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R&D towards large-liquid scintillator detectors and measurement of neutrino mass hierarchy with reactor antineutrinos at ~60km

Large liquid scintillator detectors have been proposed for a variety of particle physics topics ranging from determination of neutrino mass hierarchy with reactor antineutrinos to study of proton decay, astrophysical and geological neutrinos. The hierarchy of neutrino mass states is incompletely known and may hold the key to understanding the nature of neutrinos and their masses in the new Standard Model. We do not know which neutrino state is lightest or its absolute mass. Measurement of mass hierarchy is key to understanding mass-generation mechanisms and the pattern of neutrino mixing and will provide important input for interpretation of next-generation neutrinoless double beta decay experiments. Measurement of the mass hierarchy is important input to the search for leptonic CP violation. An unambiguous determination of the mass hierarchy provides important understanding of the fundamental nature of neutrinos with profound impact in the next decade and beyond.

Measurement of mass hierarchy through reactor antineutrino disappearance is possible in a precision oscillation experiment over ~60km baselines. An exposure of ~4000kton-GW_{th}-years with energy resolution of $< 3\%/\sqrt{E}$ and energy response understood at the sub-percent level are required to reach a $\Delta\chi^2=16$ measurement of mass hierarchy. This reactor measurement is complementary to accelerator appearance measurements; it is independent of the CP violating phase and matter effects and has substantially different systematic uncertainties. Measurements from both reactor and accelerator experiments will probe our understanding of the three generation neutrino model, provide confidence in the determination of mass hierarchy and potentially probe the CP violating phase. Such an experiment would also make precision measurements of θ_{12}, Δm^2_{21} and Δm^2_{32} and would potentially be sensitive to additional physics such as geoneutrinos, solar neutrinos, atmospheric neutrinos and proton decay.

Two experiments are currently proposed to make this measurement: Daya Bay II in China and RENO-50 in South Korea, although other locations may be suitable. The current design of RENO-50 includes a 5kton liquid scintillator detector ~50km from a ~17GW_{th} power plant. Daya Bay II proposes a 20kton liquid scintillator detector ~700m underground and ~60km from two nuclear power plants with ~40GW_{th} power. The Institute of High Energy Physics has secured funding from the Chinese Academy of Science and is moving forward rapidly to complete a Conceptual Design in late 2013 and, with a ~5 year construction, start operations in 2020 as shown in Fig. 1.

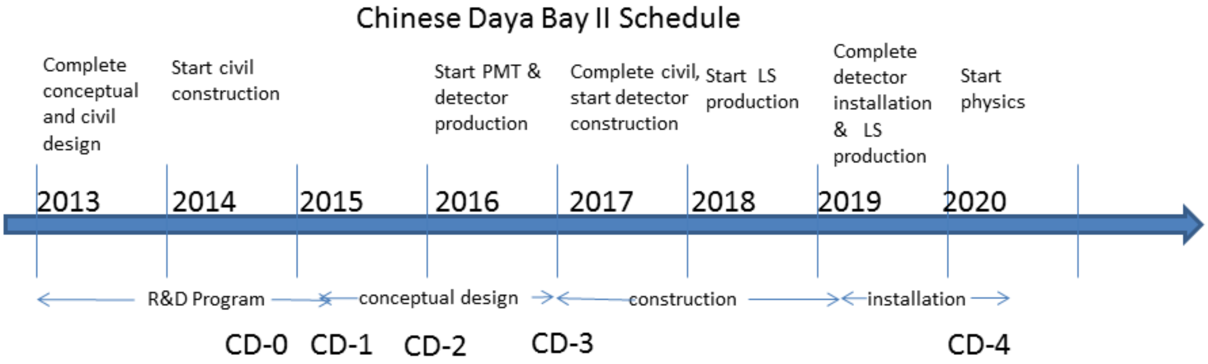

Figure 1: Daya Bay II schedule as context for a timely U.S. R&D effort.

The technical challenges of achieving $< 3\%/\sqrt{E}$ energy resolution and a nonlinearity measured to a fraction of 1% over the detector volume are daunting. We propose extensive R&D on the key components of such an experiment to establish feasibility of the required energy response. Successful conclusion of this R&D would enable a reasoned U.S. decision as to whether to proceed with an experiment. The institutions proposing this R&D plan have a wealth of experience in neutrino physics and reactor neutrino physics in particular. The current effort includes groups at BNL, UCB/LBNL, Cincinnati, Hawaii, Hawaii Pacific, Houston, IIT, Illinois, Princeton, RPI, Washington, William & Mary and Wisconsin that have been involved in the recent discoveries in neutrino physics and have made critical contributions to the Daya Bay, Super-K, GALLEX, KamLAND, LBNE, MINOS, MicroBooNE, SNO+ and SNO experiments. The groups involved in this effort are well placed to pursue the proposed R&D in a way that capitalizes on each group's strengths. This R&D is of significant value to the U.S. Intensity Frontier program in addition to its generally useful detector development. The aggressive Chinese Daya Bay II schedule establishes a benchmark for U.S. competitiveness in an international context. The timeliness of a measurement will be important not only for its scientific impact but also for planning the future direction of neutrino physics.

