Proton Decay Search

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December 16, 2005

Abstract

A large-scale water Cherenkov detector is proposed to search for proton decay. There are twelve individual detectors, each with fiducial volume of 91 kTon and are surrounded by 45,000 photomultiplier tubes. Two principle decay modes are discussed for partial lifetimes of the proton. For the full running time of 20 years, an expected lower bound on the lifetime of the proton will be $\tau_p > 10^{35}$ years for $p \rightarrow e^+\pi^0$, and $\tau_p > 4 \times 10^{34}$ years for $p \rightarrow K^+\bar{\nu}$.

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1   Why Proton Decay?

Perhaps the first thing to ask about a proton decay search is why do we expect the proton to decay? Sakharov first proposed in 1967 three postulates that needed to be satisfied in order to explain the universe as we observe it assuming it evolved from a "Hot Big Bang". The first is a CP-violating reaction (to account for the matter/anti-matter asymmetry), the second is a period of non-equilibrium dynamics (to form galaxies) and the third is a baryon-number violating process (to have baryonic matter in the universe). It is this third process that we are focused on: if baryon number is not perfectly conserved (as has been observed thus far), then the lightest baryon (the proton) must be unstable and decay. So in order to explain how the baryonic matter in our universe originated, that baryonic matter must decay.

The best theories that incorporate the Standard Model (SM), while at the same time extending it to include baryon decay, are so-called Grand Unified Theories (GUTs). They work under the assumption that the forces we see in the SM are really artifacts of a single force from a larger symmetry that was broken at a much higher energy scale. This new force introduces new particles whose masses are of the order of the energy scale at which the larger force was broken – the GUT scale ($\sim 10^{16}$ GeV). These new particles, sometimes called "X" and "Y" bosons, can intermediate interactions which would violate baryon number, causing the proton to decay. And while this reaction would violate some of the symmetries we see in the SM like baryon and lepton number, it would preserve the larger symmetries of the GUT. The original GUT proposed was $SU(5)$, it is the smallest gauge group that can contain the SM gauge groups $SU(3) \times SU(2) \times U(1)$. And while the original minimal $SU(5)$ has been ruled out because it predicts a lifetime of the proton much shorter than the current limits, there are many viable extensions of it as well as more exotic gauge groups that can reduce to the SM.

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Figure 1: This is the non-SUSY GUT reaction for the decay of a proton intermediated by an "X" boson. It takes a proton and goes to a pion and a positron.

There are two main types of GUTs, ones that simply try to incorporate the SM and others

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Figure 2: This is a SUSY GUT reaction for the decay of a proton intermediated by a gluino and includes a 4-lepton/slepton vertex. It takes a proton and goes to a kaon and a neutrino.

that also incorporate supersymmetry (SUSY). From the first ones, the principle decay mode is $p \rightarrow e^+\pi^0$, while the SUSY GUTs predict the dominant decay mode to be $p \rightarrow K^+\bar{\nu}$. Naturally, each specific model predicts which decay modes will contribute and in what proportion. The figures display some of the more common decay modes predicted; one is for a regular GUT and the other is for a SUSY GUT. Since these are predicted to be the dominant decay modes, these two reactions will be the focus of the search for proton decay.

2   Detector History

The world's current best limits on the lifetime of the proton come from the Super Kamiokande (SuperK) water Cherenkov detectro experiment in Japan's Kamioka mine. This detector design is based on that very successful model. Unfortunately, the only way to continue to push up the lower limit of the proton lifetime is to look at more protons for longer. With this in mind, each individual detector is designed to have 4 times the fiducial volume of the SuperK detector, which is then copied and repeated a dozen times. The designed run time will be 20 years. The current upper limits placed on the dominant decay modes that will be discussed are from SuperK ([1],[2]).

$$\tau_p > 5.4 \times 10^{33} \text{ yr for } p \rightarrow e^+\pi^0$$
$$\tau_p > 2.3 \times 10^{33} \text{ yr for } p \rightarrow K^+\bar{\nu}$$

Despite the successes of SuperK there has been one major problem. On November 12, 2001, several thousand of the inner detector PMTs were destroyed in a cascade failure. The PMTs are designed to be able to withstand depths in water of up to 80 m without needing additional

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Figure 3: An open view of the Super Kamiokande detector.[6]

housing[8]. While refilling the detector, one PMT collapsed and caused a pressure wave which destroyed virtually all of the PMTs that were under water at the time. The current best technology for PMTs are the same PMTs used in SuperK and are 10 years old, and new improvements could certainly be made. Better quantum efficiency for detecting Cherenkov photons, a flatter surface to allow for a wider acceptance, stronger housing without needing additional support and cheaper mass production cost are all areas of possible improvement in PMT design. One of the principle goals of the R&D for this project will be to design a better PMT to meet these needs.

