WAITING FOR THE PROTON TO DECAY: 1983 RESULTS FROM THE NEW DEDICATED EXPERIMENTS*

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ABSTRACT

Three new dedicated experiments searching for proton decay came on the air during the last year or so. Orders of magnitude more neutrino events, as well as possible nucleon decay candidates, have been recorded. Significant new limits have been placed on many modes of nucleon decay. Representative lower limits at 90% C.L. for the lifetime/branching ratio for $p \to e^+\pi^\circ$ of 2.0×10^{32} years, $p \to e^+K^\circ$ of 3.1×10^{31} years, $p \to \mu^+K^\circ$ of 2.6×10^{31} years, and $n \to \bar{\nu}K^\circ$ of 0.8×10^{31} years have been set by the IMB group. Many other limits have also been set by the HPW, IMB, Kamioka, Kolar, and Mont Blanc experiments. Contained interactions have been observed in four detectors at rates expected from atmospheric neutrino induction, within the 30-50% errors on the calculations. The status[1] of the operational experiments is discussed, and typical restrictive results are reviewed. Detectors under construction are also mentioned.

1. INTRODUCTION

In the past year, three new dedicated water Cherenkov experiments to measure the proton lifetime (HPW, IMB and Kamioka) have come on line and already have produced new results. The two pioneering fine grained experiments (Kolar and Mont Blanc) continue to accumulate data. A large tracking calorimeter (Frejus) is partially operational and the technology for another (Soudan) is being developed. This review concentrates on the two experiments with extensive new limits (IMB and Kamioka) and presents a status report on the others.

The burgeoning effort on proton decay experiments was stimulated by compelling physics arguments that challenge the permanence of the proton. Speculation on the possible demise of the nucleon was initiated by Sakharov's precocious work[2] in 1967: the baryon excess in the universe implied proton instability. An independent line of reasoning, based on the desire to unify the theories of the strong interaction and the electroweak force, inspired several other authors[3] (Pati and Salam; Georgi and Glashow; Georgi, Quinn, and Weinberg) to include both quarks and leptons in the same multiplets. Within these multiplets, virtual transitions of quarks into leptons and antiquarks, albeit slow, naturally give rise to an unstable nucleon.

The lifetime[4] ($4.5 \times 10^{29 \pm 1.7}$ years) predicted by SU(5), the simplest grand unified theory, is tantalizingly close to the experimental bound derived from past cosmic ray neutrino experiments. This predicted rate and the dominant $p \to e^+\pi^\circ$ decay mode are well within the capabilities of the new detectors. These

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detectors are large enough to both yield a significant event rate and to totally contain the events. They are based on technologies developed for large neutrino experiments at accelerators. At this time the most restrictive lifetime/branching ratio limit[5] (2.0×10^{32} years by the IMB group) does not support the predictions of the simplest grand unified theory. Further, the ultimate sensitivity of the experiment to the simplest model could be a factor of five better than this value. Thus a definitive statement about minimal SU(5) appears to be forthcoming. The preliminary values of the several new limits on $p\rightarrow e^+\pi^\circ$ are compared in Table I.

In contrast with SU(5), supersymmetric models and those incorporating supergravity suggest decays with unknown rates into modes with much different characteristics, e.g., a kaon and a lepton. These modes are much more difficult to distinguish from neutrino background. Apparent candidates have been recorded by several of the experiments. A given event can generally be interpreted as a candidate for several different proton decay modes. I illustrate the status of the work by showing the preliminary values of the 90% confidence level limits or the rates in Tables II and III for $p\rightarrow\mu^+K^\circ$ and $p\rightarrow\bar{\nu}K^+$ resp. (At this stage of the experiments we assume that a rate can be measured by a single event!) Each of these modes contrasts with the characteristic "two" body $p\rightarrow e^+\pi^\circ$ decay, where all the mass of the proton appears as electromagnetic energy. For $p\rightarrow\mu^+K^\circ$, the signature can be the three-tracks of the $\mu^+\pi^+\pi^-$ final state,or two $\mu\rightarrow e\nu\nu$ delayed decay chains, or a significant amount of isotropic light from the $\mu^+\pi^\circ\pi^\circ$ final state. For the $p\rightarrow\bar{\nu}K^+$ mode, perhaps the most difficult yet accessible mode, a monochromatic μ^+ from the K^+ decay and a subsequent μ decay signature may be all that is available.

