MINI-REVIEW ON PROTON DECAY SEARCHES

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Among several proton decay (or nucleon decay in general) search experiments, most recent two experiments and their results are presented. First one in this article is Super–Kamiokande which utilizes a largest water Cherenkov detector with 50,000 tons of ultra pure water. Second one is Soudan 2 which is a iron tracking calorimeter with a total mass of 974 tons. In both experiments, various decay modes have been studied and no evidence for nucleon decays has yet been found. Experimental lower limit for nucleon partial lifetime was obtained for each decay mode and is 4.4×10^{33} years for $p \to e^+\pi^0$ mode and 1.9×10^{33} years for $p \to \bar{\nu}K^+$ mode at 90% confidence level from Super-Kamiokande.

1 Introduction

Most of Grand Unified Theories (GUTs) allow baryon number violated transitions between leptons and quarks and proton decay channels into lighter leptons and mesons become open. Therefore, the decay of the proton is one of the most dramatic predictions of various GUT models[1]. In the past two decades, several large mass underground detector experiments have looked for proton decay but no clear evidence has been reported[2].

It has been noted that there are several indirect evidence of GUT such as the observed family-structure of elementary particles and the meeting of the three gauge couplings. Moreover, recent discovery of finite, small neutrino mass[3] also suggests the physics at the energy scale far beyond the standard model[4]. Proton decays would provide the window for viewing the new physics and it is important to push up the experimental sensitivity for this processes. In this article, most recent two experiments, Super–Kamiokande and Soudan 2, are presented.

2 Super–Kamiokande

2.1 The Super–Kamiokande Detector

Super–Kamioka is a large water Cherenkov detector located in a mine 2700 meters-water-equivalent below the peak of mountain[5]. The detector holds 50 ktons of ultra-pure water contained in a cylindrical stainless steel tank and separated into two regions: a primary inner volume viewed by 11146 50 cm photomultiplier tubes (PMTs) and a veto region, surrounding the inner detector, viewed by 1885 20 cm PMTs. The fiducial volume is 22.5 kiloton and total detector livetime for physics analysis is now 1144 days corresponding to 70.4 kt·year exposure. Physical quantities of an event are automatically measured such as vertex position, the number of Cherenkov rings, momentum, particle type and the number of decay electrons by reconstruction algorithms[5].

2.2 $p \to e^+\pi^0$ search

This decay mode has a characteristic event signature, in which the electromagnetic shower caused by the positron is balanced against the two showers caused by the gamma rays from the decay of the π^0. This signature enables us to discriminate the signal events clearly from atmospheric neutrino background. To extract the $p \to e^+\pi^0$ signal from the event sample, these selection criteria are defined[5,6]: (A1) the number of rings is 2 or 3, (A2) all rings have a showering particle identification (PID), (A3) 85 MeV/c^2 < π^0 invariant mass < 185 MeV/c^2, (A4) no decay electron, (A5) 800 MeV/c^2 < total invariant mass < 1050 MeV/c^2 and total momentum < 250 MeV/c. Criterion (A2) selects $e^\pm$ and γ. Criterion (A3) only applies to 3-ring events. Criterion (A5) checks that the total invariant mass and total momentum correspond to the mass and momentum of the source proton, respectively. The total invariant mass and total momentum distributions after criteria (A1)–(A4) are shown in Figure 1.

From $p \to e^+\pi^0$ Monte Carlo sample, detection efficiency is estimated as 43%. Expected number of backgrounds from atmospheric neutrino interactions is estimated from atmospheric neutrino Monte Carlo sample as 0.1 events. Finally, there is no candidate events found in data sample. From these results, the lower limit on partial lifetime of proton is obtained as 4.4×10^{33} years at 90% confidence level (CL).

2.3 $p \to \bar{\nu}K^+$ search

The $p \to \bar{\nu}K^+$ mode is generally favored by GUT models implemented with supersymmetry[7]. Because produced K^+ is expected to have momentum below Cherenkov threshold, the K^+ is generally invisible in a water Cherenkov detector. Therefore, experimental searches are performed by looking for decay products of the K^+. There are two prominent decay channels of K^+; $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^0$ and three search methods for $p \to \bar{\nu}K^+$ have been developed[8].

