THE OAK RIDGE LABORATORY FOR NEUTRINO DETECTORS (ORLaND): ITS RELATION TO NEUTRINO TELESCOPES

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ABSTRACT

Physics opportunities at an intense, pulsed stopped-pion neutrino source are discussed. Emphasis is placed on neutrino interactions relevant to the interpretation of data from solar neutrino and supernova neutrino detectors (telescopes). Some discussion is also given concerning the measurement of neutrino-nucleus cross sections that shed light on stellar evolution and supernova collapse and nucleosynthesis, processes for which we build neutrino telescopes.

1. Introduction

The Oak Ridge Laboratory for Neutrino Detectors (ORLaND) is a proposed national and international user facility to be located near the target station of the Spallation Neutron Source (SNS) under construction at the Oak Ridge National Laboratory. The neutrino laboratory would be an underground detector hall capable of housing one large ($\sim$2000 *ton*) multi-purpose Čerenkov / Scintillating Čerenkov detector, and between six and eight smaller detectors ($100 - 200$ *tons*). The hall would be located approximately 7 meters underground, with 3 meters of steel and 1 meter of concrete overhead, and between 6 and 9 meters from the target building. The steel and concrete overburden will attenuate the soft component cosmic rays completely, and attenuate the muon flux by a factor of 4. The materials between the target and the laboratory would be equivalent to 12 meters of steel in shielding against neutrons from the SNS; see figure 1. The proton beam will be pulsed which will severly reduce the background from cosmic rays.

The bunker or hall design is a cylinder approximately 33.5 meters deep and 25 meters in diameter. It is designed to have 3 levels to support the smaller detectors; the large detector would penetrate upper floors. The tank to contain the large detector is designed as a triple walled steel tank with an outside diameter of 14 meters, and 14 meters deep. A one meter thick liquid scintillator veto detector will surround the inner wall of the tank, and will cover the top and bottom.

The central volume of the detector will be lined with approximately 5000, 33 cm diameter photomultiplier tubes to provide a 50% photo-cathode area coverage. The central volume could be filled with H_2O, pure mineral oil, mineral oil with dilute scintillator, or a variety of acquious solutions. One possible configuration under consideration has an acrylic container of d_2O located in the center of the detector, surrounded with either pure H_2O or mineral oil. The large detector is being designed to be as versatile as possible. Some of the experiments possible with this detector involve the following reactions: $^{16}O(\nu_e, e^-)^{16}F$, $d(\nu_e e^-)pp$, $^{16}O(\nu_x, n\gamma)^{15}O$, $^{16}O(\nu_x, \nu_x' p\gamma)^{15}N$, $\nu e^- \rightarrow \nu' e^{-\prime}$, $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ (oscillation), $\nu_\mu \rightarrow \nu_e$ (oscillation), $^{12}C(\nu_e, e^-)^{12}N$, $^{12}C(\nu_x, \nu_x')^{12}C^*$, and with such a large detector and intense flux, possibly $^{13}C(\nu_e, e^-)^{13}N$ [2].

With the smaller detectors of various configurations, many neutrino - nucleus cross sections important in our understanding of stellar evolution and collapse can be measured , for example: $^{56}F(\nu_e, e^-)^{56}Co$, as well as (ν_e, e^-) reactions on other metallic targets, and $^{37}Cl(\nu_e, e^-)^{37}Ar$, $^{71}Ga(\nu_e, e^-)^{71}Ge$, and $^{127}I(\nu_e, e^-)^{127}Xe$ to support the accurate interpretation of chemical solar neutrino experiments [2].

There are many other important experiments that can be performed at such a facility, for example those that address fundamental questions of weak interactions in nuclei and the strange quark content in the nucleon. This report, however will concentrate on topics directly or indirectly associated with neutrino telescopes. A second motivation for giving this talk and writing this report is to openly invite world wide participation in suggesting, proposing and participating in experiments of broad interest to the fields of particle physics, nuclear physics, and neutrino aspects of nuclear astrophysics.

2. The Spallation Neutron Source as a Neutrino Source

The SNS will produce its intense source of neutrons with a 1 GeV pulsed beam of protons impinging on a mercury target. This will be accomplished with a superconducting linear accelerator and accumulator ring. The proton beam will be a 2 milliampere beam, delivering 2 megawatts on target, in 600 ns wide pulses at 60 Hz. It is well known that this will produce about 10^{15} π^+ and π^- per second. About 99.6 % of the π^- are rapidly slowed and absorbed on the high - Z nuclei prior to decay. Of the remaining 0.4%, $\sim$ 95% of the μ^- from the decay are also absorbed, resulting in only a small fraction of $\overline{\nu}_e$ from the decay $\mu^- \rightarrow \nu_\mu + e^- + \overline{\nu}_e$. On the other hand, the π^+ are slowed in approximately 0.25 ns, and decay at rest via $\pi^+ \rightarrow \mu^+ + \nu_\mu$ ($\tau \simeq 26ns$) and $\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$ ($\tau \simeq 2.2\mu s$). The SNS will produce $\sim 10^{15}$ neutrinos of each flavor per second. The flux of each flavor at 50 meters from the target will be $\sim 3 \times 10^6/cm^2/sec$.