General agreement among the experiments for the limits is apparent from Tables II and III. However, the alternative interpretations of each event and the evaluation of the neutrino background for each candidate are under intense scrutiny. The flux of atmospheric neutrinos[6] is uncertain within a factor of ±30%. Most importantly, the characteristics of multipion production are difficult to calculate. The IMB experiment has used the Gargamelle neutrino data[7] to simulate the background. This is fraught with the uncertainty in scaling from the pion reabsorption in the freon of the bubble chamber to the oxygen in a water detector. On the other hand, the Mont Blanc experiment evaluates the neutrino background with the results of a neutrino beam test at CERN. However, the neutrinos were incident at 90° and 45° to the iron plates of that anisotropic detector, leaving uncertainties for neutrinos at 0° to the plates.

Perhaps the most important indication of the initial success of the experiments is the number of recorded atmospheric neutrino-induced events (~250). This number has been increased by about two orders of magnitude over the last year. Table IV records the preliminary statistics. Remarkably, a neutrino event rate of ~100 events/kiloton year of fiducial volume is observed by four experiments. The neutrino rate in each experiment is consistent with the expected value calculated by each group, within the ±30% flux uncertainty.

Let me also say a word about the depth of the detectors. The greater the shielding above an experiment, the lower the cosmic ray muon rate, and the slower the data acquisition system must work. On the other hand, the detectors at the greatest depths are generally forced (by the limited size of the cavities there) to have a source material with a high density to achieve a sufficient 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 the three experiments in the U.S., typically 10^8 muons traverse a detector per year. This places a burden on pattern recognition if one is to eventually glean a few proton decay events per year. In practice the muon-induced background has presented no problem for the shallow detectors to date. In the deep Alpine tunnels of Europe, and the still deeper Kolar gold fields, muons and muon-induced background are rare. On the other hand, monitoring the minute-by-minute integrity of the detector is much more difficult without frequent muon traversals.

2. RING-IMAGING CHERENKOV CALORIMETERS

The new detectors fall into two classes: totally-active ring-imaging Cherenkov detectors with light collected from water by phototubes, and sampling calorimeters with particle ionization tracked by gas tube arrays. The features of the seven detectors mentioned above are compared in Tables V and VI.

For both ring-imaging calorimeters and dense-tracking devices, I will first consider in detail one detector for illustrative purposes. (It turns out that the techniques used within each detector class by the various groups are very similar.) Then I will contrast each of the other detectors in the class with the illustrative example.

2.1 THE IRVINE-MICHIGAN-BROOKHAVEN DETECTOR IN THE MORTON-THIOKOL SALT MINE

As a typical Cherenkov calorimeter, I first discuss thoroughly the experiment which has produced the most restrictive results this year, the IMB experiment.[5] (I also know it best due to my association with the IMB group.) The detector is a large rectangular volume of water, 22.8 × 17.8 × 16.9 m, viewed by 2048 photomultiplier tubes (PM's) covering all six faces. The fiducial volume of 3300 metric tons or 2.0×10^{33} nucleons begins 2.0 m in from the tube planes, which, in turn, begin nominally 0.5 m in from the walls.

Above the threshold β of 0.75, charged particles in the water give off Cherenkov light. A stopping track lights up a ring of PM's, each at about the one photoelectron level. By utilizing the relative timing of the lit PM's and their geometric pattern, the vertex position of single tracks can be reconstructed to an accuracy of ~ 1 m. For multi-track nucleon decay events with opening angles greater than 90° (so that the Cherenkov cones do not overlap), the vertex can be reconstructed to within 50 cm.

Three independent analysis chains find events with their vertex in the fiducial volume. These events could be atmospheric neutrino interactions, possible proton decay candidates, or other new physics. The details of one of these analysis chains are presented here; the results are consistent with those of the other chains.