Table 1 summarizes the funding request for the R&D tasks described in this proposal. Individual tasks and budgets are discussed in the following sections.

Table 1: Budget Request Summary Table (all amounts are in FY13 $K)

R&D Tasks	**FY 2013**	**FY 2014**	**FY 2015**	**Total**
Liquid Scintillator	205	560	590	1,355
PMTs	230	365	365	960
Calibration	270	420	395	1,085
Electronics	155	340	340	835
Simulations	35	355	330	720
Project Development	105	260	260	630
TOTAL	**1,000**	**2,300**	**2,280**	**5,585**

I. Research & Development Plan

This R&D plan outlines a vigorous program to establish the viability of a ~60km reactor neutrino disappearance measurement of the mass hierarchy with a large liquid scintillator detector. We plan detailed simulations to optimize detector designs. We plan research to develop stable liquid scintillator with high light output and long attenuation length, improved light detection efficiency, high precision energy calibration and highly linear electronics with large dynamic range. This R&D will address and resolve critical scientific and technical issues and associated risks. This effort will require ~2 years, leading to a possible determination of Mission Need (CD-0) in ~FY 2015.

I.1: Liquid Scintillator R&D (BNL, Hawaii Pacific U., U. Hawaii, U. Washington)

Multi-kiloton scintillation detectors for high-precision reactor antineutrino oscillation experiments must satisfy a number of stringent scintillator requirements: chemical stability for the life of the experiment, high scintillation light output and long attenuation length. Various organic liquid scintillators (LS), such as linear alkyl benzene (LAB), 1,2,4-trimethylbenzene (or pseudocumene, PC), phenylxylylethane (PXE) and phenylcyclohexane (PCH), each typically in combination with a fluor (e.g. PPO) and a wavelength shifter (e.g. bis-MSB), have been used in reactor experiments because they produce large numbers of photons for low energy reactor antineutrino interactions (few MeV) detected via the inverse beta-decay reaction. The antineutrino signal is a coincidence between a prompt positron and the delayed capture of a neutron on a free proton in an (n,γ) reaction after thermalization in the LS. This delayed coincidence tag of the 2.2MeV neutron capture gamma in a ~200-μs window after the positron serves as a powerful tool to reduce random background.

The key liquid scintillator requirements are:

a) High intrinsic light-yield: ≥15,000 scintillation photons per MeV
b) Superior optical attenuation length of 30m or better.

The latter is particularly crucial for a multi-kton scale detector. Daya Bay uses LAB doped with 3g/L PPO and 15mg/L bis-MSB that emits ~10,000 scintillation photons per MeV and has an attenuation length of ~18m at the emission wavelength of 430nm. This scintillator gives ~220 p.e./MeV (at ~12% photo-coverage); an energy resolution of 7.5%/√E. KamLAND's scintillator contains 20% pseudocumene in 80% normal-dodecane (nD) doped with 1.52g/liter PPO without a wavelength shifter. Overall KamLAND got 250 p.e. (34% photo-coverage) per MeV with 6%/√E energy resolution. None of the known scintillator combinations achieve the requirements for a long-baseline experiment. Extensive R&D activities are needed to optimize liquid scintillator performance and assess its feasibility for such an experiment.

The proposed R&D tasks are:

1. Purification of the scintillator, fluor, wavelength shifter mixture. We will control scintillator impurities (e.g. non-radioactive chemical species that adversely affect optical properties) and develop methods to remove and assay residual radioactive contaminants, mainly from the naturally occurring ^{238}U and ^{232}Th decay chains. Characteristically, liquid scintillator purchased from industry has an attenuation length of ~10m with most impurities introduced during the production process. The best optical attenuation length achieved for a liquid scintillator is L_{attn}~20m at 430nm (LAB, after extensive purification). Several technologies, such as vacuum distillation (SNO+, KamLAND, Borexino) or column extraction (industrial, petrochemical) can improve optical transmission. A combination of extraction column during the distillation phase might further improve the transparency. Another approach is the use of high-purity starting materials (e.g. nD instead of mineral oil for LAB) as the feedstock for scintillator production such that cleaner liquid can be obtained. Other means of purification by

separation resin or solvent washing will be tested. For instance, PPO (known to be a dirty material) can be cleaned by water-washing, recrystallization or solvent-distillation.

