ORLaND: A Proposed Facility to Investigate Neutrino Properties Relevant to Astrophysics

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ORLaND, the Oak Ridge Laboratory for Neutrino Detectors, is a proposed underground facility adjacent to the target station of the Spallation Neutron Source (SNS). The 1.3 GeV, 2 MW beam of protons striking the Hg target in $60Hz$, $600ns$ pulses will be the world's most powerful source of intermediate energy ν_μ, ν_e and $\overline{\nu}_\mu$. The possible experiments relevant to astrophysics are discussed. This laboratory is planned as a general user facility with space enough for a 2000 ton Cerenkov detector and 5 or 6 smaller detectors of between 50 and 200 $tons$. A proposed program is discussed that includes the following cross sections measurements as examples: $^2D(\nu_e, e^-)pp$, $^{16}O(\nu_e, e^-)^{16}F$, $^{56}Fe(\nu_e, e^-)^{56}Co$, and many other reactions. A program of research and development of neutral current experiments is also planned.

1. INTRODUCTION

The critical importance of neutrino physics to our fundamental understanding of nature makes a compelling case for a high intensity, pulsed neutrino source. Using the nucleus as a laboratory, neutrino experiments have the capability to revise and extend our understanding of the Standard Model, as well as to probe the sub-structure of the proton and the neutron. Neutrinos are key players in the dynamics of exploding supernovae and in the ignition of the primal p-p chain of stellar burning, and can provide unique information needed to further our understanding of the nuclear–astrophysics of these and other cosmological phenomena. Intrinsic neutrino properties, such as mass, influence the dynamics of the universe through their possible contribution to dark matter. The question of neutrino oscillations between flavor states is intimately related to our understanding of the physics of supernova evolution and to the validity of the Standard Model.

Neutrinos are playing an ever-increasing role in nuclear astrophysics. Measurements of neutrino reactions on ^{16}O and ^2H are very important for the interpretation of solar neutrino data and anticipated supernova data from the Solar Neutrino Observatory (SNO) and SuperKamiokande. These reactions could be measured only at ORLaND in the foreseeable future.

Neutrinos strongly impact the dynamics of the collapse preceding supernova explosions and the formation of heavy elements. They carry off a large fraction of the gravitational energy of the collapse, rapidly cooling the core, while possibly reheating stalled shock fronts to create the ejecta observed in supernova remnants. To understand these processes, extensive supernova modeling projects require a large body of neutrino-nucleus interaction data that can only be obtained at facilities like ORLaND. Almost no such data exist, and there are no existing or approved facilities that could produce them.

Some neutrino-nucleus interactions have interesting analogs to electron-nucleus interactions studied in recent experiments. Low-energy neutrino-nucleus interactions yield information on the strangeness content of nucleons and nuclei and on the weak axial form factors. Existing electron scattering measurements of the axial form factor are ambiguous and are limited by uncertainties in our understanding of radiative corrections. Radiative corrections are much less important for neutrino scattering, so that low energy neutrino measurements, such as could be performed at ORLaND, would be of great value. Finally, a study of the intrinsic neutrino properties, will provide valuable information relevant to open questions on the nature of dark matter, and physics beyond the standard model.

2. THE SNS AS A SOURCE OF NEUTRINOS

The SNS at ORNL will consist of a 70 mA, H^- ion source, a $\sim 0.4\,km$ long superconducting $1.3\,GeV$ proton accelerator, and a $220m$ circumference accumulator ring that can deliver $2MW$ ($9.6\times10^{15}\,protons\,sec^{-1}$) on a mercury target. The protons will impinge on the target in pulses of full-time duration of $600ns$ ($FWHM\ 380ns$) at a frequency of $60\,Hz$. This design is optimized to produce intense, short-time-duration pulsed neutron beams required for studying the structure of materials. In addition to the intense neutron beams, $1.3\,GeV$ protons on mercury is a copious source of pions. About 17% of the incident protons will produce pions that decay into muons, electrons and neutrinos.

The π^- are slowed and captured on nuclei very rapidly in the high-Z target and shielding. Those that decay prior to capture produce a μ^- that also captures on a nucleus with high probability. Only a small fraction of negative muons decay before capture and produce neutrinos via: $\pi^-\rightarrow\mu^-+\overline{\nu}_\mu$ ($T_{1/2}=26\,ns$) and $\mu^-\rightarrow e^-+\nu_\mu+\overline{\nu}_e$ ($T_{1/2}=2.2\,\mu s$). The high probability of nuclear capture of π^- and μ^- results in a very small flux of $\overline{\nu}_e$. See Figs. 1, 2 and 3.