Whenever 12 tubes anywhere in the detector fire within 50 ns of each other, the detector is triggered. Since the energy calibration yields 4 MeV/photoelectron, this corresponds to a threshold of 50 MeV. There are 2.3×10^5/triggers per day, predominantly straight through cosmic ray muons. A requirement of 30-300 lit PM's, reduces the data by a factor of three. This range includes most nucleon decay modes. Under the hypothesis that the lit tubes were illuminated by a single point source of light, the second step locates that point. By requiring that this point lies within the fiducial volume, a factor of 100 of the entering tracks is eliminated, while saving 80% of neutrino interactions originating in the fiducial volume. Over 90% of multitrack events, e.g., most nucleon decay modes, are saved.

The remaining triggers are primarily short stopping muons or tracks that clip the corners. The light illuminating a PM is then required to emanate at the Cherenkov angle of 41° from a hypothesized track. If the likelihood is high that the vertex is at the surface of the detector, the event is rejected as an entering track. About 3 events per day remain with a best fit in or near the fiducial volume and with > 40 PM's. Physicists scanning with a color graphics system help the fitter to optimize the vertex. This reduces the number of contained events to ~ 1 event per day. The combined efficiency to keep the predominantly low energy, single track ν events (averaged over ν types and energies) is 75%.

The number of contained events, 169 in 204 live days, is consistent with that predicted using either of two neutrino flux calculations[6] and the above detection efficiency. Neutrino events observed by the Gargamelle collaboration in a freon-filled bubble chamber[7] are used to simulate what is expected in the detector. The Gargamelle events are weighted to mimic the expected atmospheric neutrino energy spectrum, and electron neutrino events are generated by changing the observed μ to an electron of the same momentum. The characteristics of the contained events are consistent with those expected from ν interactions. The energy distribution[5] agrees well, and the event vertices[5] are distributed uniformly in the detector and are reasonably isotropic in direction.

A muon decay electron is identified by a coincidence of 5 or more PM's in a 60 ns window up to 7.5 μsec after the main event. Using a sample of entering stopping tracks, the efficiency is measured to be 66±5% for μ^+ decay detection. About 30% of the neutrino events are expected to have an identified μ decay, compared to 30±8% observed.

To look for $e^+\pi^\circ$, events with two tracks (each with more than 40 tubes and an opening angle greater than 100°) are retained.

Three events remain.[5] Each has either too much energy to be a proton decay, or too small an opening angle, or a visible μ decay. In oxygen, an intranuclear cascade program indicates that 40% of the π°'s are lost outside of the cuts on energy and opening angle. This gives a limit for a 250 live day exposure of

$$\tau/B(p \rightarrow e+\pi^\circ) > (1/2.3) \times (250/365) \times 2\times10^{33} \times (10/18) \times 0.9 \times 0.68$$
$$= 2.0\times10^{32} \text{ years,}$$

where 0.68 represents the probability for π°'s to survive nuclear interactions averaged over all protons in water and 0.9 is the efficiency for reconstructing events with a back-to-back, equal-energy-sharing, 1 GeV energy deposition. Also no candidates remain for $p \rightarrow \mu^+\pi^\circ$, leading to

$$\tau/B\ (p \rightarrow \mu^+\pi^\circ) > 1.2 \times 10^{32} \text{ years.}$$

One search for $p \rightarrow \mu^+K^\circ$ is based on the decay $K^\circ_S \rightarrow \pi^\circ\pi^\circ$, which gives off 4 γ's producing a nearly isotropic source of Cherenkov light. The rings from the four tracks overlap, so it is difficult to separate the showers. Instead, the "isotropy" $\underline{I}$ of the event is measured. This is the magnitude of the vector sum of the unit vectors from the vertex to each lit PM, normalized by the total number of lit PM's. For an isotropic event, $\underline{I}$ is near 0; for an event with a single short track, $\underline{I} \sim 0.7$, the cosine of the Cherenkov angle.