The spectra of ν_μ, $\overline{\nu}_\mu$ and ν_e are shown in figure 2. Analytical expressions for the spectra of $\overline{\nu}_\mu$ and ν_e are given by:

$$N(\nu_e) = (12/W^4)\, E_\nu^2\, (W - E_\nu), \tag{1}$$

and

$$N(\overline{\nu}_\mu) = (6/W^4)\, E_\nu^2\, (W - 2/3\, E_\nu), \tag{2}$$

where $W = 52.83\, MeV$.

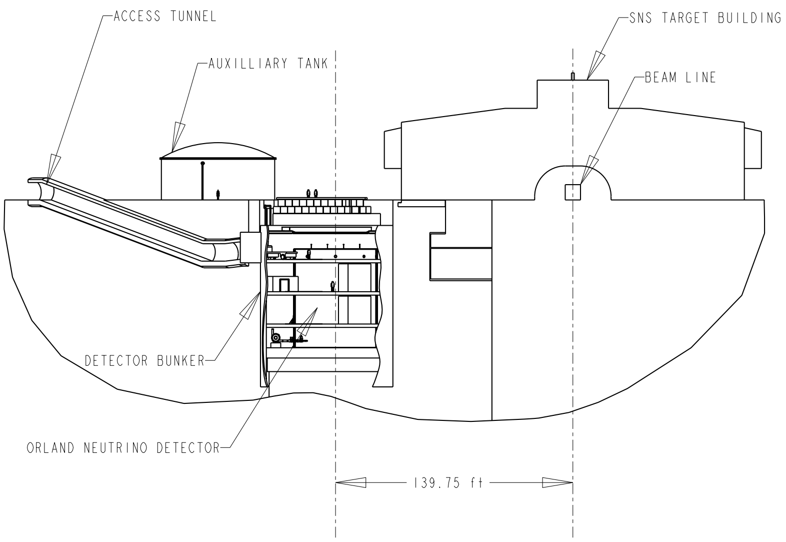

Figure 1: Diagram of the ORLaND facility showing the location relative to the SNS target station.

One can immediately appreciate the special relationship between the neutrino spectra from a stopped-pion source and neutrino astrophysics by comparing figure 2 to the spectra in figure 3. Figure 3 shows typical neutrino spectra expected from supernova collapse. The evolution of such spectra are calculated, for example, by A.Mezzacappa [3] with a supernova collapse model. As the star collapses and the core reaches $\sim 10^{12}\, gm/cm^3$, the neutrinos experience significant trapping. The original pulse of ν_e from e^- capture on protons rapidly equilibrates to all flavors by interacting with the dense matter. The ν_μ $\overline{\nu}_\mu$ ν_τ $\overline{\nu}_\tau$ interact only by neutral currents, whereas ν_e and $\overline{\nu}_e$ interact much more strongly by both charge current and neutral current interactions. Therefore the muon and tau neutrinos escape from the core at an earlier stage of collapse and at much higher core temperature yielding the higher energies. The $\overline{\nu}_e$ escape somewhat earlier than ν_e, because at this point, the core is neutron rich, and $\overline{\nu}_e + n \rightarrow e^- + p$ is far less probable than $\nu_e + n \rightarrow p + e^-$, allowing more $\overline{\nu}_e$ to escape at a higher temperature [4].

The important thing is that the SNS approximately appears to neutrino detectors to be a supernova going off nearby at 60 times per second. The physics of neutrino telescopes designed to observe supernova can be well studied at such a facility.

It is clear that in addition to the study of neutrino cross sections of interest to astrophysicists, fundamental properties of neutrinos can also be accurately studied at the SNS. The total flux of $\nu_\mu, \overline{\nu}_\mu$ and ν_e, the 600 ns pulse width, and the planned 2000 ton detector will make the precision measurement of $\sin^2\theta_w$ at very low momentum