2. Search for a new cost-effective scintillator that can be mass-produced. Pseudocumene was selected by early experiments (Palo Verde, CHOOZ) due to its large scintillation output; however, it has a low flash point and poor material compatibility, thus a second, non-aromatic solvent (mineral oil or n-dodecane) has to be added to offset those effects. Such mixtures degrade the light-yield and complicate the scintillator handling (binary system). Instead, LAB with mild reactivity and high flash point (singular system) has been chosen by current experiments (Daya Bay, RENO and SNO+). LAB is the end result of extensive R&D by SNO+, including a search of commercially available scintillators. We propose a similar, improved survey of commercially available liquid scintillators.
3. Large Stokes-shift fluorophores. Most liquid scintillators have long optical transmission in the region of 440–550nm (e.g. LAB has L_{attn}~30m measured at 450nm emission) where the PMT has good QE. Identification of fluor/shifter combinations with high light-yield through comparison of fluorescence emission and intrinsic light-yield is the main objective of this task.
4. Temperature effects and time dependent characteristics. Significant improvement in liquid scintillator light yield could be achieved by lowering the temperature (e.g. ~5% more light at 10^oC compared to 20^oC measured by IHEP). We propose to confirm the temperature dependence and study time dependent characteristics of LS along with possible pulse shape discrimination of different scintillator samples. Pulse shape discrimination may play an important role in intrinsic background rejection in large liquid scintillator detectors. We will finalize the LS temperature and pressure dependence effects utilizing upgraded apparatus previously used for Hanohano R&D.
5. Light-yield measurements. Quenching reduces scintillation light output. The light-yield of scintillators will be screened at BNL with different radioactive sources: α, β and γ. The selected scintillators will then be sent to U. Wash. for systematic study of the light yield as a function of electron energy. The energy response of the liquid scintillator is input to the MC.
6. This detector is likely to be the largest scintillator detector built in the next 5 years. One potential problem is that laboratory equipment is normally not comparable in size to the detector. This creates ambiguity when extrapolating laboratory measurements to the detector; for instance, Daya Bay and KamLAND observed 10~15% more scintillation light in the detector than in laboratory measurements. This is likely due to re-absorption/emission or scattering of light propagating through the scintillator. We propose to build a one-dimensional tube with length close to the detector size to (1) investigate light propagation mechanisms as a function of path-length and (2) verify photoelectron yield at ~20m.

Table 2: R&D Task for Liquid Scintillator — Budget by Fiscal Year (all amounts are in FY13 $K)

Budget Item	FY 2013	FY 2014	FY 2015	Total
Personnel	160	430	440	1,030
M&S	45	130	150	325
Totals	**205**	**560**	**590**	**1,355**

I.2: PMT R&D (BNL, Hawaii, Houston)

PMT R&D will focus on several key components: light collection efficiency, mechanical performance, magnetic shielding and optoelectronic performance. Studies of light collection efficiency will focus on Winston cones, verification of PMT mechanical performance will focus on hydrodynamic simulation and optoelectronic performance will focus on magnetic shielding, ringing, overshoot and base nonlinearity.

1.2.1: Winston cones (Hawaii)

Winston cones have been utilized to increase light detection efficiency using specular reflection from metallic, mirror-like ellipsoidal surfaces and funneling light toward PMT photocathode surfaces. The current detector design requires ≥80% photocathode coverage and Winston cones may prove to be an attractive option to collect light lost in the spaces between PMTs. While Winston cone design for flat non-imaging surfaces is well understood, collecting light on the spherical PMT surface is not only a function of the shape of the Winston cone but also of the photocathode surface and any spatial non-uniformity in photocathode detection efficiency. The University of Hawaii group (task led by J. Maricic) proposes to design Winston cones that will utilize the leftover space between PMTs and reduce the risk of PMT implosion chain reactions. Simulation studies will address potential issues with timing, light yield non-uniformity, photocathode non-uniformity and their effects on detector performance. This work will build on Winston cone design and prototyping for the Water Cherenkov option of LBNE by J. Maricic. Simulation studies showed that Winston cones not only increase light detection efficiency but the improved light collection leads to a number of benefits such as significantly improved energy resolution, vertex reconstruction and pulse shape analysis.

A key requirement for mass hierarchy sensitivity is excellent energy resolution, requiring bright scintillator and excellent light collection efficiency. SNO and Borexino have successfully implemented light concentrators to enhance light collection by as much as 1.3 to as much as 2.5 times at just a few percent of the PMT channel cost. The enhancement factor is a function of PMT geometry, spacing and fiducial volume. Following experience of previous experiments a number of simulation studies must be performed to optimize light concentrator design to best achieve the physics goals:

a) Simulations — specify the geometry, including length and geometric field of view for light concentrators, based on:
   - Needed light collection efficiency.
   - Calculation of the spatial non-uniformity with and without Winston cones.
   - Calculation of the fiducial volume increase by overlapping angular coverage as a function of increase in the number of PMT channels.
   - Study effects of the light reflection from the concentrators back into the detector.
   - Study energy response uniformity.
   - Study PMT angular acceptance.

b) Experimental studies:
   - Compatibility and aging of proposed materials: measure radioactivity levels and long-term stability in liquid scintillator against leaching and changes in light collection efficiency.
   - Light concentrator material choice (aluminum, silver), single vs. multiple coating layers and coating thickness to maximize reflectance at a wide variety of angles.
   - Light concentrator production procedures: spinning, polishing, spraying and anodization.
   - PMT timing and dark rate change.

We propose to specify the device geometry in year 1 with simulations and initial measurements. Close collaboration with the detector simulation group is expected, starting with identification of the PMT size and type. Work in years 2–3 will be devoted to experimental studies, including cost estimates and a plan to interface with the PMT construction schedule.