E_C, the visible Cherenkov light yield of a massless, nonshowering particle of total energy E_T, is also measured. For an electron, photon, or π°, $E_C = E_T$. For a muon, $E_C \approx E_T - 250$ MeV due to the muon rest mass and the energy deposited below Cherenkov threshold. A scatterplot of E_C vs $\underline{I}$ for the contained events allows isolation of a region in which 90% of the events for the μ^+K°, $K^\circ_S \rightarrow \pi^\circ\pi^\circ$ mode, but only one neutrino event, are expected. Three observed events fall inside the region. The first has 600 MeV in one track, which is not possible for this decay mode. The second event has no evidence of a μ in the backward direction. The third event is a possible candidate, although it could also be neutrino-induced. Setting a conservative limit by not subtracting the neutrino background estimate of one event yields an initial limit for a 132 day exposure of

$$\tau/B > (1/3.9) \times (132/365) \times 2\times10^{33} \times (10/18) \times 0.21 \times 0.9 \times 0.95,$$

or 1.8×10^{31} years at 90% C.L., where 0.21 is the branching ratio for $K^\circ \rightarrow \pi^\circ\pi^\circ$ (including those K°_L interactions which also give a signal) and 0.9 ± 0.1 is the detection efficiency. The correction for nuclear absorption of K°'s (and not $\overline{K^\circ}$'s) is 0.95.

A second method to search for $p \rightarrow \mu^+K^\circ$ uses the decay $K^\circ_S \rightarrow \pi^+\pi^-$ and the subsequent $\pi^+ \rightarrow \mu^+$ decay. This mode gives two muon decays. Since the mean number of PM's hit is 45 for $p \rightarrow \mu^+K^\circ$, $K^\circ_S \rightarrow \pi^+\pi^-$, at least 20 PM's are required to fire. The detection efficiency for this mode is 0.83 ± 0.1; the probability for the π^+ to stop and decay into a μ^+ is 80%. The overall detection efficiency is $0.80\times0.83\times(0.66)^2\times0.94 = 0.27$, where the 0.94 corrects for the time overlap probability of two muon decays. Two events with two μ decays are observed. One event has only a single clean track with 500 MeV total energy. One of the muon decays probably comes from a π^+ produced below Cherenkov threshold by a ν interaction. Since a simulation of 250 $p \to \mu^+K^\circ$, $K_S^\circ \to \pi^+\pi^-$ events yields no event with a single track of energy this high, it is not a viable candidate. Based on the one remaining possible candidate, the 90% C.L. limit for this decay mode is $\tau/B > 1.3\times10^{31}$ years.

Combining the limits on $p \to \mu^+K^\circ$ into the two independent modes gives a 90% C.L. limit of $\tau/B(p \to \mu K^\circ) > 2.6\times10^{31}$ years.

The expected region of energy vs isotropy space for $n \to \nu K^\circ$, $K_S^\circ \to \pi^\circ\pi^\circ$ contains 3 candidates; again this number is consistent with the background expectation. Without subtracting the background, a conservative 90% C.L. limit of

$$\tau/B(n \to \nu K^\circ) > 0.8\times10^{31} \text{ years},$$

is obtained.

2.2 THE HARVARD-PURDUE-WISCONSIN DETECTOR IN THE SILVER KING MINE

The Harvard-Purdue-Wisconsin Group[8] has constructed a 0.7kT (metric) cylindrical water Cherenkov detector in a former silver mine at Park City, Utah at about the same depth as the IMB detector. Their phototubes are distributed throughout the counter volume so as to be as close as possible to the emission point of the light. In addition, the walls of the tank are covered with mirrors to permit capture of light that would ordinarily be lost at the walls. This requires multihit recording electronics to register the pulses of light in the same PM from several bounces. Typically a factor of four more photoelectrons per MeV of dE/dx are collected by this geometry than that in the IMB detector. This leads to a factor of two better energy resolution. The fiducial volume is limited by the small size of the cavity. To use as much as possible of the 0.7kT as fiducial volume, the water tank is surrounded by an external veto of tube counters to tag entering and exiting particles.

The superior light collection and the multihit time electronics makes this detector ideal for sensing the double muon decay signature discussed earlier to isolate events such as μ^+K°, $K_S^\circ\to\pi^+\pi^-$. Initially they use a 0.42 kT fiducial volume, 1m in from the cylindrical sides of the detector and 1.5 m from the top. Their 0.27 year run yields one contained double muon decay candidate with a preliminary value of $\tau/B=2\text{x}10^{31}$ years. Interpreted as a 90% C.L. limit, this data yields a preliminary limit of $\tau/B>0.9\text{x}10^{31}$ years if this event is not a candidate.

