timing resolution is degraded by the waveshifter lifetime, and secondly, all directional information is lost since the reemission of the light is isotropic.)

After the transmission of direct Čerenkov light through 10 m of water (the "radius" of the IMB detector) the light which is left is essentially all in the visible region where water is very transparent. The mean free path at the wavelength of maximum transmission (~440 nm) is >40 m in pure water. The IMB phototubes have a wavelength sensitivity which closely matches the surviving photon spectrum.

To test the method, a water tank with a 10-m baseline was built at the University of Michigan. The test was made with Čerenkov light from cosmic ray muons traversing the water (defined by a coincidence between two counters). Phototubes immersed in the water recorded the light from the Čerenkov cone of the muons. We predicted a signal of 2.5 photoelectrons at 35 ft. Actually three photoelectrons were seen. The water was purified by the same scheme being planned for the mine, and the amount of water circulating per unit time was scaled to match that anticipated for the final detector.

The deployment of PM's in the mine detector has been mimicked in a vertical test tank, 21 m deep. The data acquisition system has also been put through its paces at Michigan on a scaled down version of the detector, consisting of 128 PM's in a black room. The tubes have been stimulated by computer-controlled LED (550 nm) or laser (330 nm) light (at the upper and lower half power points of the transmitted spectrum). Alternatively, cosmic ray muons produced Čerenkov or scintillation light in the room by passing through small pieces of plastic. Reconstruction of these mock events confirms the calculation of detector resolutions. Currently the 2048 PM acquisition system is being installed in the mine. The double-lined cavity is now fully outfitted and ready to be filled with water. The IMB detector should be operational in the winter of 1981.

When operational, most background is expected from entering muons or the remnants of their interactions in the rock nearby the detector. We believe we can reject these backgrounds by insisting that light emanate only from the inner part of the water cube (fiducial volume). The outer shell is an anticoincidence counter (by software). However, we have to expect a background from atmospheric neutrinos which will initiate, inside the fiducial volume, events which might sometime mimic proton decay. We therefore found it important to use the results[15] of the Gargamelle neutrino experiment (where the PS neutrinos had roughly the same spectrum as the atmospheric ones) to simulate this ultimate background. We calculate that in one year of running, less than one neutrino event will mimic the N → $e^+\pi$ decay mode. That would correspond to a limit close to 10^{33} yr.

The Harvard–Purdue–Wisconsin (HPW) Group[16] is building an 800 ton water detector in the old silver mine at Park City, Utah, where Keuffel and his group did their cosmic ray research. It has about the same depth as the IMB detector and also uses the water Čerenkov technique, both with and without a wavelength shifter. Their phototubes are distributed throughout the counter volume to obtain good energy resolution. In an attempt to use as much of the 800 tons of fiducial volume as possible, the detector will eventually be surrounded by an external shower counter. The internal water volume will be operational in the fall of 1981.

The Pennsylvania group[14] has been collecting data for the last year; this is due to the happy circumstance that they built some time ago a supernova neutrino detector in the Homestake Mine where Davis's solar neutrino detector is located. In fact their detector is the water shield which surrounds Davis's chlorine tank. The Pennsylvania detector has developed from a neutrino detector into a proton decay detector. Unlike the IMB and HPW detectors, the water volume is optically segmented. They look for $\mu \rightarrow e$ decay, making use of the inherent time delay of $\sim 2\ \mu$ sec; a muon could either be created directly from nucleon decay or indirectly as a decay product of the presumably more copiously produced charged pions. (The other Čerenkov detectors also record the muon decay signature.) Using a Monte Carlo study of the energy distribution expected from nucleon decays which lead to a $\mu \rightarrow e$ decay signature, they conclude that none of their observed candidates are due to proton decay. To interpret the data they use the theoretical branching ratio predictions of SU(5) and report a limit of $>1 \times 10^{30}$ yr for the proton lifetime.