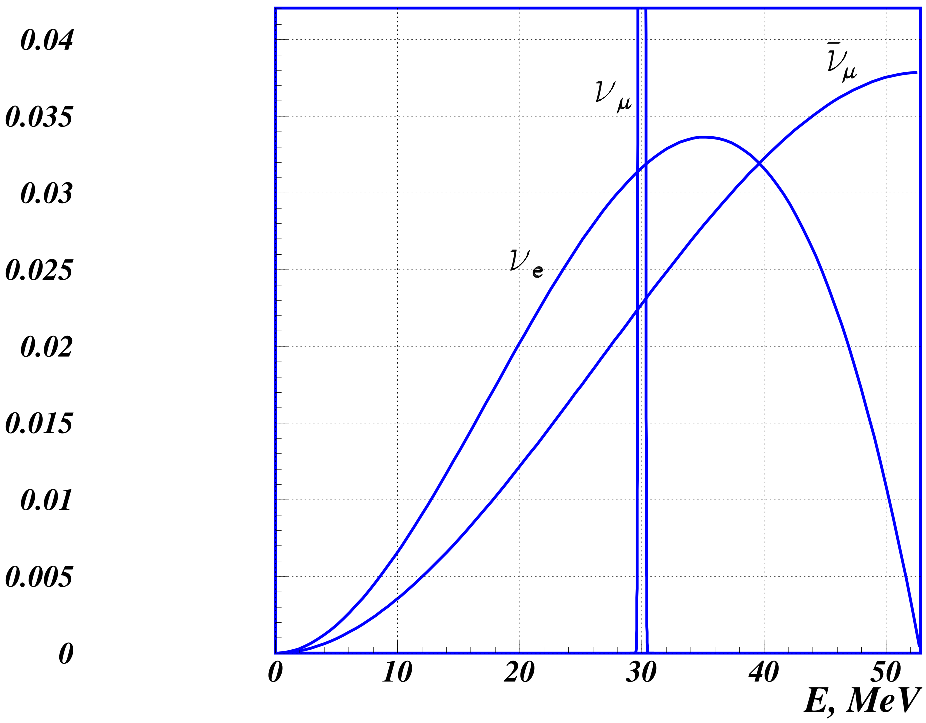

Figure 2: Neutrino spectra from pions decaying at rest.

exchange possible [5]. From this, the interference between charge and neutral currents in (νe^-) elastic scattering can be deduced far more accurately than reported recently by the LSND collaboration [6]. It will also be possible to probe the parameter space of $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations two orders of magnitude in $\sin^2 2\theta$ beyond present sensitivities, and one order of magnitude beyond the projected sensitivity of MiniBooNE [7]. Irrespective of confirmation of the LSND signal (or non confirmation) this extension of the $\delta m^2 - \sin^2 2\theta$ sensitivity is of importance to supernovae physics as well as Big Bang Nucleosynthesis.

3. Calibrating the Sun

One of the most important experiments presently ongoing to understand the sun and its production of neutrinos is that at the Sudbury Neutrino Observatory (SNO)[8]. The two reactions to be exploited are:

$$\nu_e + d \to p + p + e^-, \tag{3}$$

and

$$\nu_x + d \to n + p + \nu_x^{'}. \tag{4}$$

Reaction (4) obviously is completely blind to neutrino flavor $(\nu_e, \nu_\mu, \nu_\tau +$ anti $\nu_s)$. An accurate measurement of the neutral current rate would be enough to completely

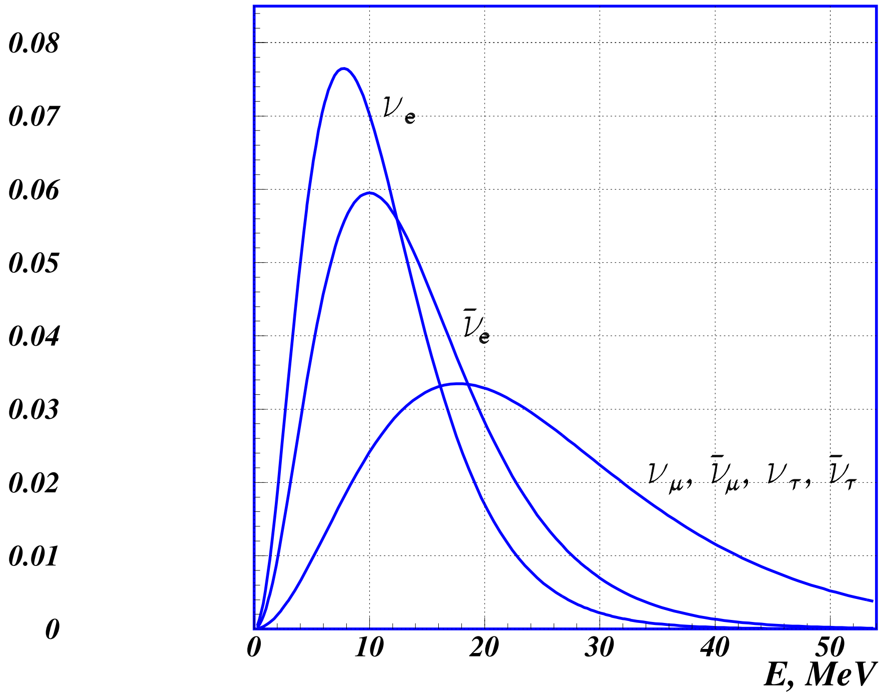

Figure 3: Typical neutrino spectra predicted from supernova during collapse assuming a Fermi-Dirac distribution with characteristic neutrino temperatures: $T(\nu_\mu\nu_\tau) \sim 8MeV$; $T(\overline{\nu}_e) \sim 4.5MeV$; $T(\nu_e) \sim 3.5MeV$.