1.2.2: PMT Mechanical simulation (BNL)

Large format photomultiplier tubes (PMTs) are key components and cost drivers for a large liquid scintillator detector to measure mass hierarchy. The PMT mechanical performance task (led by J. Ling and N. Simos) proposes to use modern hydrodynamic simulation code to check PMT mechanical performance, including survival of an assembled PMT array under significant hydrostatic pressure and subjected to shock waves caused by the failure of a single PMT.

Large format semi-hemispherical PMTs are leading candidates for a detector. Following the

Super-Kamiokande incident, the ability of PMTs to withstand hydrostatic pressure has become a critical issue for any large detector readout by PMTs. A combination of chemistry of the PMT glass in liquid aided by the external stress will induce corrosion. Even with good quality control, microscopic cracks in the PMT glass act as concentrators of stress and have the potential of propagating a macroscopic crack. Once the concentrated stress exceeds the fracture strength of the glass, a macroscopic crack will rapidly propagate across the glass thickness resulting in an implosion. In a large volume of water under pressure the inward rushing of water following implosion will result in an outward going shock wave front. The propagating shock wave can impact neighboring PMTs with enough force to cause them to fail, leading to a cascade failure. High-fidelity simulations on an array of bare PMTs at BNL showed that cascade failure is possible for certain PMT array configurations.

Based on PMT implosion tests at both the Naval Underwater Warfare Center (NUWC) and BNL for LBNE [1, 2], we understand basic characteristics of PMT implosions and effective techniques to mitigate the risk of a “chain-reaction”. More importantly our high-fidelity hydrodynamic simulation results agree with the experimental data. They show that that cascade failure is possible for certain PMT array configurations. With the LBNE results and hydrodynamic simulation, we can predict results for the large liquid scintillator geometry with its potentially different glass properties.

Based on prior experience a number of simulation studies must be performed to address PMT mechanical performance:

- Further simulation tuning to better match the LBNE test data.
- Conduct dedicated impact tests to measure PMT glass fracture properties for simulation input.
- Simulate and analyze the PMT mechanical stress.
- Simulate the shock wave created by a single bare PMT implosion under pressure.
- Simulate the shock wave created by one single PMT implosion with protection.
- Simulate the possible “chain-reaction” with PMT arrays.
- Iteration of simulation with variation of PMTs and assemblies.

To enhance existing computational capabilities and to enable multi-faceted sensitivity analyses of PMT arrays to provide design guidance, we propose to purchase and install multiple code licenses in a dedicated high power computer to speed up simulations. Year 1 will focus on single PMT implosion and years 2–3 will focus on multiple PMTs, including a PMT assembly.

1.2.3: PMT Magnetic Shielding & Signal Characterization (Houston)

PMTs are susceptible to magnetic fields, such as the Earth’s field. PMTs studied for Daya Bay showed charge collection variation as large as 50% depending on orientation of the PMT with respect to the Earth’s field. This will introduce sizable non-uniformity in the energy response of a large scintillator detector, a challenge to achieving the required mass hierarchy energy resolution.

One solution is local shielding of PMTs against magnetic fields with a high permeability sheet wrapped around the PMT. Daya Bay utilizes a flexible alloy (FINEMET) with high saturation magnetic flux density, low core loss and high permeability. The thin conical shield is wrapped around the PMT up to the PMT bulb equator. Charge collection variations are reduced by a factor of 3–4 [3]. The residual variation may still be too large though. Increasing shield coverage will affect light collection, so a new material or configuration is needed. Another solution is a compensation coil to cancel the Earth’s magnetic field throughout the detector as was adopted by Super-Kamiokande and studied by the LBNE WCD. There are advantages and disadvantages for each method.

We propose to carry out extensive tests at the University of Houston to find the best shielding solution. Signals from candidate PMTs with controlled light sources will be measured to compare various shielding methods. The effects of residual charge collection variation due to Earth’s field on energy resolution will be simulated. In conjunction with the magnetic shield study, we will also characterize the performance of candidate PMT and base. Effects such as ringing [4], overshoot and electronic nonlinearity may affect the energy resolution of low-energy events and the ability to measure through muons adequately because of the large range of energy deposition.

We propose to support a postdoc 3 years to carry out the R&D. The postdoc will spend half of his/her time initially on lab work and the rest on simulation. Dawei Liu at the University of Houston has experience in similar studies for Daya Bay, and will provide assistance and scientific oversight. The M&S, estimated at $10k per year, includes a dark box with controlled light source and magnetic shielding materials. Existing electronics and DAQ hardware at Houston will be used for these studies. It is assumed that candidate PMTs and bases will be available.