The π^+, on the other hand, are produced with an average energy of $\sim 200\,MeV$ and are rapidly stopped ($< 0.3ns$) but are not captured on nuclei. They decay via: $\pi^+\rightarrow\mu^++\nu_\mu$ and $\mu^+\rightarrow e^++\nu_e+\overline{\nu}_\mu$. At $1.3\,GeV$, each proton produces 0.098

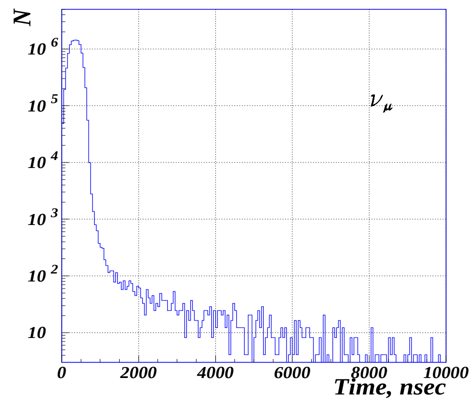

Figure 1. Time dependence of the $\nu_{\mu's}$.

π^+ and 0.061 π^-. This results in a production of 0.94×10^{15} neutrinos of each flavor (ν_μ, $\overline{\nu}_\mu$ and ν_e) per second with 9.6×10^{15} protons sec^{-1} on target.

All of the neutrinos are emitted isotropically so that the flux of each of the ν_μ, $\overline{\nu}_\mu$ and ν_e neutrinos would be $3\times10^6\ sec^{-1}cm^{-2}$ at $50m$ from the target. The stopped-π^+ neutrino spectra are well known experimentally, and can be expressed analytically as follows:

$$P(\nu_e)=\frac{12}{W^4}E_\nu^2(W-E_\nu), \qquad (1)$$

and

$$P(\overline{\nu}_\mu)=\frac{6}{W^4}E_{\overline{\nu}}^2(W-\frac{2}{3}E_{\overline{\nu}}). \qquad (2)$$

The ν_μ emitted in the two body decay of the π^+ is monoenergetic at $\sim 30\ MeV$, and $W=52.83\,MeV$. The spectra are shown in Fig. 4.

Selecting events recorded $\sim 700\,ns$ after the accelerator pulse on target allows the separation of events due to interactions involving ν_μ, from those involving $\overline{\nu}_\mu$ and ν_e.

3. THE ORLaND FACILITY

The planned laboratory is being designed to accommodate one large ($\sim 2000\,ton$) Cerenkov

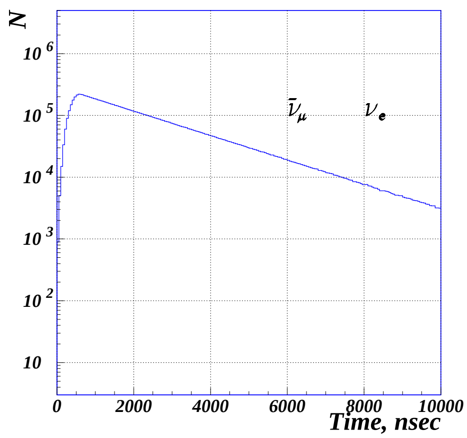

Figure 2. Time dependence of $\overline{\nu}_\mu$ and ν_e emitted in μ^+ decay.

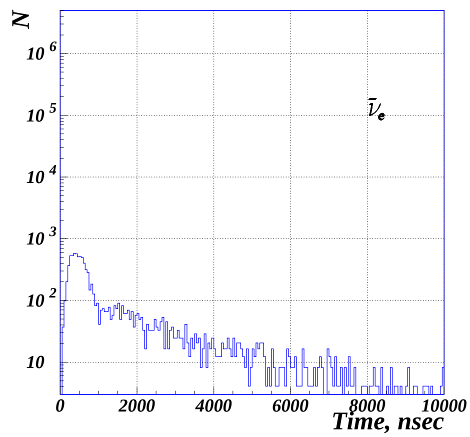

Figure 3. Time dependence of $\overline{\nu}_e$ from the decay of uncaptured μ^-.

detector, and 5 or 6 smaller detectors, ranging from 50 to 200 *tons*. The planned structure is a cylindrical concrete bunker, 24 meters inside diameter, 29 meters high, buried with the top 4.6 meters underground, with a tunnel access. The 4.6 meters overhead would be filled with about 2.6 m of prestressed concrete beams covered by 2 meters of steel. It would be covered and out of sight. See Fig. 5.