determine the total production rate of ν_e's, independently of neutrino oscillations,but only as precisely as we know the cross section. The measurement of the ratio of the rates $R(\nu_e e^-)/R(\nu_x, \nu_x^{'})$ will be of great help to settle the solar neutrino problem, but again only if we know the cross sections. The only measured cross section is that of $d(\nu_e, e^-)pp$, and is known with an accuracy of 37% at a 68% confidence level [9]. The neutral current rate has only been measured with reactor neutrinos, and also with insufficient accuracy for use in the interpretation of SNO data [10].

A computational feasibility study has been made for a precision measurement of the cross section $\sigma[d(\nu_e, e^-)pp]$ at ORLaND. The detector configuration used in the study was an acrylic sphere containing d_2O, suspended near the center of the large detector containing either H_2O, or pure mineral oil. A sphere of ~ 5.5 meter diameter would contain ~ 100 tons of d_2O. The theoretical total cross section is $5.4 \times 10^{-41} cm^2$ [11] which would yield ~ 9000 events per year. The measurement of the excitation function would then be possible.

Let us assume that the rest of the 2000 ton volume was filled with H_2o. The theoretical cross section for $^{16}O(\nu_e, e^-)^{16}F$ is 6.1 times smaller so that there should appear a sudden difference in event rate between the d_2O and H_2O volumes, clearly defining the mean radius of the d_2O volume, and hence the fiducial volume. While a statistical accuracy $< 1\%$ is straight forward, the systematic errors due to the uncertainty in the neutrino flux and fiducial volume must also be very well controlled.

To achieve this, the neutrino - electron elastic scattering rate would have to be monitored throughout all of the experiments. This cross section, $\nu_x e^-$, is accurately predicted by the standard model, and its rate can be measured to $< 1\%$, but only with a 2000 ton detector. With this combination, one can hope to approach the measurement of $\sigma[d(\nu_e, e^-)pp]$ with an uncertainty between 2 and 3%.

One exciting possibility is to use this cross section to make an isospin rotation to independently determine the cross section [12] for the reaction:

$$p + p \rightarrow d + e^+ + \nu_e, \tag{5}$$

which is at the top of the chain of reactions that generates 99.75% of the neutrinos from the sun. One can also use the results of the effective field theory calculations [13] which reproduce this cross section, as well as that of the neutral current disintegration of the deutron, given in eq.(4), within an unknown parameter called a counter term. This counter term can be deduced from measuring the cross section of reaction (3) as a function of electron energy. This is an indirect calibration of the solar fusion rate. It is of crucial importance in the solar model, and holds one of the important keys to our understanding of energy production in the sun [14].

4. $d^2\sigma/dE_e d\Omega$ of the Reaction $^{16}O(\nu_e, \overline{e})^{16}F$

There are several motivations for this measurement. It is a rigorous test of theoretical treatments of weak interactions in nuclei [15]; it is an important reaction in the formulation of nucleosynthesis in stellar collapse models [4], and it is intimately connected to the core temperature of supernova through the forbidden contributions [16].

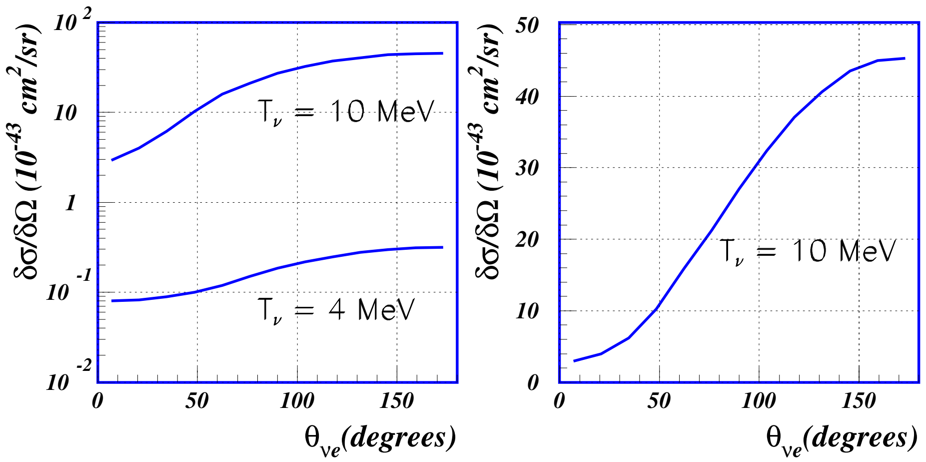

Figure 4: Differential cross sections for the reaction $^{16}O(\nu_e, e^-)^{16}F$, calculated by Haxton [16].