Table 3: R&D Task for PMT R&D — Budget by Fiscal Year (all amounts are in FY13 $K)

Budget Item	FY 2013	FY 2014	FY 2015	Total
Personnel	140	305	305	750
M&S	90	60	60	210
Totals	**230**	**365**	**365**	**960**

A full-scale test of the PMT configuration at NUWC is not included in this budget. Such a test program may be warranted. The CRADA between Brookhaven Science Associates (operator of BNL) and NavSea (operator of NUWC) remains active and further testing would be within its scope. A full testing program to validate PMT survivability would take ~1.5 years and cost of $1–2M. This is a major undertaking and should not be underestimated, although may well be necessary before construction of such a detector.

References:

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[2.] *J. Ling, et al. "Implosion Chain Reaction Mitigation in Underwater Assemblies of Photo-multiplier Tubes" , submitted to NIM*

[3.] *Escontrias, et al. "Light-weight Flexible Magnetic Shield for Large-Aperture PMTs", to be submitted for publication.*

[4.] *Jiang, et al. "Suppressing ringing caused by large PMT signals", Chinese Physics* ***C36****:235–240.*

I.3: Detector Calibration and Systematic Error R&D (Wisconsin, Hawaii, BNL)

Determination of mass hierarchy with reactor antineutrinos relies on precision measurement of the energy spectrum. Spectral distortions from the oscillation of reactor antineutrinos over ~60km are the key mass hierarchy signature. Excellent energy resolution ($< 3\% / \sqrt{E}$) and well-understood energy response (at the level of about 0.2%) are prerequisites for this measurement. For comparison, previous kton scale liquid detectors such as SNO and KamLAND determined the energy scale to 1–2%. The future detectors are 5–20 times larger. An order of magnitude improvement in our ability to calibrate and understand the energy scale of large liquid scintillator detectors is needed to measure the mass hierarchy with reactor antineutrinos. The success of the calibration program will determine whether a large liquid scintillator detector will be able to determine the mass hierarchy.

KamLAND, Daya Bay, Double Chooz and RENO have shown that the liquid scintillator energy scale from 0.5–10 MeV is not linear. The causes are still under investigation, but include scintillation quenching, Cherenkov light emission, readout electronics effects and positional variation of detector energy response. Precise understanding of the energy response of a large liquid scintillator detector requires a comprehensive calibration program to:

- determine the detector response to various particle types (β, e^+, neutrons and γ)

- evaluate the energy response in the center and throughout the detector volume
- calibrate event reconstruction to determine the fiducial volume
- monitor stability of the energy response and provide corrections as needed.

The multi-kton size of proposed scintillator detectors poses extraordinary challenges to deployment of point-like calibration sources throughout the detector volume, the number of calibration source positions that can be sampled in a finite time and the understanding of the integrated detector response. As part of this calibration R&D program we will investigate mono-energetic radioactive sources as well as man-made variable energy sources, point-like sources and uniformly distributed sources, as well as short-lived isotopes and positron emitters.

The objectives of the R&D program proposed here are to:

a) Define elements of a comprehensive calibration program that meets the required precision.
b) Demonstrate technical feasibility of calibrating a large, multi-kton detector.

The specific R&D tasks include:

1. Select and design a comprehensive suite of calibration sources
2. Develop concepts for deployment and precise positioning of radioactive and light sources throughout a 20kton detector.
3. Develop a concept for injection and distribution of short-lived radioactive isotopes to calibrate the detector volume with uniformly distributed sources.
4. Study feasibility and cost of a 1–10MeV electron accelerator for the calibration of the reactor antineutrino spectrum with a variable energy device in the region of interest.

The overall calibration task is coordinated by Professor Karsten Heeger from Wisconsin with contributions from Hawaii, William & Mary and BNL. Heeger draws on his experience as the scientific lead for design and construction of the KamLAND 4π full-volume calibration system and U.S. L2 manager for Daya Bay antineutrino detectors. The specific R&D tasks are described below.

I.3.1: Calibration Source Selection and Design (Wisconsin, BNL)

The detection of antineutrinos with a large liquid scintillator detector requires calibration of the detector response to e^+,β, γ and neutrons over the energy range 0.5–10 MeV. The energy range of interest is determined by the reactor spectrum. This R&D tasks defines calibration sources, design, rate and encapsulation requirements and demonstrates expected energy calibration.

Radioactive sources of well-defined energy can establish low-energy detector response to gammas. Typical sources used in experiments such as Daya Bay include the ^{68}Ge (1.02MeV) positron annihilation and ^{60}Co (2.506MeV) gamma source. Neutron calibration sources include ^{241}Am-^{13}C, ^{252}Cf or Am-Be. Stable and pulsed LED sources as well as light sources based on scintillator sources (e.g. ^{137}Cs) are useful for PMT calibration. The source rate and specific geometric design (including encapsulation) will be optimized with GEANT4 simulations. Prototype sources will be procured, fabricated and characterized at the University of Wisconsin. Based on these specifications we will estimate calibration time requirements. Gamma sources are easy to obtain and encapsulate but their energies are limited to <3MeV. Higher-energy calibrations require other approaches.