3   The MegaTon Cherenkov Detector

3.1   Design

This detector consists of multiple large water Cherenkov detectors. The design for an individual detector is a spherical inner detector (ID) shape, 60 m in diameter housed in a larger cylindrical outer detector (OD) to act as a veto. The ID, with a diameter of 60 m will have

113 kT of water contained in its volume. However, due to constraints in reconstruction of events, only about 91 kT will be part of the fiducial volume. The inner and outer detectors must be optically sealed off from each other as much as possible. Any gaps in the construction of the structure must be covered over with thick, black polyethylene sheets to ensure light from the OD doesn't enter the ID. This design will then be repeated 12 times to give a total fiducial volume of 1.1 MT. The total fiducial volume will contain 3.7×10^{35} protons.

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Figure 4: An artist's rendition of the proposed detector design. This design would be copied for 12 total detectors.

The best phototubes currently in production (and the ones SuperK used) are Hamamatsu R3600-06 50 cm hemispherical photomultiplier tubes (PMTs). As stated earlier, further R&D work is hoped to improve upon this model, but for now this model will serve as a guide. The ID will be lined with PMTs to have a coverage of 50%, requiring approximately 45,000 PMTs in each detector. The OD will only need about 15,000 PMTs since it's not doing precision tracking but rather being used as a veto from cosmic rays and other background events. This gives 60,000 PMTs in each detector, or about 720,000 PMTs total. The ideal scenario would allow for these PMTs to be directly submerged in water. In the frequency region (high-frequency optical) that is of interest, the quantum efficiency of the PMTs is between 10-20%. Due to the hemispherical design, the maximum acceptance angle of the PMTs is about 75°, with acceptance at this angle roughly 50%. However, because the 2 m closest to the PMT wall is considered "dead space" and not part of the fiducial volume (it's too difficult to reconstruct events so close to the wall), this acceptance is enough.

The reason for the spherical design is to minimize the flight distance for the Cherenkov photons from the decay products. Also, the spherical design would help with the reconstruction of events due to the symmetry of the detector. While the overall design is to simplify these considerations, there are some other things that will be more difficult. A spherical shape will be more difficult to build "in-situ", so considerable engineering effort and analysis will

have to be spent to ensure the support structure for the PMTs is stable. The PMTs will be assembled in groups of 12 in modules that will be installed individually onto the super-structure. Tessellating these modules onto this curved surface will also require some work, but similar work on a much smaller scale was done for the SNO experiment in Canada.

There are many other considerations to take into account before construction could begin, the most important of which is the site that would be chosen to house the detectors. It needs to be well-shielded from cosmic rays, so a good figure of merit would be protected by 4000 mwe (meters-of-water-equivalent). SuperK was approximately 2600 mwe and had a subsequently larger atmospheric background. 4000 mwe is a very attainable goal, since many other cosmic ray and neutrino studies have been done at that depth (Homestake mine is an excellent example). The walls surrounding the detector should have a low activity rate. The OD protects the ID from most natural radioactivity, however radon levels in the air can build up in the mine where the detectors rest. To offset this problem, the air for the detectors will be drawn from outside the mine/cave and filtered to keep this background to a minimum. SuperK also ran into a problem of an excessive magnetic field from the Earth ($\sim$450 Gauss) which caused their PMTs to behave poorly. This was well above the ambient magnetic field of the Earth ($\sim$50 Gauss), and hopefully a site can be chosen that will not have this problem. If this does become a problem, though, large Hemholtz coils can be used to partially cancel the magnetic field and allow for normal operation of the PMTs.

The two most important things for a water Cherenkov detector are the PMTs, which have been discussed at length, and the water itself. The water must be highly purified in order to allow for the longest attenuation length possible. The water purification system would involve several filtration systems, including reverse osmosis and degasification. SuperK's filtration system was able to achieve optical attenttuation lengths of up to 100 m, a similar performance can be expected. This is extremely important to ensure that the photons radiated undergo minimal attenttuation and scattering.

3.2   Calibration

With 12 seperate detectors all running at the same time, it will be crucial to eliminate systematic errors in the design by proper calibration. Water transparency can be measured using a diffuser ball lit up by a laser from a fiber optic guide, most importantly in the 350 nm-500 nm wavelength regime. To allow for frequency-dependent measurements, frequency-splitting filters can be employed. Also, the laser light could be directly shined into the detector to measure the scattering of light in the frequency regions the Cherenkov radiation is emitted and the PMTs are most sensitive to.