The calculation by Haxton [16] shows a very strong angular distribution of electrons from the reaction, with a very strong energy dependence as shown in figure 4.

Aside from a direct test of the weak interaction nuclear physics, this measurement would provide valuable information for the interpretation of supernova data recorded with large water Čerenkov detectors. Let us assume that there would not be neutrino oscillations of the type $\nu_\mu, \nu_\tau \to \nu_e$ from the collapse process. Then considering figures 4, we expect the emitted e^- to be almost isotropic and probably lost in the isotropic distribution of e^+ from $\overline{\nu}_e + p \to e^+ + n$. If, however, the ν_τ and ν_e escaping from the core at higher temperature, were converted to ν_e by oscillations, then they could be energetic enough to enjoy forbidden transitions to higher excited states of ^{16}F with a very strong back angle emission of e^-. This could be a unique signal for $\nu_\tau \to \nu_e$ oscillations.

The cross section calculated by Haxton, $<\sigma>= 8.84 \times 10^{-42} cm^2$ [16], results in a total event rate of 12,300 events per year, including the reduction due to the 30% detector efficiency. A precision measurement of $d^2\sigma/dEd\Omega$ would require about two years of data.

Two related reactions are those mediated by the weak neutral current, namely $^{16}O(\nu_x, \nu_x^{'} n\gamma)^{15}O$, and $^{16}O(\nu_x, \nu_x^{'} p\gamma)^{15}N$. These reactions have been investigated theoretically by Langanke, Vogel, and Kolbe [17], and Kolbe, Langanke, and Thielemann [18]. Using their cross sections, the reaction resulting in ^{15}O would produce $\sim 4 \times 10^3$ events per year, while that resulting in ^{15}N would result in $\sim 2.1 \times 10^4$ events per year. This reaction could be isolated from others by using the 600 ns pulse of ν_μ's, and identified by the resulting gamma rays. These reactions have also been suggested as mechanisms to explore the temperature of supernovae [17].

5. Neutrino-Electron Elastic Scattering

There are two compelling motivations for making precision measurements of this elastic scattering cross section. One is to use this fundamental process to obtain an accurate measurement of the neutrino flux. The other is to measure $\sin^2\theta_w$ at a very low value of momentum exchange [5].

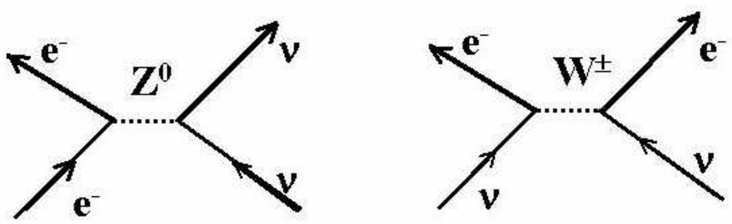

Figure 5: Feynman diagrams describing electron-neutrino elastic scattering.

The differential cross sections are given by [19]:

$$\frac{d\sigma(\nu_i)}{dT} = \frac{2G_F^2 m_e}{\pi}[g_{iL}^2 + g_R^2(1-\frac{T}{E_\nu})^2 - g_{iL}g_R\frac{m_e T}{E_\nu^2}] \qquad (6)$$

where i substitutes for e or μ, and

$$\frac{d\sigma(\overline{\nu_i})}{dT} = \frac{2G_F^2 m_e}{\pi}[g_R^2 + g_{iL}^2(1 - \frac{T}{E_\nu})^2 - g_{iL}g_R\frac{m_e T}{E_\nu^2}]. \tag{7}$$

In the above, $g_R = \sin^2\theta_w$; $g_{eL} = \frac{1}{2} + \sin^2\theta_n$, and $g_{\mu L} = -\frac{1}{2} + \sin^2\theta_w$. We define the ratio, R, as follows:

$$R \equiv \frac{\sigma(\nu_\mu e)}{\sigma(\nu_e e) + \sigma(\overline{\nu}_\mu e)}, \tag{8}$$

keeping in mind that ν_μ events can be cleanly separated from ν_e and $\overline{\nu}_\mu$ events using the pulse structure. Integrating over the electron's final kinetic energy, R can be expressed in terms of $\sin\theta_w$ as follows:

$$R = \frac{3/4 - 3\sin^2\theta_w + 4(\sin^2\theta_w)^2}{1 + 2\sin^2\theta_w + 8(\sin^2\theta_w)^2}. \tag{9}$$