Let us turn to the dense detectors, which are complementary to the Čerenkov devices in that they respond to dE/dx (rather than β) and produce raw event "pictures" to which we are accustomed (rather than the less familiar rings of light that characterize the Čerenkov method). Of course, the trade-off is that the dense detectors lack directionality, so it is harder to locate a vertex and to prove the back-to-back nature of a decay. One recognizes the vertex of a two-body decay originating inside a heavy nucleus by the angle between the two exciting particles due to the Fermi motion of the decaying nucleon. Most of the dense detectors lack muon decay sensitivity.

The Indian–Japanese Collaboration has reported[17] the data from 205 days of operation from a 140T detector. The device consists of horizontal slabs of iron ½ in. thick separated by proportional tubes (10 cm × 10 cm in cross section) in an alternating x–y grid. The 1600 tube detector has a horizontal area of 4 m × 6 m. The discriminators on the tubes are set to fire if a particle deposits an energy >$\frac{1}{2}$ of that of a minimum ionizing particle. The noise rate of a tube near the edge of the detector due to the radioactivity in the rocks is 100 Hz; inside the detector the rate drops to 2 Hz due to the self-shielding. The radioactivity rate is a crucial measure of the health of the detector; the cavity is so deep in the Kolar gold fields that only two muons per day fire the detector, a rate too small for monitoring. The resolving time of the tubes is 1 μ sec; no time-of-flight (directional) information nor muon stop signature is available. The pulse heights on each tube are recorded if a fivefold coincidence occurs between any five layers.

The authors have recorded three neutrino interactions in the detector, while four to six were expected. On the other hand, they have reported two other events which they consider as proton decay candidates. However, the limited detector volume renders the events hard to interpret. In particular, the events appear at the edge of the detector, with at least one particle entering or exiting. Further, the events are nearly vertical. This has led some skeptics to challenge the candidates as due to effects of vertically entering cosmic ray muons. It could be that vertical events are preferentially selected by the five-layer trigger with horizontally layered counters. Perhaps the candidates could have been induced by electron neutrinos near the edge of the detector. These are expected at the same rate as the observed candidates. In any case, the candidates show that a 140T detector, even when very well shielded by great depth, is limited in its ability to contain proton decay candidates (only an event in the inner $\frac{1}{10}$ of the detector would be fully contained). If the observed events are considered as proton decay candidates, the lifetime would be $(8.4^{+11}_{-5.5}) \times 10^{30}$ yr, where they assume that the detection efficiency x branching ratio is 50%.

A detector of similar mass is being constructed in the Mont Blanc Tunnel by the CERN–Frascati–Milano–Turino Collaboration.[18] Their advantage is a grid size (1 cm)^2 substantially finer than that of the Indian–Japanese experiment (10 cm)^2. Further, they have studied showers and tracks from CERN calibration beams of electrons, pions, and neutrinos in one of their modules. This should strengthen the confidence in their interpretation of any events. The detector is scheduled to be on-line in the fall of 1981.

The University of Minnesota/Argonne group are operating a prototype 30T detector in an old iron mine in Minnesota.[19] They use an inexpensive concrete medium which can be built in small modules. Gas proportional counters made from thin steel tubes are embedded in ferroconcrete.

A kiloton detector using iron slabs is being designed by a collaboration of Orsay–Ecole Polytechnique-Saclay.[20] They trigger the flash chambers used for tracking by interspersed Geiger tubes. The time resolution of the Geiger tubes is sufficient to record delayed muon decays.

There are at least four other massive detectors under consideration. A new project,[21] intended as a laboratory open to the international physics community, has been officially approved by the Italian Government, to be built under the Gran Sasso mountain some 150 km from Rome between two almost completed auto tunnels. This facility will provide an enormous underground experimental area measuring 50 × 50 × 20 m at great depth (4 kmwe). Another large new underground project is being developed in Japan by a Tokyo–KEK–Tsukuba group at 2.7 kmwe.[22] Containing 3400 tons of water Čerenkov detector surrounded by 1056 specially developed 20 in. phototubes, it is expected to be operational in April 1982. In addition, both the Pennsylvania group (with new support from Brookhaven) and the Minnesota–Argonne people (with Oxford joining in) have submitted proposals to the U.S. Department of Energy for kiloton detectors.

We can thus expect that within the next year or so the conjectures concerning proton decay will finally be subjected to deep scrutiny!

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