The bunker would be placed near the target station building such that the steel target shield, structural concrete, and soil is equivalent to 10m of steel shielding against neutrons. The overhead shield will eliminate the hadronic component of cosmic rays and cut the total rate by a factor of 4. The proton pulse structure will further reduce cosmic ray background by $\sim 2 \times 10^{-4}$. There are three floor levels planned outside of the large detector tank diameter, each capable of supporting several detectors of between 50 and 200 *tons* for neutrino-nucleus cross section measurements discussed later. Earlier articles give more details of the facility [1,2].

4. POSSIBLE EXPERIMENTS at ORLaND

Experimental neutrino physics involves severe difficulties arising from the complexity of large detector systems, small event rates, and long running times. Consequently, significant research and development effort will be required as a prelude to the design and implementation of experiments. The experiments discussed below are in a preliminary stage of planning, and reflect present understanding and development.

4.1. Calibrating the Sun

The importance of a timely experiment serving as a "Calibration of the Sun" [3], suggests neutrino-deuteron scattering as one of the first experiments at ORLaND. The standard solar model tells us that 99.75% of the energy from the sun is generated in a complex series of nuclear reactions starting with $p + p \to d + e^+ + \nu_e$ [4]. It has been recognized for many years that a direct measurement of this cross section is extremely difficult. At ORLaND, the reaction ν_e + d $\to$ e$^-$ + p + p, which is equivalent by detailed balance, can be studied. The cross section can be calculated for

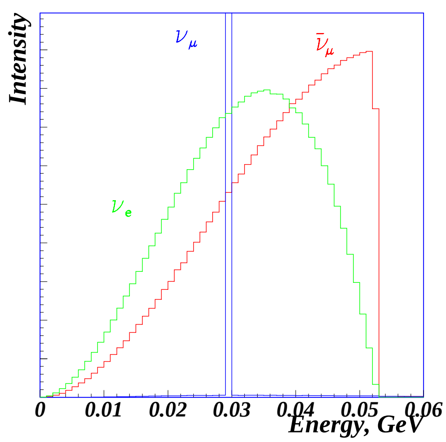

Figure 4. Spectra of neutrinos from stopped π^+ and μ^+ decays.

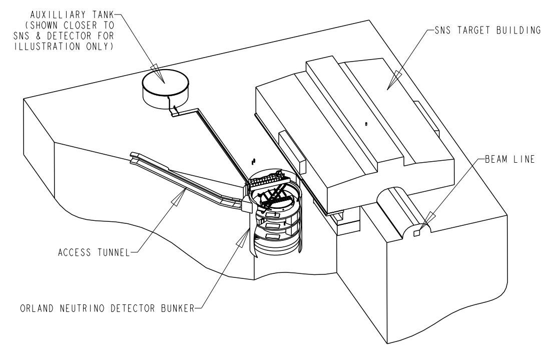

Figure 5. Artist's conception of the ORLaND bunkers (left) and the SNS target station (right).

both reactions with effective field theory up to a common "counter-term." The "counter term" can be determined experimentally from the ν_e + d data taken at ORLaND. Theory then provides a mechanism for extrapolating the ORLaND results to the solar energy regime. This result will not only contribute to our understanding of the sun as a laboratory of nuclear and neutrino astrophysics but will also advance understanding the application of effective field theory to nuclear physics.

An experiment of approximately 30 fiducial tons of D_2O, either in a small Cerenkov detector or imbedded in the middle of the 2000 *ton* H_2O detector has been considered in some detail. Monte Carlo simulations suggest that approximately five years of data would yield a reliable charged current cross section measurement. This can be obtained by straightforward isospin rotations of the transition operators. This result is important for interpretations of the data from SNO experiment since the neutral current cross section, for which the SNO results are sensitive, can be obtained[5,6] from our measurements by straightforward isospin rotations of the transition operators in the neutrino scattering Hamiltonian.