2.3 THE TOKYO-KEK-TSUKUBA DETECTOR IN THE KAMIOKA METAL MINE

A large underground project has been developed in Japan by a Tokyo-KEK-Tsukuba group.[9] Containing 3000 total tons of water, the Cherenkov detector is surrounded by 1056 specially-developed 20" diameter phototubes. It has been operational at 2.7 kmwe since July

1983. The greater depth of this detector decreases the muon flux by a factor of 15 relative to the IMB device. This decreases the number of triggers at proton decay light level to the point where, with simple total photoelectron cuts, 65,000 events are left for hand scanning by physicists.

The remarkable advantage of this detector is its 20% photocathode coverage of the surfaces of the detector, a factor of 12 greater than the IMB detector. This translates into one photoelectron produced for a dE/dx loss of 0.3 MeV at $\beta=1$. For example, the energy resolution on the μ^+ in a $p \to \bar{\nu} K^+$, $K^+ \to \nu \mu^+$ decay is calculated to be 9%, and the position resolution on the e^+ from the μ^+ decay is sufficient to link the two tracks together spatially. The observed energy spectrum of electrons from stopping muons fits the V-A hypothesis well.

The detector is triggered on a > 5 MeV energy deposition. In 0.32 kT years of exposure, the detector has recorded 57 contained events, 40 with a single ring and 17 with multi-rings. Contrasting this with the 117 single and 3 double rings seen in the initial IMB run shows the power of high photocathode coverage in resolving overlapping rings. A further advantage of the Kamioka detector relative to IMB is the ability at 90% confidence level to distinguish showering tracks (π°, γ, $e^\pm$) from meson tracks ($\pi^\pm, \mu^\pm$). The amount of scattering of the light about the major Cherenkov cone is used to separate particle type.

In a manner similar to the IMB cuts on E_C and $\underline{I}$, the Kamioka group places cuts on the total energy deposited and the energy distribution (lepton side vs hadron side) to isolate decay candidates. They use their ability to resolve individual rings and to identify particle type to decrease the neutrino background below the levels achieved in the IMB detector: They require that the invariant mass of a combination of two or more rings fit the mass of the hypothesized intermediate particle (K, ρ, ω, η).

The data has been analyzed to set limits on over 35 possible nucleon decay modes, including the multibody leptonic modes suggested by Pati and Salam. In general, their preliminary 90% C.L. limits are the following:

1 GeV electromagnetic modes ($e^+\pi^\circ$, $e^+\eta^\circ$, $e^+\omega^\circ$...) $\gtrsim 2\times10^{31}$ yr

muon + 0.5 GeV electromagnetic modes ($\mu^+\eta^\circ, \mu^+\omega^\circ$...) $\gtrsim 1\times10^{31}$ yr

neutrino + meson modes ($\bar{\nu}\pi+, \bar{\nu}\rho+, \bar{\nu}K+$...) $\gtrsim 0.5\times10^{31}$ yr

The limits for complementary neutron decay modes are similar.

Despite the fact that the Kamoika and IMB detectors look mechanically similar, they have quite different systematics. The Kamioka people have superior energy resolution and achieve background discrimination through high dynamic range on the pulse heights of the PM tubes. They have no timing on individual PM's. In contrast, the PM's of the IMB detector essentially provide only topological formation since they each operate at the 1 photoelectron level. On the other hand, good timing on each tube that fires provides the information necessary to reconstruct tracks with the IMB technique.

3. DENSE TRACKING DEVICES

The dense detectors and Cherenkov devices are complementary. The first responds to dE/dx rather than β, and produces event "pictures" of the tracks of the event, rather than the less familiar rings of light produced by tracks in the Cherenkov detectors. The trade off is that the dense detectors generally cannot determine the sense of direction of a track. Therefore it is difficult to establish the 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 exiting particles. This is due to the Fermi motion of the decaying nucleon.

The sensitivity of dense detectors to decay modes with greater than two bodies can be superior to that of Cherenkov detectors if the granularity is fine enough. The ability to define a vertex in a tracking detector (and to distinguish the tracks in multibody events) is determined by the cell size, which can be as small as 0.5 cm. Contrast this with the ~50 cm resolution of the Cherenkov devices.