In the first method, K^+ decays into μ^+ are looked for. The μ^+ is expected to have monochromatic momentum of 236 MeV/c. Selection criteria for this decay mode are defined as: (B1) the number of rings is one, (B2) the ring has a nonshowering PID, (B3) one decay electron, (B4) 215 MeV/c < muon momentum < 260 MeV/c, Figure 2 shows muon momentum distributions. Because there is no significant excess in the signal region, we applied spectrum fitting to ob-

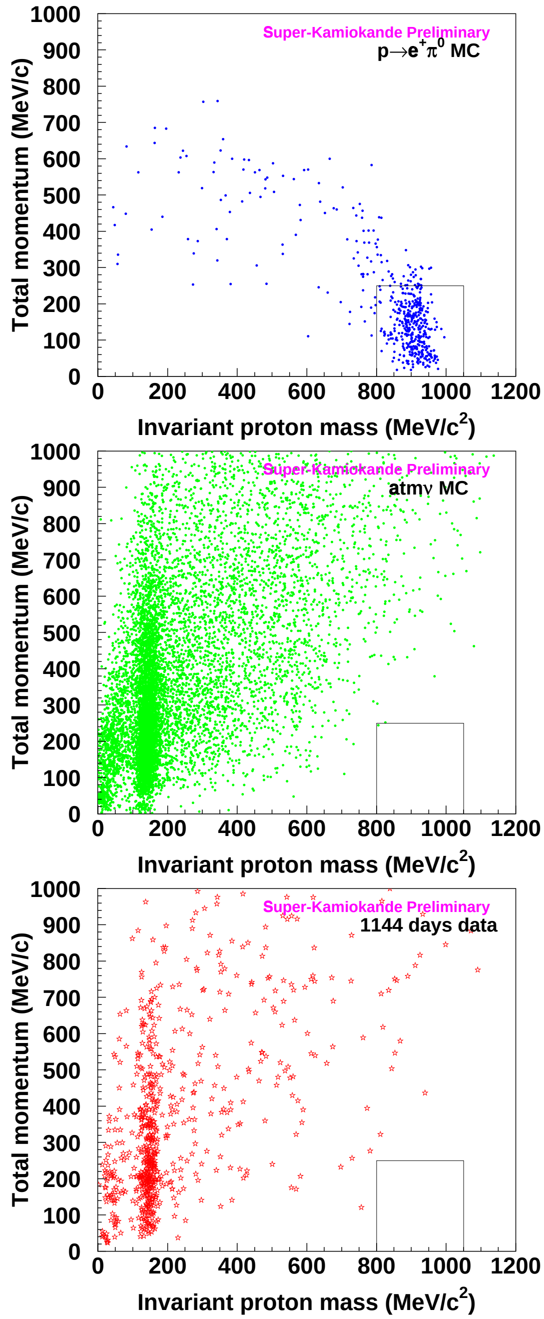

Figure 1. The total invariant mass and total momentum distributions after criteria (A1)–(A4) (see text) for 3 samples: (top) $p \to e^+\pi^0$ Monte Carlo, (middle) atmospheric neutrino Monte Carlo corresponding to 900 kton·year, (bottom) data corresponding to 70.4 kton·year. The boxed region in each figure shows the criterion (A5) for the $p \to e^+\pi^0$ signal.

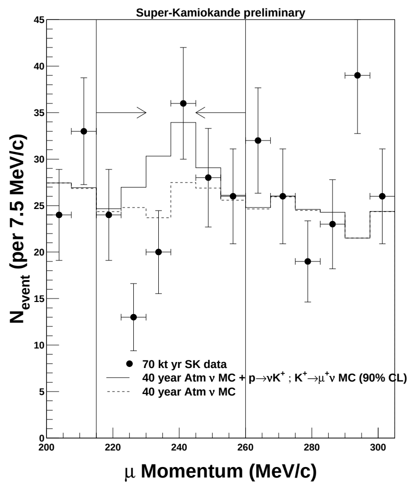

Figure 2. Reconstructed muon momentum distributions after criteria (B1–B3) (see text). Solid (dashed) line shows the estimated 90% CL number of proton decays + atmospheric neutrinos (atmospheric neutrinos). The black points with error bars show the data with the statistical errors.

tain upper limit of signal events. The dashed line shows the fitting result for backgrounds and solid line shows proton decay signal + backgrounds which gives the 90% CL upper limit of the number of signals. From this analysis, we obtained the partial lifetime limit for $p \to \bar{\nu} K^+$ decay mode as 4.3×10^{32} years at 90% CL.

In the second method, additional criterion is required to eliminate the remaining backgrounds. This criterion requires nuclear deexcitation γ from the residual ^{15}N nucleus. We expect the γ to be observed proceeding to the K^+ decay with the time difference corresponding to the K^+ lifetime ($\tau_{K^+} = 12$ nsec). By this criterion along with criteria (B1–B4), expected number of backgrounds is reduced to 1.1 events while detection efficiency including the kaon decay branching ratio is 9.3%. Candidate events are looked for in the data sample but no candidate is found. Obtained partial lifetime from this method is 9.5×10^{32} years at 90% CL.

