The Search for Proton Decay at Super-Kamiokande

Kenneth S. Ganezer for the Super-Kamiokande Collaboration
Department of Physics
California State University, Dominguez Hills

Introduction

Seventy years ago (in 1929) Weyl proposed that the proton was absolutely stable[1]. In later years this hypothesis was advanced by others including Stueckelberg and Wigner[1]. Nonetheless, experimental searches for baryon number violation have been conducted since 1959[2]. These studies are motivated by a variety of concerns including the lack of observation of a baryon number dependent force as required by a new local symmetry such as baryon conservation. Another motivation is the emergence of baryon and lepton number violating processes in grand unified and supersymmetric theories. This is a consequence of baryons and leptons being placed in the same multiplets. Baryon number violation can occur in over fifty modes of nucleon decay to elementary particles as well as in neutron-antineutron oscillations. Each of these processes can be studied by Super-Kamiokande through a separate customized analysis. In this talk we present results on two proton decay modes, $p \rightarrow e^+\pi^0$ and $p \rightarrow \bar{\nu} K^+$,for a 33 kton exposure at Super-Kamiokande. Both of these modes are of interest in the minimal supersymmetric (SUSY) SU(5) theory. Here $p \rightarrow \bar{\nu} K^+$ is the dominant mode with a partial lifetime that varies from 10^{29} to 10^{35} years. For $p \rightarrow e^+\pi^0$ the partial lifetime in SUSY SU(5) is 5 x 10^{34} years or longer.

The Super-Kamiokande Detector

Super-Kamiokande is a ring imaging water Cherenkov counter at the Kamioka Observatory of the University of Tokyo Institute for Cosmic Ray Research (ICRR). The detector is 1000 m (2700 meters water equivalent) below Mt. Ikenoyama near the city of Kamioka Japan. It contains 50 ktons of ultra-pure water in a cylindrical stainless steel tank that is separated into two regions: a primary inner volume viewed by 11,146 50 cm diameter photomultiplier tubes (PMTs) and a veto region, surrounding the inner volume, and viewed by 1885 20 cm PMTs. The tank is 41.4m high and 39.3 m in diameter.

When relativistic charged particles travel through water they emit Cherenkov light in a cone of opening angle 42 degrees (for $\beta \approx 1$) relative to the direction of travel (the track). When the Cherenkov cone intersects the walls of the detector it forms rings of light that may be imaged. For each PMT, we measure the amount of charge after multiplication and the time when the PMT was hit. From this information it is possible to reconstruct the position (vertex) of events whose charged secondaries are contained by the detector (contained events) and the number, identity, momentum, and energy, of the individual charged particles in the event.
More details on Super-Kamiokande can be found in Ref. [4].

Results for $p \rightarrow e^+ \pi^0$

Sketches of the kinematics for an idealized $p \rightarrow e^+\pi^0$ event and of its PMT charge signature in Super-Kamiokande are given in fig. 1 and fig. 2 (from Ref. [4]). Real events differ from this idealized picture as a result of Fermi motion of bound protons in oxygen, nuclear interactions of pions inside and outside the nucleus, coherent nuclear effects of the decaying proton, and asymmetry in the energy of the two gamma rays from the decaying pion.

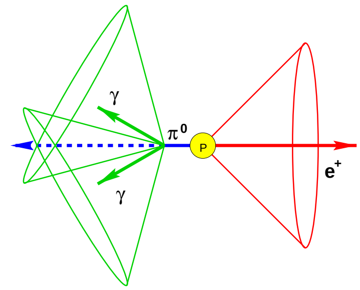

Figure 1. Idealized $p \longrightarrow e+\pi°$ decay in Super-Kamiokande.

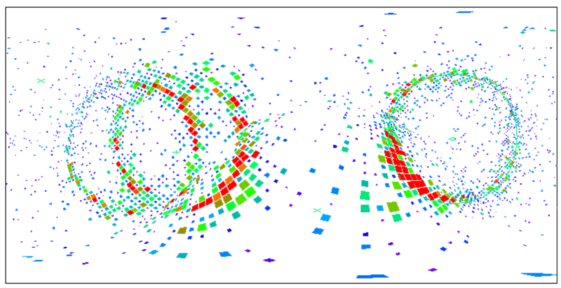

Figure 2. $p \longrightarrow e+\pi°$ MC event display.