The dense detectors also generally lack μ^+ decay sensitivity, or have a low efficiency for them. Negative muons are not seen at all since they are absorbed by the iron nucleus before decaying. This deficiency with respect to particle identification can be turned into an asset. The differential sensitivity to electric charge could provide a means of change identification.

The high cost per unit of mass of sampling detectors makes fine-grain calorimeters above the planned 1.0-1.5 kT mass of the Frejus and Soudan detectors prohibitively expensive. This is a substantial disadvantage if the lifetime, as it now appears, is $>5\times10^{31}$ years, which necessitates detectors of a minimum total mass of ~10 kT for reasonable event rates.

A potential advantage of the dense detectors using iron is the possibility of implementing a magnetic field throughout the detector. This could facilitate both charge determination and measurement of muon polarization.

I will first examine in detail the pioneer dense tracking experiment in the Kolar Gold Fields, and then contrast the other detectors with it.

3.1 THE INDIAN-JAPANESE DETECTOR IN THE KOLAR GOLD FIELDS

The Indian-Japanese Collaboration has reported[10] data from 2.5 years of operation of their 140T detector in the Kolar gold fields. The device consists of horizontal slabs of iron, 1/2" thick, separated by proportional tubes (10 cm x 10 cm in cross section) in an alternating x-y grid. The 1600 tube detector has a horizontal area of 4 m x 6 m and a height of 4 m.

The discriminators on the tubes are set to fire if a particle deposits an energy > 1/2 of that of a minimum-ionizing particle.

The noise rate of a tube near the edge of the detector is 100 Hz due to the radioactivity in the rock. Inside the detector, this rate drops to 2 Hz because of the self-shielding of the iron. The radioactivity-induced rate is the basic measure of the health of the detector. (The cavity is so deep that only two muons per day traverse it!) Not only is the muon rate insufficient for monitoring, but also the background that it might induce is orders of magnitude lower than that in any other detector. The pulse heights on each tube are recorded if a five-fold coincidence occurs between any five layers. Since the resolving time of the tubes is 1 μsec, neither time-of-flight (directional) information nor muon stop signature is available.

The authors have recorded nine contained interactions in the detector, while 4-6 were expected. Indeed four of the events do not fit any of the neutrino hypotheses expected by the authors. The events are considered to be proton decay candidates. However the limited detector resolution renders the events hard to interpret. The proton decay candidates include tracks that have an abnormally high number (relative to straight-through muon tracks) of proportional tubes that did not fire, particularly next to the kink that is presumably the vertex. These gaps may be characteristic of electromagnetic showers in the detector. The authors argue that the candidates are not induced by electron neutrinos, although the expected rate is comparable to that of the observed candidates.

The many non-contained events in the Kolar detector show that a 140T detector, even when very well shielded by great depth, is limited in its ability to contain 1 GeV decay candidates (only an event in the inner 1/10 of the detector is fully contained). If the events are considered as proton decay candidates, the lifetime for several possible decay modes is $\tau/B=1.1\times10^{31}$ years, where the authors make no background subtraction.

3.2 THE CERN-FRASCATI-MILAN-TURIN DETECTOR IN THE MONT BLANC TUNNEL

A dense detector of 150T total mass has been operated in the Mont Blanc Tunnel for 1.5 years by the CERN-Frascati-Milan-Turin collaboration[11]. Their advantage is a grid size $(1\text{ cm})^2$ of limited streamer tubes which is substantially finer than that of the Indian-Japanese $(10\text{ cm})^2$. The tubes have bidimensional readout (both x and y for each cell). Unlike the Kolar experiment where the dE/dx loss in each tube is recorded, the Mont Blanc tubes provide only position information in each plane.

The group has studied showers and tracks from CERN calibration beams of electrons, pions, and neutrinos in a prototype module. The neutrino events were taken with a beam tuned to mimic the expected energy distribution of atmospheric muon neutrinos. (One cannot get ν_e events at an accelerator!). These ν_μ events have provided a powerful method of evaluating the expected neutrino background to the various configurations observed in the detector.

The depth of this detector is a factor of three greater than that of the detectors in the U.S. (Alpine tunnels are an asset!), but a factor of two shallower than the depth of the Kolar detector.