Short-lived isotopes offer an opportunity for calibration with well-known beta spectrum, with higher-energy gamma rays that are otherwise inaccessible or with distributed sources throughout the detector volume. Short-lived sources were successfully deployed in SNO to simulate the ^{8}B neutrino spectrum. Two examples of artificially produced short-lived calibration sources are ^{16}N and ^{8}Li. The ^{8}Li isotope can be created with a commercial deuterium-tritium (DT) neutron generator through the ^{11}B(n,α) reaction and it decays with a Q-value of ~16.0MeV. The main beta-decay branch has end-point energy of 12.96MeV. The ^{8}Li isotope can be carried several meters to a decay chamber suspended inside the detector using a gas/aerosol transport system as in SNO [5]. The ^{16}N isotope can be produced via the ^{16}O(n,p) reaction in CO_2 gas. A gas stream in capillary tubing can transfer the isotope into a decay chamber. In the case of SNO, the decay and trigger chamber blocked energetic beta particles but permitted the 6.13MeV gamma ray to enter the detector [6]. The ~6MeV gamma ray was the primary energy calibration in SNO as well as verification of the energy resolution and energy scale position dependence. As part of this R&D proposal, we will study the use of these (or similar) sources for a 20kton liquid scintillator detector. We will build a test stand with a DT generator, transfer tubing and liquid scintillator test chamber to understand and demonstrate the transfer of the isotopes over the longer distances involved in a multi-kton liquid scintillator detector. Postdoctoral researcher D. Webber from Wisconsin will lead this effort with scientific oversight from Heeger and senior scientist H. Band. Researcher T. Wise will provide technical assistance.

Calibration of the entire volume of a large liquid scintillator detector can only be achieved with distributed sources in the scintillator. Detector calibration with uniformly distributed sources allows calibration of the integrated detector response and comparison of events of known energies in different regions of the detector. At SNO ^{24}Na and ^{222}Rn were successfully used for in-situ detector calibration. We will survey short-lived isotopes, their production and injection concepts with a gas or scintillator stream into the detector [7]. We will focus on possible positron sources. U.Wisc will identify isotopes and develop a technical concept for injection and distribution of sources. The principles of isotope injection will be studied with a test chamber. Technical work will be led by Wise. Scientific oversight will be provided by Heeger, Band and Webber (U.Wisc) and M. Yeh (BNL).

Deployment of a variety of positron sources with energies in the non-linear range would provide a more direct indication of the energy scale for the reactor antineutrino signal. Most positron isotopes have short half-lives (from minutes to hours) such that loading them into scintillator would be a challenge. Water-based scintillator loading technology has proven loading (any) ions of interest within a short period time with an efficiency of ~100%. This might make feasible the loading of positron-sources to investigate scintillator non-linearity. The BNL group will study the use of water-based scintillators for the loading of short-lived radioactive sources.

I.3.2: Source Deployment Concept for Point Sources (Hawaii)

Precise positioning of calibration sources throughout the target volume is important for assessing energy response non-uniformity within the detector. This task will be challenging due to the size of the 20kton detector. This R&D task will develop concepts for calibration with radioactive point sources using a camera-based system for source monitoring and positioning.

Rapid development of high quality, affordable cameras in recent years provides an attractive option for detector calibration with sources, using cameras to locate the source. Such an approach has been used in Borexino and led to 2cm positioning precision using a system of cameras mounted on the detector walls. A system of cameras mounted on the walls of the large scintillator detector may potentially allow locating mobile sources to 1cm. Utilization of such a system would not only provide knowledge of the precise source location, but would simplify the design of the 3D calibration system. The University of Hawaii group (task led by J. Maricic and R. Milincic) proposes to develop preliminary camera and 3D positioning system designs. Such a 3D positioning system would be free of the need for high precision remote operation and would be much easier and cheaper to fabricate.

The task includes choice of cameras, component radioactivity measurements, housing design, software development, optimization of light illumination and design of the calibration deployment system in conjunction with the cameras. The work will build upon the previously designed calibration system for the Double Chooz experiment and the DarkSide camera and calibration system.

I.3.3: Injection and Distribution System for Short-Lived Isotopes (Wisconsin)

Calibration of the entire volume of a large liquid scintillator detector can only be achieved with sources distributed in the scintillator. Injection and deployment of such sources in a 20kton-detector poses challenges including production and injection of isotopes over long distances and their distribution and mixing in the detector. Two approaches are under consideration: Either a series of fixed injection points or a movable tubular system that can be used to deliver the short-lived isotope into different detector regions. Wisconsin senior engineer Jeff Cherwinka and designer Amy Pagac will develop a conceptual design and define the detector integration requirements with the source positioning system (I.3.2). A prototype injection system will be developed and tested with the DT generator (I.3.1). Scientific oversight will be provided by Band and Heeger.

I.3.4: A Variable-Energy Charged Particle Accelerator for Calibration (Wisconsin)

The goal of a large scintillator detector is a precise measurement of the spectrum of reactor antineutrinos in the energy range between 1–8 MeV. Spectral distortions due to neutrino oscillations, including the effects of mass hierarchy leave a signature over a several-MeV wide window. Radioactive sources provide either monoenergetic calibration or a continuous energy spectrum from beta-decay events. Precise calibration of the full energy spectrum would benefit from a calibration device with variable energy that allows a scan of the energy region of interest.

