Proposal for a very large water Cherenkov detector

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Abstract

We propose that a very large water Cherenkov detector with mass in the range of ~ 1000 kton be built at the National Science Foundation's Deep Underground Science and Engineering Laboratory (DUSEL) and that Fermi National Accelerator Laboratory take the lead in the design and construction of this detector facility. Such a detector facility will be a landmark scientific endeavor. It has the dynamic range in energy, and background reduction capability needed for a broad attack on the physics of nucleon decay, neutrino oscillations, and supernova neutrinos, three areas of profound scientific interest highlighted in recent National Academy, HEPAP, and APS Reports. Recent Homestake Collaboration preliminary engineering studies have shown that there are no technical obstacles to building this detector at depths as great ~ 6000 feet. An international collaboration with deep expertise can be assembled to build this detector in a relatively short period. This project is of the correct scale, scientific importance, and timing to be a major focus of the US High Energy Physics Program before the International Linear Collider and fulfills the requirement of investment in a facilities that maximizes the discovery potential during the next two decades.

Introduction

We propose that a very large water Cherenkov detector with mass in the range of 1000 kton be built at DUSEL and that Fermi National Accelerator Laboratory take the lead in the design and construction of this detector facility.

Such a detector facility will be a landmark scientific endeavor. It has the dynamic range in energy, and background reduction capability needed for a broad attack on the physics of nucleon decay, neutrino oscillations when coupled to a long baseline accelerator neutrino beam, and supernova neutrinos, three areas of profound scientific interest. A facility with this ability fits the requirement put forth by the Under Secretary for Science, Dr. Raymond Orbach, as "the right investment choice to ensure the vitality and continuity of the field during the next two to three decades and to maximize the potential for major discovery during that period"[1].

Fortunately, there is a triple convergence that makes such a project unique and exciting in the US. The first is the imminent decision from the National Science Foundation to select a location for a Deep Underground Science and Engineering Laboratory. One of the major criteria for this decision is the ability of the candidate sites to host such a detector. The second is the depth accessible ($\sim$ 5000 ft) in the US at any of the candidate sites for the large excavation needed for the detector. And the third are the neutrino oscillation parameters[2] that make the optimum distance for the long baseline experiment $\sim$ 1500km.

The physics

A number of recent efforts have examined the physics, the technology, and the feasibility of the detector. The most recent is the US Long Baseline Neutrino Experiment Study[3], which was carried out in response to a charge from FNAL and BNL to examine the potential for an accelerator neutrino experiment with a very large detector coupled to a conventional beam. The main finding of this report is that the key to the physics of neutrino CP violation is a truly capable very large detector. This conclusion is independent of the unknown neutrino parameter, θ_{13}, the spectrum of the beam, or the baseline, which must be adequate to see oscillations of $\nu_\mu \to \nu_e$ above background. It furthermore shows that a neutrino beam from the 120 GeV upgraded Main Injector gives the best sensitivity to CP violation as well as resolution of the neutrino mass ordering in a detector $\sim 1500km$ away. The parameter sensitivity is ultimately limited by the purity of the beam down to $\theta_{13} > 2^o$. Although CP violation is the main goal for such a detector, the same detector will also see very large multiple oscillatory structure in the channel of $\nu_\mu to \nu_\tau$ conversion. A single facility therefore can yield precise measurements of all neutrino oscillation parameters.

A well instrumented very large detector, in addition to its accelerator based neutrino program, will be extremely sensitive to proton decay, one of the top priorities in fundamental science. Provided that this detector is located underground and well shielded from cosmic rays, it will extend the limits on proton decay into modes such as $p \to e^+\pi^0$ to 10^{35}yr sensitivity or beyond, a level suggested by gauge boson mediated proton decay in super-symmetric GUTs. Indeed, there is such a natural marriage between the requirements to discover leptonic CP violation and observe proton decay that it is hard to imagine undertaking either effort without being able to do the other. In Table I we list the physics capability of the proposed detector facility and in Table II the detector parameters are listed.