3.3 THE ORSAY-ECOLE POLYTECHNIQUE-SACLAY-WUPPERTAL DETECTOR IN THE FREJUS TUNNEL

An order of magnitude improvement in mass over the Italian and Indian-Japanese detectors is the goal of the collaboration of Orsay-Ecole Polytechnique-Saclay-Wuppertal[12] in another Alpine tunnel. The granularity (3mm thick iron plates) is a factor of three finer than the Kolar and Mont Blanc experiments, giving it superior tracking resolution. They have also improved the dense detector technology by interspersing planes of Geiger tubes in the detector. These tubes trigger flash chambers that are used for tracking. In addition, the time resolution of the Geiger tubes is sufficient to tag delayed μ^+ decays. This detector is expected to be operational with an initial mass of 300T starting in the spring of 1984. A 1 kT mass should be running by the end of 1984.

3.4 THE ARGONNE-MINNESOTA-OXFORD-RUTHERFORD-TUFTS DETECTOR IN THE SOUDAN IRON MINE

The University of Minnesota-Argonne group has constructed a prototype 30T detector in an iron mine in Minnesota. They used an inexpensive ferro-concrete medium which can be built in small modules. Gas proportional counters made from thin steel tubes were embedded in the concrete. This prototype suffers because of its small mass. With the addition of Oxford, Rutherford Lab, and Tufts the group is developing a 1.2kT version of their prototype. Since the concrete and gas tube array does not scale from 30T to 1000T, it will be replaced with corrugated steel drift chambers that have a 0.5m drift length and readout at both ends. A 3T prototype is currently under study. This detector[13] is scheduled to start operation in the middle of 1985.

4. CONCLUSIONS

Within the coming year, we will clearly have a plethora of data concerning proton decay limits (or measurements!) from a variety of detectors with very different systematic errors. In addition, the advent of the highly instrumented and shielded multikiloton detectors--with sensitivities two orders of magnitude greater than previous efforts--do seem to save the capability of reaching to a sensitivity of 10^{33} years for the $e^+\pi^\circ$ mode predicted by of the simplest grand unified theories. On the other hand, lurking at the 5×10^{31} year level could be decays into a variety of multitrack, low energy decay modes. We need more exposure, better resolution detectors, and more sophisticated background evaluations to plumb this challenging region.

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TABLE I

Typical Preliminary Values for $p \rightarrow e^{+}\pi^{\circ}$ Mode*
January 1984

	90% C.L. Limit or Value	Candidates*	Expected ν Background	Fiducial Exposure
IMB	$>20 \times 10^{31}$ yr	0	~0.2	2.26 kT yr
Kamioka	$>2.6 \times 10^{31}$ yr	0	0.0	0.32 kT yr
Kolar	$=1.1 \times 10^{31}$ yr	1	0.3	0.15 kT yr
Mont Blanc	$>1 \times 10^{31}$ yr	1	1	0.13 kT yr

TABLE II

Typical Preliminary Values for $p \rightarrow \mu^{+}K^{\circ}$ Mode*
January 1984

	90% C.L. Limit or Value	Candidates*	Expected ν Background	Fiducial Exposure
HPW	$=2 \times 10^{31}$ yr $>0.9 \times 10^{31}$ yr	1	0.02	0.11 kT yr
IMB	$>2.6 \times 10^{31}$ yr	2	5	1.2 kT yr
Kamioka	3×10^{31} yr $>0.8 \times 10^{31}$ yr	1	0.0	0.32 kT yr
Kolar	$=1.1 \times 10^{31}$ yr	1	0.3	0.15 kT yr
Mont Blanc	$=3 \times 10^{31}$ yr $>1.3 \times 10^{31}$ yr	1	0.16	0.13 kT yr

TABLE III

Typical Preliminary Values for $p \to \bar{\nu} K^+$ Mode*
January 1984

	90% C.L.	Candidates*	Expected ν Background	Fiducial Exposure
IMB	$>1.2\times10^{31}$ yr	3	5	1.7 kT yr
Kamioka	$>0.7\times10^{31}$ yr	3	1	0.32 kT yr
Mont Blanc	$>0.5\times10^{31}$ yr	0	-	0.13 kT yr

*The candidates in each experiment generally can also be interpreted as examples of other decay modes.

