Study of 1 Megaton water Cherenkov detectors for the future proton decay search

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Abstract. The sensitivity of a possible future 1 Megaton water Cherenkov detector for proton decay searches was studied. For $p \to e^+\pi^0$ decay mode, the detection efficiency and the number of atmospheric neutrino backgrounds were estimated by using a detailed Monte Carlo simulation program. Moreover, their dependence on the number density of the photomultiplier tube (PMT) was investigated. With the PMT density of the Super-Kamiokande detector (2 PMT/m^2, 40% photocathode coverage), we will reach to 1.5×10^{35} years partial lifetime limit at 90% confidence level by 10 years livetime of the detector (10^4 kton·year exposure). With a 1/4 (1/9) PMT density, the sensitivity for $p \to e^+\pi^0$ mode is decreased to 1×10^{35} years (7×10^{34} years).

INTRODUCTION

Baryon number violated nucleon decay search could be the direct test of Grand Unified Theories (1). In the past two decades, several large underground detector experiments have looked for the signal but no clear evidence has been reported (2, 3, 4, 5, 6, 7, 8). In table 1, proton decay search detectors and their results are summarized. One of the detector types is a ring imaging Cherenkov detector with a target of water; Kamiokande, IMB, and Super-Kamiokande (SK), and another is a fine grained tracking calorimeter with a main target of iron; Fréjus and Soudan 2. One of important advantages of water Cherenkov detectors is that we can obtain the large target volume with reasonable cost. Moreover, there are free protons in water which decay products are free from imperfectly known nuclear effect and total momentum invalance caused by Fermi motion of protons.

To push up the proton decay search, we would need a much larger detector. Therefore, feasibility of a water Cherenkov detector with fiducial volume of 1 Megaton, which is about 50 times larger than that of the SK detector, was studied. Among various proton decay modes, sensitivity for $p \to e^+\pi^0$ mode was studied in detail. Moreover, sensitivity dependence on the PMT density was studied in order to evaluate the proper PMT density.

DETECTOR DESIGNS

As is shown in table 1, current lower limit on partial lifetime of protons via $p \to e^+\pi^0$ mode has been set as 3.3×10^{33} years by the SK detector and the detector will reach to 10^{34} years in 10 years livetime. It seems natural to require that the next generation detector should have sensitivity over 10^{35} years for the decay mode. According to the requirement, I assumed the fiducial mass of the next generation detector is 1 Mton.

Figure 1 shows some detector designs. “A la Super-K” is a cylindrical tank measuring 100 m in height and 120 m in diameter. “Cubes” and “Doughnut” (9) comprise of 20 sub-detectors. I assume that all surfaces of each sub-detector in “Cubes” and “Doughnut” are instrumented with PMTs. Therefore, the geometry of these sub-detectors is close to that of the SK detector. I utilized the SK simulation program to estimate the performance of the 1 Mton detectors, “Cubes” or “Doughnut”. However, due to much longer travel length of Cherenkov photons, results of my study presented here may not be applicable to ’a la Super-K’.

As is shown in figure 1, we need more than 300 thousands PMTs to obtain the same PMT density as the SK detector. Although these numbers may not be impossible, it is useful to consider the possibility to reduce them. I studied the following three detector configurations; detector-(A) which has same PMT density as the SK detector ($\sim 300,000$ PMTs/Mton in total), detector-(B) which has 1/4 PMT density of the SK detector ($\sim 80,000$ PMTs/Mton in total), and detector-(C) which has 1/9 PMT density of the SK detector ($\sim 35,000$

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Table 1. Proton decay search detectors. Water Cherenkov detectors (Kamiokande, IMB-3, and Super-Kamiokande) and iron tracking detectors (Fréjus and Soudan 2) are listed. Partial lifetime limits have been set at 90% confidence level.

detectors	fiducial mass [kt]	exposure [kt·yr]	limit on $p \to e^+\pi^0$ [10^{31}yrs]	limit on $p \to \bar{\nu}K^+$ [10^{31}yrs]
Kamiokande	1.04	3.76	26 (2)	10 (2)
IMB-3	3.3	7.6	54.0 (3)*	15.1 (3)
Super-Kamiokande	22.5	52.2	330 (4)†	
		33		67 (5)
Fréjus	0.6	1.58	7.0 (6)	
		1.3		1.5 (7)
Soudan 2	0.77	3.56		4.3 (8)