In the third method, K^+ decays into two pions are used. Selection criteria for this method are: (C1) the number of rings is 2, (C2) all rings have a showering PID, (C3) 85 MeV/c^2 < π^0 invariant mass < 185 MeV/c^2, (C4) 175 MeV/c < π^0 momentum < 250 MeV/c, (C5) 40 p.e.s < photo electrons emitted by π^+ < 100 p.e.s, (C6) one decay electron. The criteria (C1–C4) select desired π^0 and the criteria (C5–C6) are defined for produced π^+. Detection efficiency including the kaon branching ratio is 6.8% and expected number of backgrounds is 1.9%. Again, there is no candidate remaining after these criteria and partial lifetime limit is 6.9×10^{32} years at 90% CL. In summary, we cannot find any candidate events for $p \to \bar{\nu} K^+$ decay mode in three methods. Combined lifetime limit from the three methods is obtained as 1.9×10^{33} years at 90% CL.

3 Soudan 2

3.1 The Soudan 2 Detector

The Soudan 2 detector is a time projection, modular iron tracking calorimeter with a total mass of 974 tons and fiducial mass of 770 tons[9]. 1 m long drift tubes fill the spaces in the stacked steel sheets with 1.6 mm thick to detect ionization electrons of charged particles.

3.2 $p \to \bar{\nu} K^+$ search

One of advantages of the Soudan 2 detector is that K^+ track from the proton decay can be imaged. Proton decay searches via $p \to \bar{\nu} K^+$ mode have been performed using two K^+ decay channels 3.56 kt·year exposure data are used for the $p \to \bar{\nu} K^+$ searches[10].

Selection criteria for $K^+ \to \mu^+ \nu$ channel are: (D1) two charged tracks with common vertex (no proton), (D2) K^+ range < 50 cm, (D3) 28 cm < muon range < 58 cm, (D4) decay electron. Detection efficiency after all criteria is estimated as 9.0% and expected backgrounds is 0.4 events and one candidate event was found.

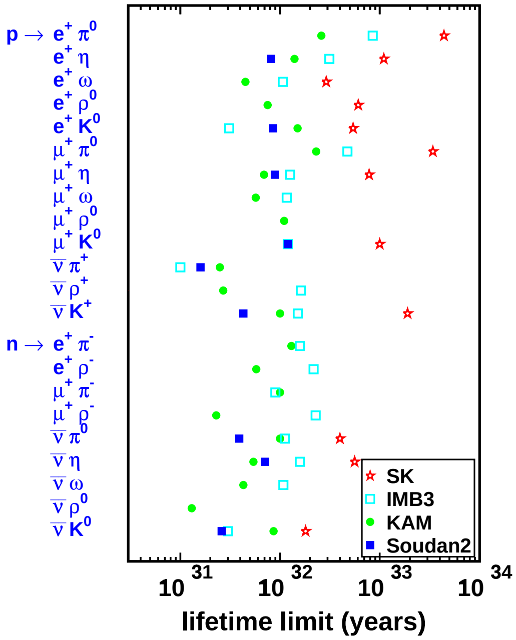

Figure 3. Obtained lifetime limits for various decay modes are summarized for Super–Kamiokande, IMB3, Kamiokande, and Soudan 2.

Moreover, selection criteria $K^+ \to \pi^+\pi^0$ channel are defined: (E1) two charged tracks and two showers, (E2) K^+ range < 50 cm, (E3) 100 MeV/c^2 $<$ invariant K^+ mass < 660 MeV/c^2, (E4) 80 MeV/c $< \pi^+$ momentum $<$ 400 MeV/c, (E5) 40 MeV/c $< \pi^0$ momentum $<$ 390 MeV/c, (F5) 10 MeV/c^2 $<$ invariant π^0 mass $<$ 290 MeV/c^2, Detection efficiency after all criteria is estimated as 5.5% and expected backgrounds is 1.1 events and no candidate event was found. From two methods, combined lower limit is obtained as 4.3×10^{31} years at 90% CL.

Summary

In this article, proton decay searches via decay modes of $p \to e^+\pi^0$ and $p \to \bar{\nu}K^+$ are presented. Figure 3 shows obtained lifetime limits for these decay modes and other various decay modes from Super–Kamiokande, IMB3, Kamiokande, and Soudan 2. In conclusion, there is no evidence for nucleon decays so far. We need to keep watching nucleons to open new physics beyond the standard model.

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