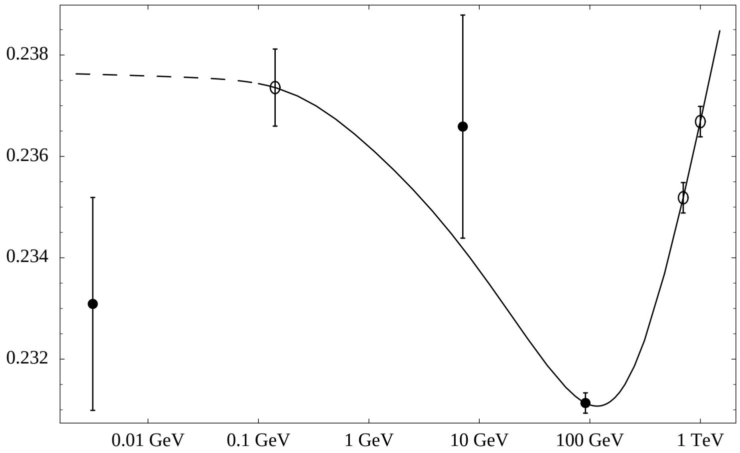

Figure 6: Predicted running of $\sin^2\theta_W$ and results of existing experiments (dark circles) along with expectations from future Møller scattering ($E158$) and e^+e^- asymmetry measurement at $\sqrt{s} = 1TeV$. (see ref. [5])

The accurate determination of the ratio of the counting rates in equation (8) would be the first accurate measurement of the interference between the two diagrams shown in Figure 5, although the LSND group has taken the first interesting step [6]. The ratio R can be taken directly from the event rates,

$$\frac{N(\nu_\mu)(\tau = 26ns)}{N(\nu_e) + N(\overline{\nu}_\mu)(\tau = 2.2\mu s)} \tag{10}$$

in which the flux cancels to an excellent approximation. The small correction due to early decays of muons can be made using equations (1) and (2).

These results can be used to measure $\sin^2\theta_w$ at a very low momentum exchange ($Q \simeq 0.002 GeV$). Previous Atomic Parity Violating experiments at low Q disagree with one popular method of determining the running of this fundamental parameter as shown in Figure 6. The experiment $E158$ is being prepared at SLAC. It involves electron scattering, and will involve radiative corrections. The νN experiment was performed at Fermilab [6]. The Z - pole determination, performed at LEP at CERN and at SLD is considered to be very reliable [20]. To be really interesting, the low - Q measurement would have to have an accuracy of $1 \leq \%$. Our computational feasibility study implies that this is possible with the 50% photo - cathode area coverage of the large detector and with the excellent pulse structure.

6. Neutrino Oscillations

The 2000 ton detector has been studied with extensive Monte-Carlo simulations, but only with a photo - cathode coverage of 25%. The combination of the detector fiducial volume (18 times that of the LSND), the $\overline{\nu}_\mu$ flux, and the pulse structure, it was determined that the statistical accuracy in the same live time would be 100 times that of LSND.

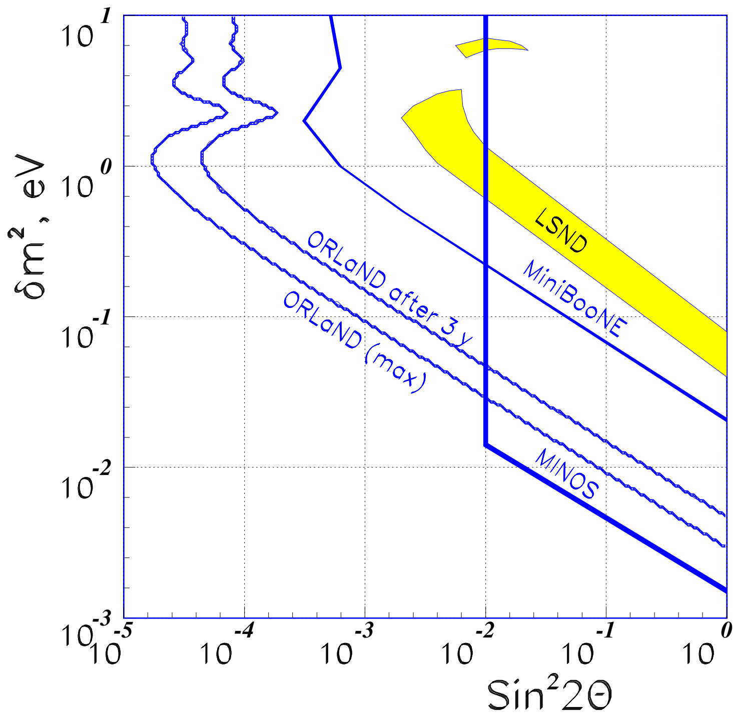

Figure 7: Projected sensitivities of the ORLaND large detector to $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations compared to MiniBooNe, MINOS, and the positive result reported by LSND.

