First Step Towards A New Proton Decay Experiment In Ice

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DOI: 10.7529/ICRC2011/V05/0325

Abstract: Grand Unified Theories (GUTs) predict a finite lifetime for the proton. The most recent limit, reported by Super-Kamiokande for a 172.8 kTon×year exposure, on the proton decay partial lifetime ($p \rightarrow \pi^0 + e^+$) corresponds to 1.01×10^{34} years. In the supersymmetric extensions of SU(5), the lifetime of the proton is expected to be lower than 10^{36} years. To reach 10^{36} years sensitivity to proton decay requires a detector with a volume on the megaton scale sensitive to sub-GeV energy. Where and how such a detector might ever be realized remains an open challenge. Installation of massive detectors underground is presently a technological challenge with costly excavation, engineering and installation. We consider here the ice cap at the South Pole which might provide an alternative scenario for a megaton ring imaging Cherenkov experiment in the search for proton decay. The ice, studied by the IceCube Collaboration, is measured to be extremely pure and transparent. Further, IceCube has demonstrated the ability to instrument a detector volume at the gigaton scale on-schedule and on-budget. The 86 strings of IceCube photosensors provide sensitivity to particle interactions with energies between tens of GeV up to extremely high energies. Given the success of the IceCube project in instrumenting the world's largest Cherenkov neutrino detector, and the DeepCore sub-array to extend the reach to low-GeV physics, it seems reasonable to consider the question if the same principle of IceCube, using the Cherenkov medium as the detector support infrastructure, could provide a cost effective and simplified path to instrument megaton scale detectors with sufficient photocathode area to permit a viable proton decay experiment sensitive to 10^{36} year lifetime and beyond. In this paper we present the very first steps of a developing design study for a proton decay detector to be potentially deployed in the center of IceCube-DeepCore, based on Geant4 and the IceCube software with realistic optical properties of the glacial ice.

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Keywords: proton decay; South Pole; IceCube; simulation; GEANT4; GENIE; GPGPU photon tracking

1 The Search for Proton Decay

In Grand Unified Theories (GUTs), introduced by H. Georgi and S.L. Glashow in 1974 [1], baryon number violating processes, like proton decay, are allowed. A favored predicted proton decay channel, by the minimal SU(5) gauge symmetry, is the decay into a neutral pion and a positron, where the neutral pion subsequently decays into two gammas. If the proton decays inside a volume of ultra-pure and transparent water (or ice), the decay products may be detected by observing the induced Cherenkov light cones, see Figure 1. Such a detection strategy is used by the Super-Kamiokande water Cherenkov experiment. The most recent limit on the proton lifetime decaying into the "golden" channel, $p \rightarrow \pi^0 + e^+$, by the Super-Kamiokande Collaboration corresponds to 1.01×10^{34} years [2]. This result, based on 12 years of data taken between 1996 and 2008, already constrains part of the supersymmetry parameter space allowed by SU(5) supersymmetric extension. In this paper we report first steps towards a new idea for a proton decay experiment at the few megaton scale. The detector material we investigate here is the deep Antarctic glacial ice at the South Pole to be potentially instrumented with novel optical modules deployed inside the existing IceCube-DeepCore fiducial volume. The deployment strategy we consider is the one used by IceCube, namely strings of photo-sensors in holes drilled with hot water.

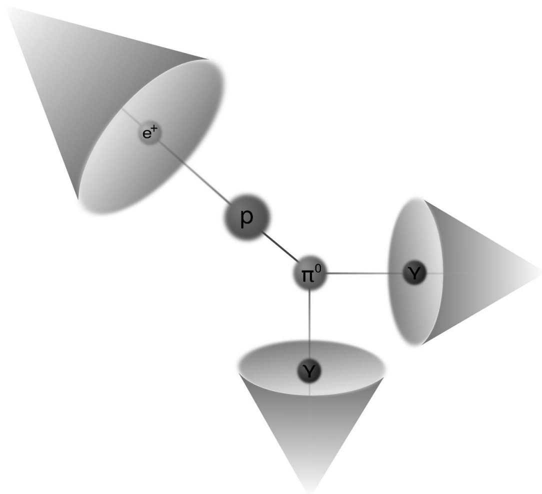

Figure 1: Artist's view of a proton decaying into a π^0 ($\gamma\gamma$) and a e^+. Shown in the figure are the Cherenkov cones that result from interactions involving the final states of the decay products.