* 85.5 by combining with IMB-1

† updated from the paper

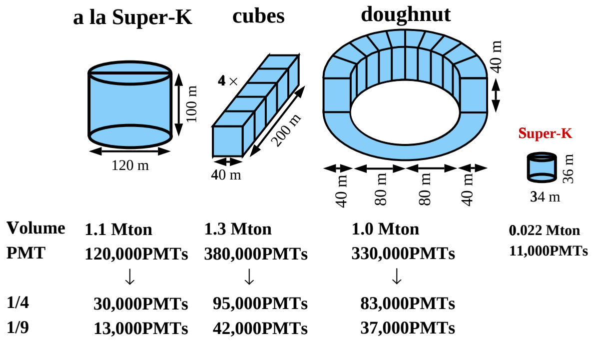

FIGURE 1. Some ideas for 1 Mton detector designs shown with the SK detector. Necessary PMT numbers are shown for each detector assuming the same PMT density with the SK detector. Below arrows, the number of PMTs are shown in case of reducing the PMT density by a factor of 4 or 9.

PMTs/Mton in total). All Monte Carlo parameters were exactly same as those of the SK detector simulation program except the PMT density. Water transparency was set at about 100 m at wavelength of 420 nm and same to the three detectors.

SENSITIVITY STUDY

Detection Efficiency for $p \to e^+\pi^0$

Figure 2 shows event displays of a $p \to e^+\pi^0$ Monte Carlo event for detector-(A), (B), and (C). Three showering rings caused by a positron (lower left) and two γ (upper right) from the decay of π^0 are seen in each detector. Although Cherenkov rings become faint in detector-(B) and (C) due to the low PMT density, it seems possible to identify these rings.

Table 2. Proton decay selection criteria. Criteria with circles are applied in each detector.

detector PMT density	(A)* 1/1	(B) 1/4	(C) 1/9
Number of rings (2 or 3 rings)	○	○	○
Particle ID (all showering)	○	—	—
π^0 invariant mass (85 – 185 MeV/c^2)	○	—	—
No muon decays	○	○	○
Total invariant mass & total momentum ($800 < M < 1050$ MeV/c^2, $P < 250$ MeV/c)	○	○	○†

* Super-Kamiokande

† Total invariant mass cut is loosened as $750 < M < 1050$ MeV/c^2

Reconstruction of an event such as vertex position, Cherenkov rings, particle type, momentum, and the number of muon decays was automatically performed (see reference-(4) for details). Using these measured quantities, proton decay criteria were defined to reject atmospheric neutrino backgrounds but accept signal. Table 2 shows the criteria for each detector. By the number of ring criterion, one positron ring and one or two of γ rings were required. Particle ID criterion selected $e^\pm$ and γ. Although I did not require this criterion in detector-(B) and (C), one would improve the S/N ratio by using a tuned program to identify a particle type. For 3-ring events, at least one pair of rings must give π^0 invariant mass. This criterion was not required for detector-(B) and (C) because there was no clear π^0 mass peak in these detector. Finally, it was checked that the total invariant mass and total momentum correspond to the mass and momentum of the source proton, respectively.

Figure 3 shows the total invariant mass and total momentum distributions of $p \to e^+\pi^0$ events for the detector-(A), (B), and (C). Boxes are the selection cri-