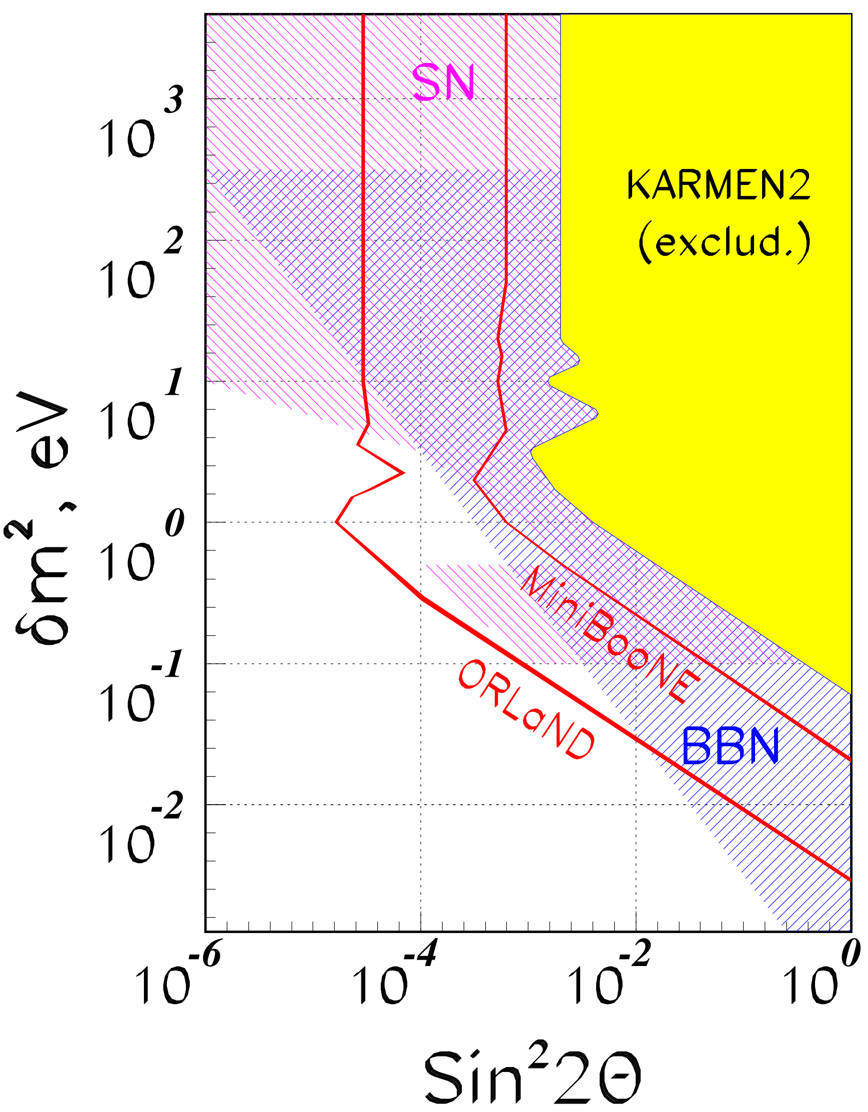

Figure 8: Projected sensitivity of the ORLaND large detector, MiniBooNE, and the region excluded by KARMEN. The lined areas denote regions of interest to Supernovae and Big Bang Nucleosynthesis models.

The technique involves searching for the appearance of $\overline{\nu}_e$ in a dilute scintillator filled detector. First, the Čerenkov cone from the positron from the reaction $\overline{\nu}_e + p \rightarrow e^+ + n$ is recorded. The neutron moderates and is captured in a mean time of $186\mu s$, resulting in a $2.2MeV$ γ - ray via the neutron capture reaction $n + p \rightarrow d + 2.2MeV\gamma$.

Figure 7 shows the projected sensitivity compared to the LSND result and the predicted sensitivity of the MiniBooNE experiment at Fermilab [1]. One unique feature of ORLaND is that the few $\overline{\nu}_e$'s that come from μ^- decay ($\overline{\nu}_e/\overline{\nu}_\mu \simeq 3 \times 10^{-4}$) come dominantly in the first $\sim 1\mu s$ due to the capture rates. Therefore it might be possible to experimentally explore this contamination for the first time. There are 4 other reactions that are sensitive to neutrino oscillations that can be utilized at ORLaND; however, we choose to discuss only the most sensitive here.