Low-energy electron accelerators have broad commercial applications in materials science, gas and water purification, sterilization and cargo inspection and customized turnkey electron and ion linacs are widely used in research [8,9]. In the energy range up to 5MeV direct current accelerators are used. Between 5–10MeV betatrons or RF linacs are favored. At these low energies no residual radioactivity is created. Direct current accelerators are offered by a number of commercial companies such as the Nissin High Voltage Corporation in Japan [10], and customized turnkey systems for research are offered by Research Instruments GmbH [11] for example. Together with accelerator experts from the Synchrotron Radiation Center at the University of Wisconsin, BNL, FNAL and/or SLAC we will study technical specifications of these devices and their potential application for calibration of a large liquid scintillator detector. Specific challenges include the stability of the beam energy and the beam delivery into the detector. Scientific oversight will be provided by Heeger and Band. Cherwinka will develop the integration requirements for such an accelerator-based system into a proposed future scintillator detector. Funds to support the technical consulting by an accelerator expert are requested as part of this task. A technical report describing the feasibility and possible implementation of an accelerator-based calibration source will be the deliverable of this work.

Table 4: R&D Task for Calibration — Budget by Fiscal Year (all amounts are in FY13 $K)

Budget Item	**FY 2013**	**FY 2014**	**FY 2015**	**Total**
Personnel	225	260	260	745
M&S	45	160	135	340
Totals	**270**	**420**	**395**	**1,085**

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I.4: Front-end and Trigger Electronics R&D (BNL, Hawaii)

The requirements and specifications of the front-end electronics and trigger system, in particular, the linearity of the charge measurement, dynamic range of time and charge measurements, multiple hit and pileup resolution capability, waveform digitization frequency, types of triggers and their implementation are critical for the experiment. This task is led by H. Takai and S. Rescia (BNL) and J.G. Learned and G. Varner (Hawaii).

A large liquid scintillator detector will have approximately 20,000 PMTs that need to be read out. The readout should address the issue of accurate measurement of low-level signals of interest while simultaneously preserving information of large signals originating from muons in the detector. To readout the detector we propose a system that will digitize and group signals close to the PMTs and transport the digital information on fiber optics to the DAQ. At the front end we plan to implement a dynamic range compressor [12] that will preserve the linearity of both low and high amplitude signals. The proposed solution will preserve the number of channels and reduce the number of cables that will carry signals out of the detector for further processing.

We propose a configuration of clustered digitization electronics, each servicing from 16 to 32 PMTs. Each digitizer unit reports (and receives instructions) via fiber optics to the central digital signal processing and recording in the main data acquisition system. The optical modules can be attached with short cables to the digitizer at ambient pressure in oil and thus not subject to leakage. The digitizer we plan to use was developed for the fifth generation TeV Array with Gsa/s sampling and Experimental Trigger (TARGET) [13]. This ASIC contains 16 channels of transient waveform recorder designed for highly pixelated photon detectors for large neutrino and muon detectors.

A compressor for liquid argon signals (also with large dynamic range) was successfully implemented during ATLAS detector R&D. For successful use it is necessary that the waveform is digitized and later reconstructed by proper algorithms. As most of the proposed front-end readout will be located inside the detector, reliability of connections and electronics is critical. In the past, electronics have been deployed in other experiments with little to no access and we are quite confident that a solution to achieve the necessary reliability is possible.

We propose that BNL and the University of Hawaii cooperate in development of a readout chain that can be immersed in the detector, group the signals in blocks of 16–32 and send digitized information to the data acquisition chain. BNL will work on developing the signal compressor and carry out studies of system reliability. Hawaii will be responsible for developing the digitization system. Short cables will connect the PMTs to submersed electronics boxes where they will be conditioned and digitized. The signal compressor will be tailored to the PMT signals with a very short shaping time to restore the signal to the baseline. The electronics board will be located in protective casing to service 16–32 channels. Design of a reliable system is central to this R&D effort.

Table 5: R&D Task for Electronics — Budget by Fiscal Year (all amounts are in FY13 $K)

Budget Item	**FY 2013**	**FY 2014**	**FY 2015**	**Total**
Personnel	60	150	150	360
M&S	95	190	190	475
Totals	**155**	**340**	**340**	**835**

References:

[12.] W.E. Cleland, D. Lissauer, V. Radeka, S. Rescia, H. Takai and I. Wingerter-Seez, Dynamic Range Compression in Liquid Argon Calorimeter, BNL 63670, DOI 10.2172/432972, 31 Dec 1996.