Besides ensuring the purity of the water, the PMTs themselves must be calibrated. Again,

a light ball placed in the center of the detector and shined can give the relative gain for all the PMTs at a specific wavelength. This can also be used to check the timing circuitry of any PMTs that need to be verified. Other sources besides light can be used to test the detector response. A small, low energy linear accelerator can be used to accelerate electrons into the detector to calibrate the absolute energy scale for the reconstruction of electrons. A Deuterium-Tritium Generator (DTG) can be employed to bombard the oxygen nuclei in the water to create N^{16}, which has a half-life of 7.13 s. This decays into a 4.3 MeV electron coincident with a 6.1 MeV γ ray. This would provide an important check for the reconstruction of low-energy γ rays.

4   Signal Analysis

4.1   Cherenkov Signals

There are two primary decays modes of the proton that will be searched for, $p \rightarrow e^+\pi^0$ & $p \rightarrow K^+\bar{\nu}$. Both of these provide unique signatures to cut on. Before discussing the specifics of each signal, first lets discuss how water Cherenkov detection works. A charged, relativistic particle that is travelling faster than the speed of light in the medium will emit Cherenkov light in a cone at a specific angle depending on the velocity of the particle. The relevant equations are [10]:

$$\cos\theta_C = \frac{1}{\beta n}$$

$$\frac{dE_{rad}}{dx} = \frac{q^2}{c^2} \int \omega \left(1 - \frac{1}{\beta^2 n^2} \right) d\omega$$

For water, with $n = 1.33$, the particle must be travelling above $\beta > .75$ or have a $\gamma > 1.5$. The energy loss is about 500 eV/cm in the spectrum we are interested in, carried away by about 200 photons/cm. This energy loss is quite small compared to the overall energy loss due to ionization in the water, which is several MeV/cm. Since the particles involved in these decays can only have a maximum energy of a few hundred MeV, they will only radiate for a very short time before falling below the Cherenkov threshold. The PMTs then detect the emitted radiation, which is typically in the short-wavelength optical range. By using the timing of the PMTs, angle of the cone and the pulse height response of the PMTs, the vertex can be reconstructed as well as the energy of the particle. Particle ID is performed based on the topology of the event. Stongly confined rings are muons, while electrons and γs "shower" due to the superposition of multiple rings being created by their pair-production partners, giving a wider ring. Given the size of the detector, the number of Cherenkov photons emitted for an average radiating particle and the quantum efficiency of the PMTs,

there will be between 30-70 PMTs signalling for each Cherenkov ring produced by a radiating particle to provide the vertexing and energy measurements.

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"Review of Proton Decay Results" lecture slides by Ed Kearns at Snowmass 2001.
http://hep.bu.edu/~kearns/pub/kearns-pdk-snowmass.pdf

Figure 5: SuperK event 27128713. The forward two (three) cones of light form the π^0, while the faint backwards cone is for a π^+. This is for the possible decay mode $p \rightarrow K^+\bar{\nu}, K^+ \rightarrow \pi^+\pi^0$. This is real SuperK data, and was considered a possible proton decay event, but was rejected in analysis cuts. [6]

4.1.1 $p \rightarrow e^+\pi^0$

In this decay mode, the emitted electron is relativistic, while in the opposite direction the π^0 immediately decays to 2γ. These high energy γs will interact in the water and pair-produce. The radiation length of water is 36cm, and the subsequent electron-positron pairs will Cherenkov radiate. So the signature for this decay mode would be one electron-like showering ring with energy of a few hundred MeV, and in the opposite direction 2-3 low-energy showering rings. With the lower-energy rings, a π^0 mass cut can be applied to the invariant mass reconstructed from the rings. Also, these rings should be within 1 m of the backwards electron and coincident in time. Together the energy of the rings should recon-struct to the original proton mass. SuperK was able to acheive a total of 43% reconstruction efficiency in this decay mode using these broad cuts.

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Figure 6: Atmospheric neutrino Monte Carlo background for $p \rightarrow e^+\pi^0$. SuperK predicted .25 events/100kTon/year. [6]

The primary background for these events are electron neutrino charged current events from atmospheric showers which breaks up a nucleus. SuperK Monte Carlo results estimated this background to be .25 events/100kTon/year. This gives about 4 events/year between the 12 detectors. However, by sacrificing some reconstruction efficiency, the background can be reduced to about .15 events/1MTon/year. The reconstruction efficiency drops down to only 17%, unfortunately. Further Monte Carlo studies would be warrented to study how to maximize efficiency to background. The neutrino background is irreducible, there is no detector design that can partially eliminate this. But given these backgrounds and a run time of 20 years, the lifetime of the proton in this decay channel could be pushed as high as 1×10^{35} [5].