One very interesting possibility offered by the sensitivity discussed above is the ability to probe regions of δm^2 and $\sin^2 2\theta$ that have real impact on models of Big Bang Nucleosynthesis and nucleosynthesis in collapsing stars as shown in Figure 8 [21].

7. Neutrino-Nucleus Cross Sections

Charge-current and neutral current neutrino-nucleus cross sections are important inputs to numerical models of supernova [3]. The only reactions that have been measured at energies of interest in astrophysical processes are $d(\nu_e, e^-)pp$ $\pm 34\%$, $^{56}Fe(\nu_e, e^-)^{56}Co \pm 36\%$, and $^{12}C(\nu_e, e^-)^{12}N \pm 10\%$. Only the ^{12}C measurement is useful; however, it could be measured to a few percent or less at ORLaND for use as a neutrino flux monitor in future scintillator experiments.

Here we give a very brief description of a highly granular detector that can be used to make an accurate cross section measurement of the reaction $^{56}Fe(\nu_e, e^-)^{56}Co$, and many other targets as discussed below. More detailed descriptions have been given earlier [22].

The detector is similar in concept to the Soudan-II detector; it consists of 10^5 iron tubes, 10 mm in outside diameter, and with 0.5 mm thick walls. This is equivalent to 3400 tubes per ton for a tube length of 3.5 m. Each tube contains a gas detector that need only detect a hit by an energetic electron, and be capable of modest timing to determine position. The detector is designed to be placed 50 meters from the SNS target station and has 10^5 tubes stacked in a $3.5m \times 3.5m \times 3.5m$ cube. The fiducial volume is a cube $2.5m \times 2.5m \times 2.5m$ and has a fiducial mass of 13.5 tons. The theoretical cross section of Kolbe, Langanke and Martinez-Pinedo [23] ($< \sigma > = 2.73 \times 10^{-40} cm^2$) was used to determine that with a predicted 30% efficiency, the event rate would be 75 events per ton per year live time.

Detailed Monte-Carlo computations were made to determine that electrons traversing the detector can be distinguished from all other particles, except for positrons. The backgrounds are predicted to be extremely low. Cross sections of any element that can be made into a rigid tubs, with the mechanical strength to allow stacking, can be measured with an accuracy of $\sim 5\%$.

A list of some interesting targets, and their natural isotopic abundance follows: $^{9}Be(100\%)$, $^{11}B(80\%)$, $^{27}Al(100\%)$, $^{51}V(99.8\%)$, $^{52}Cr(84\%)$, $^{55}Mn(100\%)$, $^{56}Fe(92\%)$, $^{59}Co(100\%)$, $^{209}Bi(100\%)$, $^{181}Ta(100\%)$ and natural Pb.

Other techniques, liquid Čerenkov detectors, fine grained hanging file detectors of alternating planes of target and , scintillator can also be used to measure cross sections of neutrino interactions on : $^{7}Li(92\%)$, $^{12}C(98.9\%)$, $^{14}N(99.6\%)$, $^{16}O(99.8\%)$, $^{19}F(100\%)$, $^{23}Na(100\%)$, $^{28}Si(92\%)$, $^{31}P(100\%)$, $^{32}S(95\%)$, $^{39}K(93\%)$, $^{40}Ca(97\%)$, $^{45}Sc(100\%)$, $^{89}Y(100\%)$, $^{115}In(96\%)$, $^{127}I(100\%)$, $^{133}Cs(100\%)$, $^{139}La(100\%)$, $^{159}Tb(100\%)$ and $^{169}Tm(100\%)$.

Further study would be necessary to formulate the best strategies of most of these measurements, as well as setting priorities based on the best examples to "tune" nuclear structure models used in collapse models.

8. Summary and Conclusions

The construction of the Spallation Neutron Source at the Oak Ridge National Laboratory presents exciting potential opportunities to the field of neutrino astrophysics, of which Neutrino Telescopes play a central role. The proposed user facility called the Oak Ridge Laboratory for Neutrino Detectors (ORLaND) is being designed to accommodate a broad selection of neutrino experiments of importance in our field. The cost of the laboratory itself, including the base triple walled tank of the large liquid detector, was estimated by two engineering companies to cost about 2.5% of the SNS project. Proposals are in preparation for submission to the US DoE Office of High - Energy and Nuclear Physics for the laboratory, and to that office and separately to the National Science Foundation for the 2000 ton multi - purpose detector.

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The following are members of the ORLaND Large Detector Collaboration and others participating in the development of ORLaND science. The large detector is now called CoNDOR, the Comprehensive Neutrino Detector at Oak Ridge.

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