TABLE IV

Typical Preliminary Event Rates
January 1984

	Observed Contained Events	Live Time	Fiducial Mass	Events/KT yr
IMB	169	0.56 yr	3.3 KT	91
Kamioka	57	0.37 yr	1.0 KT	154
Kolar*	9**	2.5 yr	0.06 KT	60*
Mont Blanc	16	1.3 yr	0.1 KT	123

*The expected geomagnetic suppression of the neutrino rate at 3° N latitude is 40%.
**Does not include 4 proton decay candidates.

TABLE V. STATUS OF NUCLEON LIFETIME EXPERIMENTS: RING-IMAGING CHERENKOV DETECTORS (JANUARY 1984)

Collaborative Institutions	University of California/Irvine University of Michigan Brookhaven National Lab Cal Tech, Cleveland State, Hawaii, University College	Harvard University Purdue University University of Wisconsin	KEK University of Tokyo University of Tsukuba
Location	Morton-Thiokol Salt Mine Painesville, Ohio	Silver King Mine Park City, Utah	Kamioka Metal Mine
Depth	1.7 kmwe	1.75 kmwe	2.7 kmwe
Detector Mass (Kilotons)	8 KT total 3.3 KT fiducial	0.7 KT total 0.42 kT fiducial initial Gas tube array as external veto	3 KT total 1 KT fiducial
Cosmic Muon Flux	3μ/sec $10^8\mu$/year	~0.5μ/sec ~$2 \times 10^7\mu$/year	$6\text{-}7 \times 10^6\mu$/year
Nucleon Source	cube of high transparency water $22.8 \times 17.8 \times 16.9$ m^3	cylinder of water 5.6m radius x 7.15m high	cylinder of water 7.8m radius x 16m high
Detection Method	2,048 5" PM's on 1m surface grid	704 5" PM's on 1m cubic lattice surrounded by mirrors	1044 20" PM's on 1m surface grid
Present Status	Operational since August 1982	Operational since Spring 1983 External veto operational November 1983	Operational since July 1983
Reference	5	8	9

TABLE VI. STATUS OF NUCLEON LIFETIME EXPERIMENTS: TRACKING CALORIMETERS (JANUARY 1984)

Collaborative Institutions	Tata Institute Osaka City Univ Tokyo University	CERN INFN Frascati Milan University Turin University	Orsay Ecole Polytechnique Saclay Wuppertal	Argonne Laboratory Minnesota Oxford University Rutherford Lab Tufts University
Location	Kolar Gold Fields South India	Mont Blanc Auto Tunnel Franco-Italian Border	Frejus Auto Tunnel Franco-Italian Border	Soudan Iron Mine Soudan, Minnesota
Depth	7.6 kmwe	5.0 kmwe	4.5 kmwe	2.2 kmwe
Detector Mass	0.14 KT total 0.10 KT fiducial	0.15 KT total 0.10 KT fiducial	1.0-1.5 KT total 0.6-1.0 KT fiducial	~1.2 KT total ~1.0 KT fiducial
Cosmic Muon Flux	2μ/day 700μ/year	~6μ/day 2 x 10^{3}μ/year	1μ/min 5 x 10^{5}μ/year	~1μ/sec ~3x10^{7} sec/year
Nucleon Source	34 horizontal iron plates 1.2cm × 4m × 6m	134 horizontal iron plates 1cm × 3.5m × 3.5m	1500 vertical iron plates 3mm × 10m × 10m	256 modules 1x1x2.1m^{3} 1.6mm corrugated iron plates
Detection Method	1600 proportional gas tubes $(10cm)^{2}$ × 4 or 6m long	47,000 limited streamer tubes $(1cm)^{2}$ x 3.5m long	1500 plastic flash tube planes $(0.5cm)^{2}$ 200 Geiger tube $(1.5cm)^{2}$ planes	hexagonal drift tubes 1.6cm diameter 1m long
Present Status	Operational since 1981	Prototype calibrated in CERN beams Operational since May 1982	Prototype calibrated in CERN beams 160T installed in tunnel	3T Prototype under test Operational ~middle 1985
Reference	10	11	12	13