[13.] K. Bechtol, S. Funk, A. Okumura, L. Ruckman, A. Simons, H. Tajima, J. Vandenbroucke and G. Varner, TARGET: A multi-channel digitizer chip for very-high-energy gamma-ray telescopes, arXiv:1105.1832 (2011)

I.5: Simulation of the Experiment

A critical element of large liquid scintillator reactor antineutrino experiments is a thorough understanding of the key design issues. A full detector simulation is crucial to investigate the impact of various factors on the mass hierarchy measurement: detector design, LS properties, backgrounds, electronics, energy calibration and reconstruction. We plan to develop a simulation package based on Daya Bay's NuWa simulation and analysis framework. NuWa was proven through Daya Bay's successful discovery of θ_{13} with a very fast analysis turnaround. Since the mass hierarchy experiment will be based on similar liquid scintillator technology, the existing physics models and material properties will save time. However, since the mass hierarchy experiment is much larger with different optical sensors and electronic systems, even with use of NuWa, considerable work is needed.

In addition to performance simulations of large liquid scintillator detectors, the simulation team is responsible to understand sensitivity under various scenarios and alternative or improved designs. One potential improvement is to deploy a 2nd detector at a 30–40km baseline. Preliminary investigations indicate that this design could mitigate detector energy scale requirements.

The implementation and maintenance of the simulation effort is estimated to require three to four NuWa experts. In 2013 we need ≥50% of their effort to set up a new NuWa branch for the large scintillator detector. We plan to finish this NuWa modification by fall 2013. The goals of stage 1 are:

1. Set up code and file repositories.
2. Implement baseline large scintillator detector design geometry.
3. Obtain preliminary detector performance simulation results for the baseline design. The emphasis will be on detector uniformity and energy resolution, which is closely related to the liquid scintillator transparency and PMT photocathode coverage.
4. Sensitivity studies will provide detector performance requirements, especially energy resolution and energy scale calibration.

Following this we need more postdocs and students to test and improve the simulation package. Stage 2 goals are expected to be achieved by the end of 2013:

1. Simulation with readily replaceable detector designs is achieved to facilitate comparison of different detector designs.
2. Preliminary event reconstruction algorithms are available. Background and calibration system design studies initiated.
3. Detailed and realistic PMT and electronics models are implemented. Preliminary understanding of PMT/electronics performance on detector performance is obtained.
4. Detector performance simulation with various liquid scintillator properties is ready. Impact of liquid scintillator coupled with PMT and electronics on performance is understood.
5. Simulation of calibration systems implemented and simulated calibration data available for performance studies.
6. Preliminary performance comparisons between different detector designs are completed.

In 2014 the 3rd stage of simulation effort will provide quantitative requirements to PMT selection, photocathode coverage, electronics performance and liquid scintillator properties. The calibration system performance will be fully evaluated and compared with design requirements. By the end of 2014, we expect concrete detector performance comparisons to inform detector designs with the best knowledge of detector material and component choices. In 2015 we expect to have detector design and performance for all primary and secondary physics topics, cross checked by different simulation teams and work will proceed to merge this knowledge into a complete simulation and analysis framework.

We expect to start with 4 postdocs and scientists. We expect the total number of postdocs will grow to ~6 with each spending ~50% of his or her time on simulations. All postdocs will contribute to the primary neutrino oscillation performance but some will focus on detector performance for various secondary physics topics like geoneutrinos, supernova neutrinos and solar neutrinos. The budget table below shows a personnel increase to this level during FY 2013, reaching full level in FY 2014.

Table 6: R&D Task for Simulations — Budget by Fiscal Year (all amounts are in FY13 $K)

Budget Item	FY 2013	FY 2014	FY 2015	Total
Personnel	10	300	300	610
M&S	25	55	30	110
Totals	**35**	**355**	**330**	**720**

I.6: Project Initiation

A decision by the U.S. to develop the capabilities inherent in a large liquid scintillator detector to measure reactor antineutrino disappearance and neutrino mass hierarchy requires an understanding of the scope of such an investment and its cost and schedule. This R&D task would develop this understanding in support of a possible decision to invest in this capability. For example, a U.S. contribution to an experiment such as Daya Bay II requires an understanding of the international schedule, definition of potential U.S. scope and development of a schedule that is consistent with the U.S. funding process. Other possible experiments will be considered. Early identification of possible issues of integration of a U.S. contribution to an international experiment is needed. The budget table below shows the effort needed to develop the scope, cost and schedule.

Table 7: Project Development — Budget by Fiscal Year (all amounts are in FY13 $K)

Budget Item	FY 2013	FY 2014	FY 2015	Total
Personnel	60	210	210	480
M&S	45	50	50	145
Totals	**105**	**260**	**260**	**625**

II. Summary

An important capability currently missing from the U.S. portfolio is a large liquid scintillator detector with excellent energy resolution capable of measuring neutrino mass hierarchy via reactor neutrino disappearance. The Chinese Daya Bay II experiment proposes a definitive mass hierarchy measurement with such a detector. Civil construction of an underground laboratory is scheduled to begin as early as 2014, with data taking projected to begin in 2020. The short time scale of the Chinese project motivates a quick U.S. response and rapid ramp-up of U.S. R&D effort to remain competitive.

A. U.S. Large Scintillator Detector R&D Collaboration

The current U.S. Large Scintillator Detector R&D collaboration includes the following groups. The collaboration is expected to grow during the R&D phase.

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