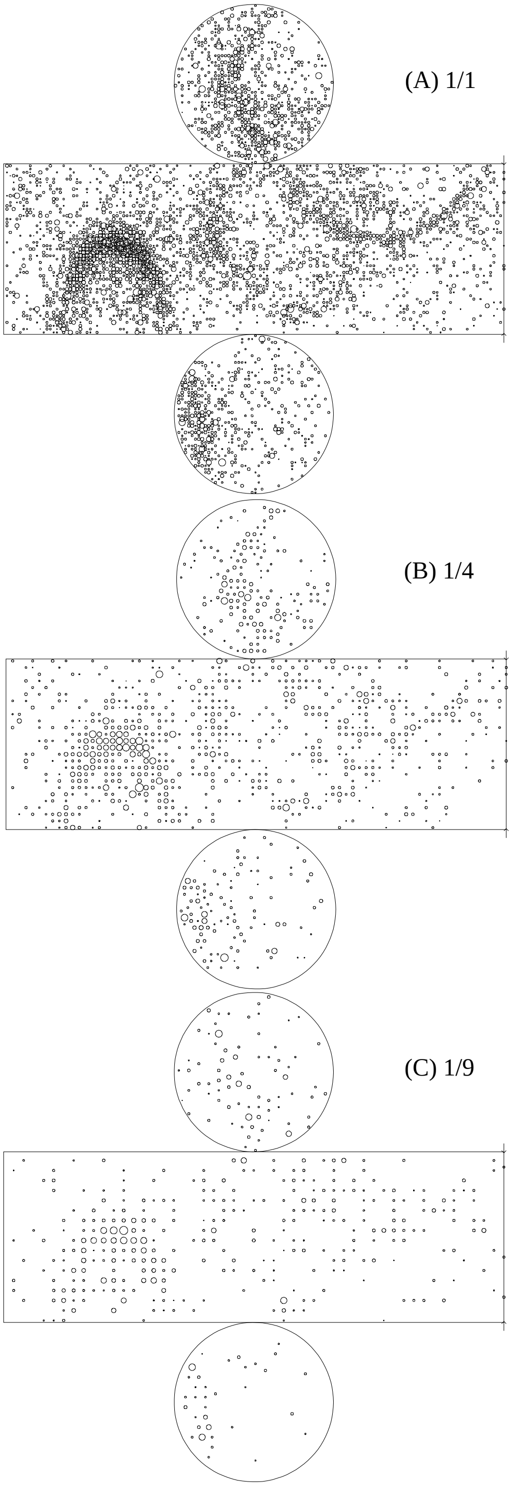

FIGURE 2. Event displays of a $p \to e^+\pi^0$ Monte Carlo event for detector-(A) with SK PMT density, (B) with 1/4 PMT density, and (C) with 1/9. Small circles indicate hit PMTs with the size proportional to detected photoelectrons. Positron ring (lower left) and two γ rings (upper right) from the decay of π^0 are seen in each detector.

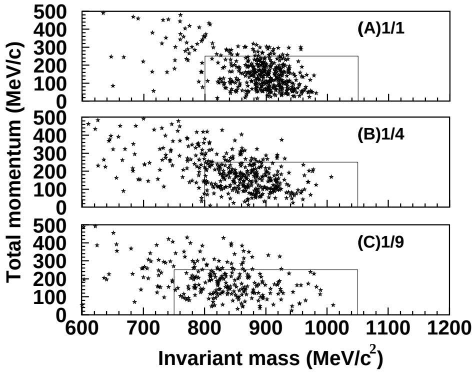

FIGURE 3. The total invariant mass and total momentum distributions for $p \to e^+\pi^0$ events in three detectors after the muon decay criterion (Table 2). The boxed region in each figure shows the selection criterion for the $p \to e^+\pi^0$ signal.

terion against the total mass and momentum. From the sample, detection efficiency in each detector was estimated as (A) 43%, (B) 32%, and (C) 21%. Dominant contribution of the inefficiency in detector-(A) comes from the π^0 interaction in the ^{16}O nucleus; absorption, charge exchange, and scattering. In case of free protons which are free from the nuclear effect, detection efficiency was about 90% for the detector-(A). The difference of the efficiency between (A), (B), and (C) came mainly from the different performance of the ring identification. The fraction of events which were reconstructed as 2 or 3-ring events was 73% for (A) whereas 57% and 36% for (B) and (C), respectively.

Atmospheric Neutrino Backgrounds

To estimate the number of background events, atmospheric neutrino Monte Carlo events were used. Here, due to limited CPUs for the reconstruction, I discarded all elastic scattering events ($\nu N \to \nu N, \nu N \to l^\pm N'$). And ν_μ charged current (CC) events ($\nu_\mu N \to \mu^\pm X$) were also neglected because most of them will be rejected by the muon decay cut. When particle ID program becomes ready, particle type information will be also usuful to reject them. I further reduced the Monte Carlo events by restricting the neutrino energy as $0.7 < E_\nu < 4$ GeV. Used Monte Carlo sample corresponded to 6.8 Mton·year exposure equivalent.