2 The IceCube Neutrino Observatory

IceCube is the world's largest neutrino detector. It is situated close to the geographic South Pole at the Amundsen-Scott South Pole Station. With an instrumented volume of roughly one gigaton, it is the most sensitive neutrino detector in a wide energy range, from tens of GeV up to the EeV scale. The detector operates on the principle of measuring the Cherenkov radiation emitted by charged particles, which have been produced in neutrino interactions. The measurements are taken with optical sensors (Digital Optical Modules, DOMs) deployed at depths between 1450 m and 2450 m, positioned along cables, called strings. IceCube consists of 86 such strings in a configuration of 78 laid out in a hexagonal grid with an inter-string spacing of 125 m and 8 DeepCore strings located at the center of the grid with an inter-string spacing of 40 m to 72 m. Each string of the standard IceCube configuration is equipped with 60 DOMs with a uniform DOM spacing of 17 m, covering a volume of ≈ 1 km^3. The DeepCore strings are equipped with 60 DOMs with high quantum efficiency PMTs and with a denser spacing of 10 m in the upper part (1,750 m - 1,850 m) and 7 m below 2,100 m. With the dense instrumentation in the deepest, clearest ice and use of the high quantum efficiency PMTs, DeepCore aims to achieve trigger threshold for muon neutrinos of $\approx$ 10 GeV [3].

2.1 The South Pole Ice as Detector Material

The optical properties of the deep ice at the South Pole are excellent with a measured scattering length in the range 40-70 m and a maximum absorption length of about 200 m measured at 400 nm (see [4] and Figure 8 in [5]). The clearest ice is found at depths below $\approx$ 2,100 m [5]. We note that the wavelength dependence for scattering and absorption length are incorporated in the simulation reported here just as they are in the IceCube general simulation chain. The site is characterized by exceptional operational conditions, including high radiopurity and low stable temperature. In this environment the IceCube optical modules operate with very low noise, providing an average dark noise rate of 400 Hz [6] and a somewhat higher rate in the DeepCore higher quantum efficiency modules.

The installation of additional future detector components could follow the well established deployment methods used for IceCube strings, exploiting the ice cap as both Cherenkov medium and support infrastructure for the detector elements. IceCube has already successfully demonstrated the ability to instrument a gigaton-scale volume water Cherenkov detector within prescribed schedule and budget constraints. If the concept of Cherenkov ring reconstruction in the ice proves feasible, the underground physics community would have an attractive alternative to the daunting technological challenge of preparing few MT-scale deep caverns for next generation experiments.

The proposed location for a new detector, at the center of the IceCube-DeepCore ice bound arrays, would benefit from an active veto against muons induced by cosmic rays. DeepCore has already demonstrated the usability of IceCube as an efficient muon veto: as reported in more detail in [8], a muon background rejection of about $8 \cdot 10^{-3}$ [7] for the overall IceCube trigger ($\sim$ 2700 Hz) is achieved with an on-line filter algorithm. Novel muon reconstruction methods, currently under investigation, are expected to provide an overall muon rejection efficiency of the order 10^{-6} [9]. Further, the inclusion of the DeepCore array in such a veto scheme is expected to enhance the efficiency for future low-energy detector installed in the ice. Although cosmic muons, and the spallation products they produce, are likely not the crucial background for the $p \rightarrow \pi^0 + e^+$ channel (as shown by Super-Kamiokande we expect the main background to be atmospheric neutrino interactions [10]) the veto does provide valuable information to identify activity in the detector with an expected minimal impact on detector deadtime.

3 Proton Decay Simulation

A first challenge, discussed here, concerns establishing a robust Monte Carlo simulation which can provide the necessary information to initiate a full design feasibility study. Dedicated software for the simulation of proton decay events has been developed that combines Geant4 [11], [12] with a custom GPU-enabled simulation algorithm for photon propagation based on the IceCube software called Icetray [13]. Geant4 is used to simulate the particle cascade starting from the decay products of the proton, e.g. π^0 and e$^+$. Integrating already existing or new Geant4 simulation code into Icetray, and to additionally add parallel processing support to Geant4, required development of a suite of tools. This suite includes a photon propagation algorithm that takes into account the optical properties of the deep glacial ice at the South Pole. Scattering and absorption are modeled using horizontal ice layers with properties derived from measurements taken by IceCube [4]. Photon propagation is one of the most computationally intensive tasks during event simulation and thus its optimization is highly desirable. Since all photons are independent and may be treated in exactly the same way, the algorithm lends itself for implementation on dedicated parallel multiprocessors, e.g. Graphics Processing Units (GPUs). One such implementation, using OpenCL [14], was developed specifically for this task. Cherenkov photon-emitting particle steps from Geant4 are collected and provided in bunches to the GPU where, in turn, photons are generated according to the Cherenkov spectrum. The photons are propagated through the detector medium until either absorbed or incident on an optical module. In the latter case, all photon properties are stored for post-processing. After propagation, information on the incident photons is transferred to the host PC and used to generate hits. Decoupling hit generation from photon propagation permits different optical module design choices to be easily evaluated. We note that, while not the focus of this particular paper, the simulations for the critical atmospheric neutrino background events will use the GENIE software package [15] which is currently being incorporated into the IceCube simulation chain.