Construction

The detector can be housed in any of the NSF candidate sites. Detailed geo-technical and engineering studies can commence shortly after the DUSEL site is selected. One site (Homestake) has secured external funding from state and philanthropic sources that may be used to assist with these studies and preparing the site. Initial studies performed by the Homestake Collaboration and consulting mining engineers indicate that excavation of the required cavities can be completed in $\sim$ 5 years. Site specific geotechnical studies are now required to advance these preliminary estimates. Several of the sites, including Homestake, have extensive excavation experience at these depths ($\sim$5000 ft) and have preliminary tunneling and rock mass ratings appropriate for these excavations.

Other than considerations for underground cavity construction, water Cherenkov detector technology is mature and requires no fundamental R&D to develop the construction plan for the physics program of nucleon decay and neutrino physics. Although cavity construction is an important element, the cost of the detector will be dominated by the well known costs of photo-multiplier tubes. Large contingency factors on cavity construction will have small effect on the overall cost of the detector.

Conclusion

The detector we have proposed in this letter will be a key facility for fundamental science for many decades. There are no technical obstacles to building it. An international collaboration with deep expertise can be assembled to build this detector in a relatively short period. And lastly, this project is of the correct scale for the US program before the International Linear Collider and one that will maintain a US leadership role in High Energy Physics and provide the vehicle needed to build and train the generation of physicists in the coming decades.

Neutrino Physics		3 σ reach
	θ_{13}	$\sin^2 2\theta_{13} > 0.005$
	Mass Hierarchy	$\sin^2 2\theta_{13} > 0.008$
	CP violation	$\sin^2 2\theta_{13} > 0.01$
Nucleon Decay		90% C.L. lifetime limit
	$p \to e^+\pi^0$	10^{35} yrs
	$p \to K^+\bar{\nu}$	2×10^{34} yrs
Neutrino Astrophysics		Numbers of events
	Galactic Supernova $E_\nu > 5$ MeV	100000 in 10 sec
	Relic Supernova $E_\nu > 19MeV$	50 per year
	Solar Neutrinos $E_\nu > 5MeV$	120000 per year
	Atmospheric Neutrinos	15000 per year

TABLE I: The physics of a very large water Cherenkov detector. For long baseline the sensitivity is given as the value of $\sin^2 2\theta_{13}$ at which 50% of δ_{cp} values will have $\geq 3\sigma$ reach for the choice of mass hierarchy with worst sensitivity. For details on beam intensity and backgrounds see [3]. For nucleon decay limits we have assumed a 10 year run for a 500 kt fiducial volume [4]. The neutrino rate from relic supernova is based on [5]; the background is estimated to be $\sim$ 100 evts per year, but it could be suppressed using new techniques[6]. Solar and atmospheric neutrino rates include the effects of oscillations[2].

[1] Remarks to the High Energy Physics Advisory Panel, Under Secretary for Science, Raymond Orbach, Feb 22-23, 2007.

[2] PDG, Review of Particle Physics, Journal of Physics G, Vol. 33, July 2006.

[3] The study report, all associated documents, presentations, plots, studies, spectra, are at http://nwg.phy.bnl.gov/fnal-bnl, Fermilab-0801-AD-E, BNL-77973-2007-IR, arxiv:0705.4396.

Detector Performance		
	Mass	500-1000 kTon
	Energy Threshold	$\sim$ 5 MeV
	Event time resolution	$\sim$ 1 ns
	Cosmic muons rate	$\sim$ 0.2 Hz (at 5000 ft)
	Burst capability	1-10 kHz
	Acc. neutrino backg.	New methods[3]
Detector Parameters		
	Number of Cavities	1-3
	Cavity Span	$>$ 50 m
	Depth	$\sim$ 5000 ft
	PMT size	10-20 inch
	PMT coverage	$>$ 25 %
	PMT time res	1-3 ns
	PMT Channels	50-200 k
	Construction	6-10 yrs
	Cost	$\sim$\$400M

TABLE II: Detector performance characteristics and specifications.

[4] M. Shiozawa, Joint BNL/UCLA-APS workshop, March 2004, Brookhaven National Laboratory. http://www.bnl.gov/physics/superbeam

[5] S. Ando, Astrophys J. **607**, 20 (2004), Also see S. Ando, talk at NNN05, April 7th 2005. http://nnn05.in2p3.fr/trans/ando.pdf

[6] John F. Beacom, Mark R. Vagins, Phys. Rev. Lett. **93**:171101, 2004