4.2. Supernova Thermometry

ORLaND can provide a valuable calibration for supernova and solar neutrino detection experiments including those probing supernova temperatures. The reaction $^{16}O + \nu_e \rightarrow ^{16} F$+e$^-$ is dominated by the electron-neutrino capture channel for thermal sources in the temperature range of $4 - 9\,MeV$ and thus provides a sensitive handle on supernova thermometry. The electron angular distribution is strongly correlated with the ν_e-energy. Therefore, measurements of double-differential cross sections, $d\sigma/d\Omega dE_e$, of the reaction $^{16}O + \nu_e \rightarrow ^{16} F$ + e$^-$ using the proposed 2000 *ton* water Cerenkov detector would be very valuable for understanding future supernova data from large detectors like SuperKamiokande and the next-generation large Cerenkov detectors. In particular, a strong yield of back-angle electron emission would require ν_e-energies far higher than those expected from standard supernova models.[7] Usually, tau and muon neutrinos decouple at smaller radii and thus at higher temperatures than those of electron neutrinos. Threshold conditions bar the higher flavors from initiating charged current reactions. However, if neutrino-oscillations occur, higher energy neutrinos of tau or muon flavor would oscillate into electron flavor, and could initiate high energy electron-neutrino events. The differential cross section measurements at ORLaND would provide the information necessary to interpret these events.

Neutrino-oxygen reactions, accompanied by photon and nucleon emission discussed below as a probe of axial strangeness, could also yield information on supernova thermometry and aid in understanding of future supernova data. In addition, UCLA and OSU have proposed using ORLaND to test and develop lead-neutron counter modules for the OMNIS supernova search detector. Neutrino–lead reactions could be studied at ORLaND as a prelude to lead perchlorate detectors that might separate ν_e and $\bar{\nu_e}$ from supernovae. These data could provide additional gauges of supernova temperatures.

4.3. Diagnosing Supernova

Core collapse of supernovae is one of the most interesting of known astrophysical phenomena. These enormously energetic stellar explosions occur for stars of mass greater than 8 to 10 solar masses. Neutrino-nucleus interactions play a central role in supernova dynamics and in supernova nucleosynthesis. Many nuclear species participate in these processes, and the corresponding neutrino interaction cross sections are critically important inputs to the large supernova collapse modeling. None are presently experimentally available except those involving ^{12}C.

At the end of a massive star's life, its core is composed of iron-group nuclei, surrounded by lighter elements in progressive layers of silicon, oxygen, carbon, helium, and hydrogen. The core collapses on itself, rebounds at supernuclear densities and generates a shock wave propagating outwards. Neutrinos from the $e^- + p \rightarrow \nu_e + n$ capture reaction propagate outwards. At a core density $\sim 10^{11}\ gm/cm^3$, neutrinos become trapped. To understand this process quantitatively, several neutrino-nucleus cross sections must be measured. The most important is $\nu_e + {}^{56}Fe \rightarrow e^- + {}^{56}Co$.

To measure this reaction at ORLaND, a fine-grained detector of iron tubes, each containing a gas proportional tube, has been designed and modeled.[8] This detector is similar in concept to the Soudan-2 detector but optimized for this measurement. Our calculations show that a detector $3.5m \times 3.5m \times 3.5m$, weighing a total of $37\,tons$, having a $13.5\,ton$ fiducial volume, could adequately measure the $\nu_e + {}^{56}Fe$ cross section. In addition, the following interesting targets are available in ton quantities that could also be studied using the same technique: ^{9}Be, ^{11}B, ^{27}Al, ^{40}Ca, ^{59}Co, ^{12}C, ^{28}Si, ^{51}V, ^{32}Si, ^{52}Cr, ^{55}Mn, ^{93}Nb, ^{209}Bi, ^{181}Ta, and natural Pb. Several of these detectors could be operated simultaneously.

4.4. Calibrating ^{8}B Solar Reactions

Identification of neutrinos emanating from the various semi-leptonic electroweak process in the solar interior are needed to improve understanding of the standard solar model. One possibility of such identification could be to exploit the differentiation in energy of neutrinos produced by the different channels. In particular, the ^{8}B electron neutrinos have a distinct energy separation from the approximately $1\,MeV$ ν_e produced in the ^{7}Be and p-e-p channels. A radiochemical–electronic hybrid detector has been proposed to separately and directly measure the flux of these neutrinos. The detector measures ν_e-induced charge current reactions on ^{37}Cl yielding ^{37}Ar final nuclei. If neutrinos come from ^{8}B, they produce electrons with up to about $14\,MeV$ of energy that generate observable Cerenkov radiation in the hybrid detector. Similar techniques may be used for hybrid detectors with ^{127}I and ^{71}Ga target nuclei, also. These detectors need to be calibrated for the solar neutrino measurements. The intense low–energy pulsed neutrino beam at ORLaND would allow a much-needed calibration of these reactions using small Cerenkov detectors.