The data sample for all nucleon decay modes is identical to that of our atmospheric neutrino analysis [3] and consists of events that are fully contained in the inner detector. Once this, "contained event" sample is isolated, specific selection criteria are applied for each nucleon decay mode. For $p \rightarrow e^+\pi^0$ the criteria are as follows: (a.) the total number of photoelectrons (P Es) must be greater than 6000 and less that 9500, (b.) there must be two or three showering type (electron or gamma like) rings, (c.) if there are three showering rings the invariant mass of the π^0 ($M_{\pi 0}$) must be greater than 85 and less than 185 MeV/c^2, (d.) the event must not contain decay electrons, (e.) the total invariant mass ($M_{inv,tot}$) must be greater than 800 and less than 1050 MeV/ c^2 and, (f) the total momentum (P_{tot}) must be less than 250 MeV/c. Criterion (a) is a loose energy cut and (b) allows for the three expected showering rings or for two rings if one of the photon rings is so weak that it is invisible. The (c.) criterion requires that in the case of three observable rings two of them reconstruct to the mass of a π^0. Since this decay mode does not involve charged pions, muons, or other particles that might decay to electrons, criterion (d) is used to veto events with such decays. Criteria (e) and (f) are used to isolate events that have the kinematics of a decaying proton that is free or in an oxygen nucleus. Thus (e) isolates events whose mass is close to that of a proton and (f) selects events whose total momentum is less than or equal to the Fermi level of a proton in an ^{16}O nucleus.

Our contained event and $p \rightarrow e^+\pi^0$ selection criteria are applied to a simulated $p \rightarrow e^+\pi^0$ event sample, to (40 years of) simulated atmospheric neutrino interactions, our primary source of contained event backgrounds, and to 45 kton years (736 days) of data. The results are shown in fig.-3 (from Ref. [4]) in which the final two criteria (e) and (f) are imposed graphically. This yields a total efficiency for $p \rightarrow e^+\pi^0$ of 44%, an expected background of .2 events for 45 kton years, and no data events. The mass distribution of atmospheric neutrino background in figure-3 matches that of atmospheric neutrino interactions (see Ref. 3). These results imply that our data is consistent with background atmospheric neutrino interactions and no $p \rightarrow e^{+}\pi^{0}$ candidate events. From this and the efficiency calculated from the simulated $p \rightarrow e^{+}\pi^{0}$ event sample we calculate a lower limit on the proton lifetime (τ) divided by the branching ratio for $p \rightarrow e^{+}\pi^{0}$ (B) (a partial lifetime) at the 90% confidence level of $\tau/B \geq 2.9 \times 10^{33}$ years. This is an improvement by more than a factor of 5 over the previous best lifetime limit for this process of 5.6×10^{32} years [6].

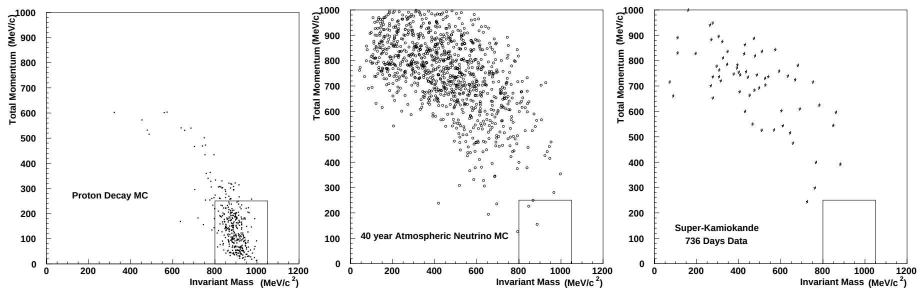

Figure 3. $p \rightarrow e{+}\pi^{\circ}$ mode. Distributions of events in total reconstructed momentum vs. total invariant mass for (a) proton decay MC, (b) atmospheric neutrino MC, and (c) data.

Results for $p \rightarrow \nu^{-} K^{+}$

Proton decay via $p \rightarrow \nu^{-} K^{+}$ can be studied in Super-Kamiokande through two distinct decay modes of the positively charged kaon, $K^{+} \rightarrow \pi^{+}\pi^{0}$ and $K^{+} \rightarrow \mu^{+}\nu_{\mu}$. A sketch of these two $p \rightarrow \nu^{-} K^{+}$ channels is given in fig. 4 from [4]. For $p \rightarrow \nu^{-} K^{+}$ and $K^{+} \rightarrow \mu^{+}\nu_{\mu}$ of a bound proton in ^{16}O, the daughter nucleus is left in the $p_{3/2}$ (excited) state of ^{15}N which promptly decays by emitting a 6.3 MeV gamma ray. Thus the $p \rightarrow \nu^{-} K^{+}$ and $K^{+} \rightarrow \mu^{+}\nu_{\mu}$ channel has two branches, one in which a prompt 6.3 MeV gamma ray is required (for a bound proton) and one in which it is not (for a free proton). Our latest $p \rightarrow \nu^{-} K^{+}$ results for an exposure of 33 kton-years (535 days) are given below and are also in Ref. [7].