I applied the proton decay selection criteria to the background sample. Figure 4 shows the total invariant mass and total momentum distributions of the atmospheric neutrino events for the detector-(A), (B), and (C). The background level was same for these three detectors

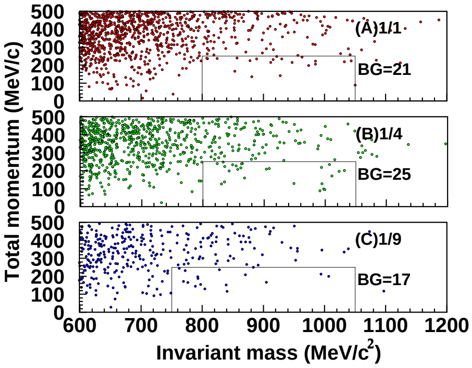

FIGURE 4. The total invariant mass and total momentum distributions for atmospheric neutrino Monte Carlo events after the muon decay criterion (Table 2). The boxed region in each figure shows the selection criterion for the $p \to e^+\pi^0$ signal.

within the statistical error. The number of background events was about 21/6.8 Mton·year $\simeq$ 3 Mton·year^{-1}.

Sensitivity for Proton Lifetime

From the estimated detection efficiencies and the number of background events, expected sensitivity for the partial lifetime of proton was calculated in Figure 5. The sensitivity was culclated at 90% confidence level assuming simple Poisson processes with backgrounds (10). With 10 years livetime (10^4 kton·year exposure), we would reach to 1.5×10^{35} years (1×10^{35} years) partial lifetime by the detector-(A) (detector-(B)). By the detector-(C), we would need 20 years livetime to reach to 1×10^{35} years.

DISCUSSIONS AND CONCLUSIONS

I have reported the sensitivity of 1 Mton water Cherenkov detector for $p \to e^+\pi^0$ mode. With the same PMT density as the SK detector, the detection efficiency is 43% and the background level is 3 Mton·year^{-1}. The efficiency becomes 32% (21%) in case of 1/4 (1/9) PMT density while background level doesn't changed much. If we require the sensitivity of 10^{35} years lifetime, we could reduce the PMT density by a factor of 4 and probably up to 9. For a more precise results, I need optimized reconstruction program for each PMT density. Especially, optimization of the Cherenkov ring identification algorithm will improve the detection efficiency of the signal.

Finally, it should be noted that the proton decay search will be no longer background free and it will be crucial to precisely understand the tail of the atmospheric neutrino interactions and the detector responce.

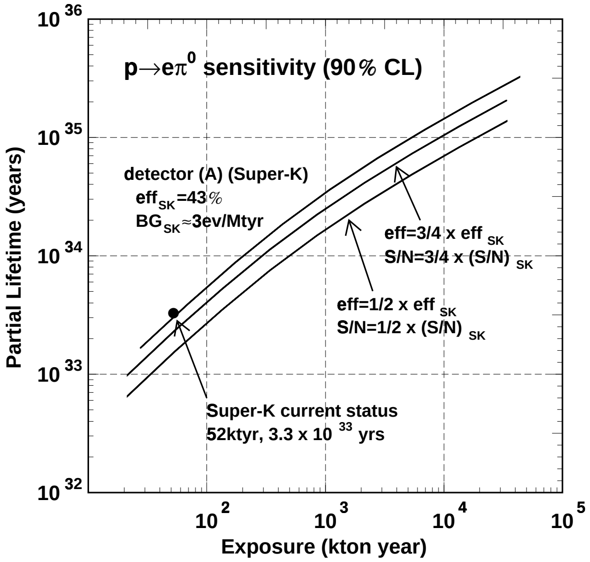

FIGURE 5. Expected sensitivity for the partial lifetime of protons. The sensitivity was calculated at 90% confidence level for the detector-(A) (upper line), detector-(B) (middle line), and detector-(C) (lower line).

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