4.5. Nuclear Strangeness

The strangeness content of the nucleus or the nucleon arises from the "sea" of virtual strange quark-antiquark pairs. The effect of such pairs on the low-energy properties of the nucleon is an open question in nuclear physics. A comparison of weak nucleon form factors with the values expected in the nuclear domain approximation (where the sea is ignored) can provide a measure of nuclear matrix elements of strange quark operators and thus probe the effects of the sea on static nuclear properties.

There are several possible approaches for strangeness measurements. At ORLaND, the most promising would be the elastic axial form factor, $G_A^Z(Q^2)$, at low momentum transfer. In the Standard Model, the axial current operator at tree level is pure isovector, and is thus related by a simple isospin rotation to the (known) charge changing axial current. The difference between $G_A^Z(Q^2)$ and $G_A^W(Q^2)$ (i.e. the corresponding charge changing matrix element, obtained at low Q^2 directly from β-decay or from charge changing neutrino cross sections) measures the strange axial form factor, $G_A^s(Q^2)$. Neutrino-nucleus elastic cross sections at low Q^2 at ORLaND would provide a measure of $G_A^s(0)$.

Among the first experiments planned will be measurements of neutrino-oxygen cross sections using a 2000 *ton* water Cerenkov detector. By adding Gd_2Cl_4 to the water, one can attempt to measure the cross section of the reaction ν + ^{16}O $\rightarrow$ ν' + n + γ + ^{15}O by triggering on nuclear gamma-rays, and later on the capture gamma-rays. It is also possible to observe the gamma rays from the reaction ^{16}O + $\nu \rightarrow \nu'$ + p + γ + ^{15}N, not followed by the capture gamma rays. The ratio $R = \sigma(\nu, \nu' p\gamma)/\sigma(\nu, \nu' n\gamma)$ of proton to neutron quasielastic cross sections is proportional to $G_A^s(0)$ and thus uniquely sensitive to the desired axial strangeness content. In this ratio, beam normalization, final state interactions, and Q^2 dependence of the axial form factor all cancel to leading order[9].

4.6. Oscillations and electroweak parameters

At any time when data are being acquired with the H_2O loaded with Gd_2Cl_4, a very sensitive search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations could be carried out with no added cost. While this would occur after the MiniBooNE result was known, it would serve two purposes. First, if the MiniBooNE result is positive, ORLaND would confirm it and measure the oscillation mixing and mass parameters required to build a "neutrino mass scenario." If the MiniBooNE result is negative, the ORLaND data could search parameter space ten times more sensitively than MiniBooNE using the water detector. Since neutrino-electron scattering will be continuously monitored for flux calibration of the beam, one could also use it to measure the electroweak parameters like the Weinberg angle at low momentum transfer.

The predicted sensitivity for observing $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ neutrino oscillations with the 2000 *ton* Cerenkov detector is shown in Fig. 6 for various exposures.

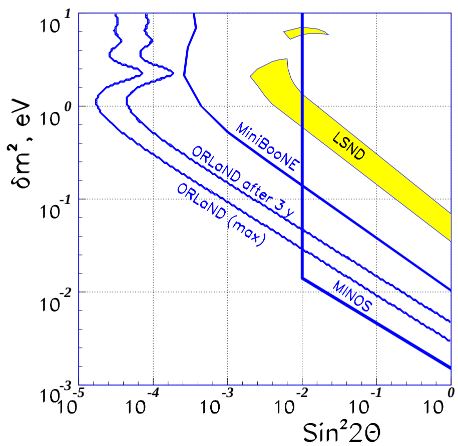

Figure 6. Predicted sensitivity of $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ neutrino oscillation measurements at ORLaND.

5. CONCLUSIONS

The experiments suggested above could be categorized into two stages. The first-generation experiments proposed are those requiring little or no development, and in many cases they would require simple scaling-up of existing techniques. They are designed to support supernova collapse theory, accurate interpretation of solar neutrino and supernova data from H_2O and D_2O Cerenkov detectors, as well as chemical solar neutrino data – past, present, and future. Sensitive neutrino oscillation and other experiments probing Standard Model physics could come with no increase in cost. Second-generation experiments involving neutral current reactions and neutrinos from decay-in-flight pions will require significant research and development and could come later.

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7. THE ORLaND COLLABORATION

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