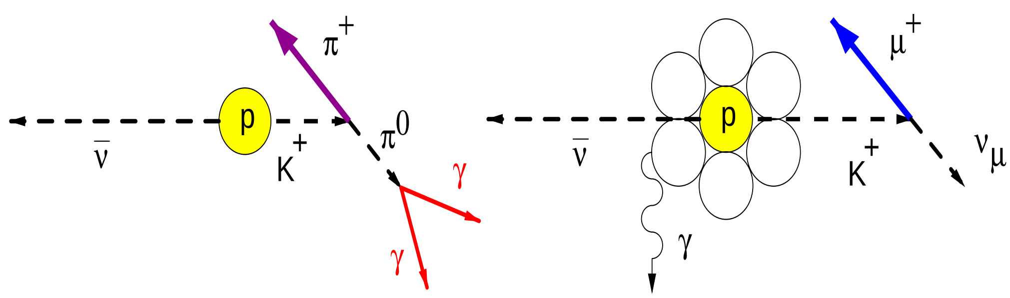

Figure 4. $p \rightarrow \bar{\nu} K^{+}$ mode, $K^{+} \rightarrow \pi^{+}\pi^{\circ}$ and $K^{+} \rightarrow \mu^{+}\nu_{\mu}$ branches.

The five specific criteria for the $p \rightarrow \nu^{-} K^{+}$ and $K^{+} \rightarrow \pi^{+}\pi^{0}$ search are (a.) two showering (electron-like) rings, (b.) one decay electron, (c.) the invariant mass of the π^{0} greater than 85 and less than 185 MeV/c^{2}, (d.) the momentum of the π^{0} greater than 175 MeV/c and less than 250 MeV/c, and (e.) the number of π^{+} photoelectrons greater than 40 and less than 100. Since the π^{+} in this channel is only slightly above the Cherenkov threshold, (e) selects events that have yielded a small amount of collected π^{+} light. Criterion (a.) selects events with two showering rings from the two π^{0} decay gamma rays while (c.) and (d.) require that the two π^{0} gamma rays reconstruct with the expected mass and momentum. The purpose of criterion (b.) is to identify positrons from the end of the π^+ to μ^+ to e^+ chain. For contained events and $p \rightarrow \nu^- K^+$ and $K^+ \rightarrow \pi^+ \pi^0$ criteria we had no candidate data events, an expected atmospheric neutrino background of .7 events and an efficiency of 6.5%. This yields a partial lower lifetime limit for $p \rightarrow \nu^- K^+$ and $K^+ \rightarrow \pi^+ \pi^0$ at the 90% confidence level of $\tau/B \geq 3.1 \times 10^{32}$ years.

For the $p \rightarrow \nu^- K^+$ and $K^+ \rightarrow \mu^+ \nu_\mu$ mode our selection criteria are (a.) one muon-like ring, (b.) one decay electron, (c.) the momentum of the muon greater than 215 and less than 260 MeV/c, and (d) the number of hit PMTs greater than 7 with the time before the muon like ring greater than 12 ns and less than 120 ns. The muon is the only visible track and is mono-energetic since K^+ decay is a two body process. Criteria (a.), (b.), and (c.) are designed to find the muon ring while the purpose of criterion (d.) is to select prompt gamma rays. Our $p \rightarrow \nu^- K^+$ and $K^+ \rightarrow \mu^+ \nu_\mu$ search used a contained event sample and criteria (a.) through (d.). We found no candidate events, had an expected background of .4 events, and an efficiency of 4.4%. This yields a partial lower lifetime limit for $p \rightarrow \nu^- K^+$ and $K^+ \rightarrow \mu^+ \nu_\mu$ at the 90% confidence level of $\tau/B \geq 2.1 \times 10^{32}$ years.

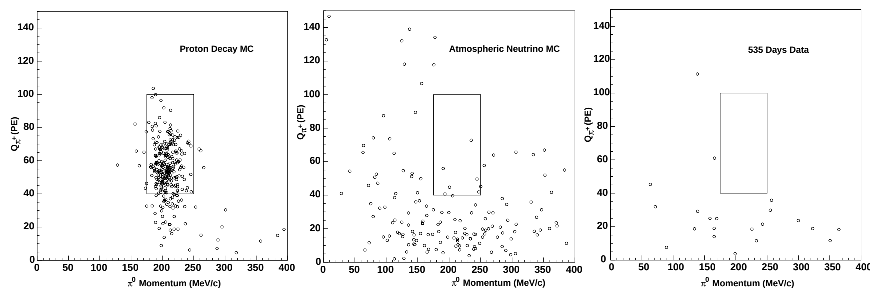

Figure 5. $p \rightarrow \bar{\nu} K^+; K^+ \rightarrow \pi^+ \pi^\circ$ mode. Scatter plot of $Q_{\pi+}$ vs. π° momentum for (a) proton decay MC, (b) atmospheric neutrino MC, and (c) data.

References

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