A first study is now underway with an idealized strawman detector, see Figure 2. The goal of such a geometry is to make it straightforward to optimize the detector geometry for proton decay. The idealized detector consists of a cylindrical arrangement of 235 strings where each string on a ring has a distance of ≈ 5 m to its neighboring strings on the same ring and the neighboring rings have a distance of 15 m to each other. We note that the 5 m distance of closest approach for the strings assumes no further improvement in the IceCube method of drilling. In the strawman design each string has 400 optical modules, spaced evenly over 400 m. The simulation has the ability to consider a variety of optical sensor technologies; from the standard IceCube digital optical modules, of which more than 5000 are currently successfully operating deep in the ice, to new multi-PMT modules [16] that have the potential to significantly increase the photocathode coverage.

4 Beyond IceCube

The goal to achieve a sub-GeV energy threshold inside the Antarctic ice requires a very densely instrumented detector compared to IceCube-DeepCore. First steps towards a better understanding of the feasibility of such sub-GeV detector is now underway. Interest in such a detector includes many members of IceCube and groups from the broader community. An informal collaboration named PINGU, for "Phased IceCube Next Generation Upgrade," has been formed in order to provide a framework for the

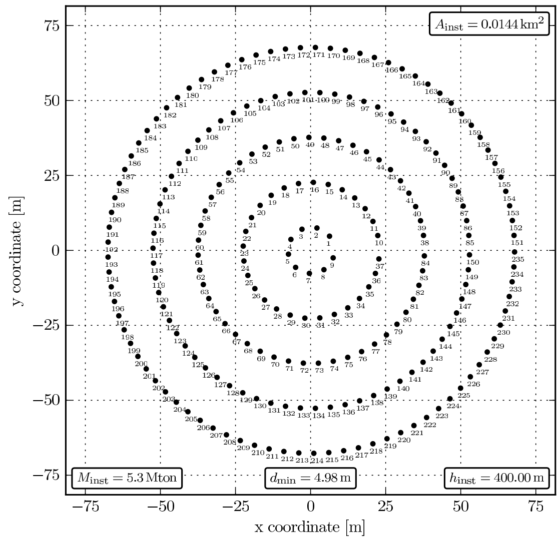

Figure 2: The geometry of the idealized proton decay detector used for this simulation study here reported.

design and R&D studies connected to future opportunities for astroparticle physics at the South Pole. A first informal PINGU workshop took place in Amsterdam in March 2011 (http://www.nikhef.nl/pub/conferences/icecube/pingu/).

The simulation tools we have introduced in this paper provide an effective starting point for determining the feasibility of an ice bound proton decay detector. As part of the ongoing study, different geometries of strings and photon sensors are considered. Particular attention at the current stage is paid to the effective photon coverage of the designs, which includes the photocathode coverage and quantum efficiency for the sensors as well as a comprehensive study of the background induced by atmospheric neutrinos. An ambitious goal has been set to test the feasibility for designing a 5 MT ice ring-imaging Cherenkov detector (1.6×10^{36} protons). The strategy aims to be competitive in terms of budget, in particular considering infrastructure costs, instrumented volume and time-line with respect to other existing design studies like for example [18, 19, 20]. The Super-Kamiokande detector collects approximately 7 p.e. per MeV deposited for a wavelength range of 350 nm to 500 nm [17] in order to reconstruct neutrinos of solar origin to energies below 5 MeV. The detector contemplated here would need to achieve a photon collection efficiency sufficient to image rings at the higher energies relevant for proton decay. In doing so, and assuming the dominant atmospheric neutrino background levels are the same, one arrives at a potential scenario for $\sqrt{N_{bkgd}}$ improvement in sensitivity for the increased fiducial volume.

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