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Figure 7: Estimated expected lower limits on the lifetime of the proton in the $p \rightarrow e^+ \pi^0$ channel based on run time and size of detector, given in MTon-years. [5]

4.1.2 $p \rightarrow K^+ \bar{\nu}$

While this decay mode is favored by many SUSY GUTs, it has several inherent experimental problems. The first is that much of the proton's energy is taken away by the neutrino and thus can't be fully reconstructed and cut on the mass of the proton. The second is that the kaon also typically decays with a neutrino, so it cannot be reconstructed accurately. Also, the initial kaon is not relativistic and will not Cherenkov radiate. However, this event does have a very unique timing signature. A proton inside an oxygen nucleus decays into a neutrino and kaon. The kaon is low-energy and will almost immediately come to rest through ionization loss in the water, while the neutrino escapes. The leftover nucleus is an excited N^{15*} nucleus, which immediately decays through a prompt γ of 6.3 MeV into N^{15}. If this γ can be collected, there is a window between it and when the kaon decays 12 ns later. The K^+ will decay 63% of the time into a muon and neutrino. This muon will Cherenkov radiate briefly before coming to rest. Again, there will be a long time window for the lifetime of the muon, 2.2 μs, and then it will decay into an electron and two neutrinos, with the electron providing another Cherenkov ring. The primary cut for this decay mode is a timing cut. A window of 12 ns between the prompt γ and the muon, then another 2.2 μs window between the muon and the electron. Collecting and identifying the prompt γ is the largest inefficiency.

Some simple momentum constraints can be applied to the muon because it is involved in 2-body decays. The electron, due to muon decay being a 3-body event, will have a larger momentum distribution. Again, the background comes from atmospheric neutrinos. SuperK was able to achieve a reconstruction efficiency of 8.7%, while limiting background to .125 events/year. This means for a megaton detector a background of 3-4 events/year. Again with some sacrifices to reconstruction efficiency, over a 20 year runtime, the partial lifetime of the proton could be pushed as high as 4×10^{34} years [5].

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http://lanl.arxiv.org/PS_cache/hep-ex/pdf/9904/9904020.pdf
Y. Hayato, M. Earl, et.al

Search for proton decay through p->\bar{\nu} K^+ in a large water Cherenkov detector
http://arxiv.org/abs/hep-ex/9904020

Figure 8: Monte Carlo simulation from SuperK for the prompt-γ peak expected in $p \rightarrow K^+\bar{\nu}$. The error bars are for 33 kTon-years of data at SuperK. [2]

4.1.3 Neutrinos

Another important physics goal which was not discussed here, but is very relevant for these large scale Cherenkov detectors, is neutrino physics. This detector would be an ideal device for studying atmospheric and solar neutrinos, as well and being a possible target for long and short baseline neutrino beam experiments. Further studies and proposals should be considered along these lines.

5 Conclusion

Super Kamiokande set out to push the realm of physics in nucleon decay by an order of magnitude, and they accomplished their goal. But the proton decay limits can only scale linearly with time and volume, and after running for 5 years, there won't be much more significant improvements in this area from SuperK. A new detector is needed, an order of magnitude larger to push the limits up by an order of magnitude. This detector design will increase the fiducial volume over SuperK by a factor of 20, and is designed to run for 20

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Figure 9: Monte Carlo simulation for the distribution in time intervals for the prompt-γ to the kaon decay. A 7 ns cut yeilds a reduction factor of 2×10^4 against background. [3]

years. With these parameters in mind, the lower limit on the lifetime of the proton will be pushed up to 10^{35} years. While the original SuperK was able to rule out the minimal $SU(5)$ GUT, this kind of limit would rule out large portions of both SUSY and non-SUSY type GUTs. This physics goal is technologically availible and can teach us more about what physics is like at the 10^{16} GeV scale, and how the forces of the SM interact at those higher energies.

References

[1] T. Hakaya, Nucl. Phys. B (Proc. Suppl.) 138, 376 (2005).

[2] Y. Hayato et al. (Super Kamiokande Collaboration) (2005) hep-ph/9904020.

[3] T. Marrodan Undagoitia et al. (2005) hep-ph/0511230.

[4] Super-Kamiokande at SUNY, Stony Brook. http://ale.physics.sunysb.edu/nngroup/superk/

[5] Masato Shiozawa, Hyper-Kamiokande Lecture (2001) http://neutrino.kek.jp/jhfnu/workshop2/ohp/shiozawa.pdf

[6] Ed Kearns, Snowmass Lecture (2001) http://hep.bu.edu/ kearns/pub/kearns-pdk-snowmass.pdf

[7] S. Fukuda et al. (Super Kamiokande Collaboration), NIM Physics Research A 418-462 (2003).

[8] Hamamatsu Corporation, Photomultiplier Tube R3600-02, -06 Datasheet (1999).

[9] The Particle Data Group, Particle Detectors Section. (2004)

[10] J.D. Jackson, Classical Electrodynamics, Third Edition, pgs. 637-40. (1998)

[11] D. Casper, The Super-Kamiokande Experiment (lecture).

[12] D. Perkins, Introduction to High Energy Physics, Fourth Edition, pgs. 361-3. (2000)