DRAFT - Fall 2010 Report from the LBNE Physics Working Group - DRAFT

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(Dated: August 22, 2010)

This document has been prepared by the LBNE Science Collaboration Physics Working Group coordinator and Topical Groups conveners at the request of the collaboration co-spokesmen and the Executive Committee. The primary purpose of this document is to assist in discussions of a collaboration statement on the Far Detector configuration. Nine topics have been identified as scientific areas that motivate construction of a long-baseline neutrino experiment with a very large far detector. We summarize the scientific justification for each topic, the expected state of knowledge in each area in 5/10/15 years, and the estimated performance in these areas for each of a set of Far Detector reference configurations specified in DUSEL/LBNE R&D Document 643-v2.

Contents

I. SUPERNOVA BURST PHYSICS

A. Motivation and Scientific Impact of Future Measurements

A nearby core collapse supernova will provide a wealth of information via its neutrino signal (see [16, 17] for reviews). The neutrinos are emitted in a burst of a few tens of seconds duration, with about half in the first second. Energies are in the few tens of MeV range, and luminosity is divided roughly equally between flavors. The baseline model of core collapse was confirmed by the observation of 19 neutrino events in two water Cherenkov detectors for SN1987A in the Large Magellanic Cloud, 55 kpc away [18, 19]. An observed high-statistics core collapse neutrino signal will shed light on a variety of physics and astrophysics topics.

Core collapses are rare events: the expected rate is 2-3 per century in the Milky Way. As for the Homestake and Super-Kamiokande detectors, the large DUSEL detector(s), once constructed, may operate for decades. On this time scale, there is a significant likelihood of a supernova exploding in our galaxy. In a 20-year run of an experiment, the probability of observing a collapse event is about 40%. The detection of the neutrino burst from such an event would dramatically expand the science reach of these detectors: from measuring the neutrino mass hierarchy and θ_{13} mixing angle, to observing the development of the explosion in the core of the star, to probing the equation of state of matter at nuclear densities, to constraining physics beyond the Standard Model. Each of these questions represents an important outstanding problem in modern physics, worthy of a separate, dedicated experiment. The possibility to target them all at once is very attractive, especially since it may come only at incremental cost to the project. The expected harvest of physics is rich enough that is essential to prepare to collect as much information as possible when a burst happens.

In contrast to the SN1987A, for which only 19 neutrinos were observed, the detectors currently on the drawing board would register thousands or tens of thousands of interactions from the burst. The exact type of interactions depends on the detector technology: a water-Cherenkov detector would be primarily sensitive to the electron antineutrinos, while a liquid argon detector has an excellent sensitivity to electron neutrinos. In each case, the high event rates imply that it should be possible to measure not only the time-integrated spectra, but also their second-by-second evolution. This is the key reason behind the impressive physics potential of the planned detectors.

The interest in observationally establishing the supernova explosion mechanism comes from the key role supernova explosions play in the history of the universe. In fact, it would not be an exaggeration to say that the ancient supernovae have in a very large measure shaped our world. For example, modern simulations of galaxy formation cannot reproduce the structure of our galactic disk without taking the supernova feedback into account. Shock waves from ancient supernovae triggered further rounds of star formation. The iron in our blood was once synthesized inside a massive star and ejected in a supernova explosion.

For over half a century, researchers have been grappling to understand the physics of the explosion. The challenge of reconstructing the explosion mechanism from the light curves and the structure of the remnants is akin to reconstructing the cause of a plane crash from a debris field, without a black box. In fact, the supernova neutrinos are just like a black box: they record the information about the physical processes in the center of the explosion during the first several seconds, as it happens.

The explosion mechanism is thought to have three distinct stages: the collapse of the iron core, with the formation of the shock and its breakout through the neutrinosphere; the accretion phase, in which the shock temporarily stalls at the radius of about 200 km, while the material keeps raining in; and the cooling stage, in which the hot protoneutron star loses its energy and trapped lepton number, while the reenergized shock expands to push out the rest of the star. All these stages are predicted to have distinct signatures in the neutrino signal. Thus, it should be possible to directly observe, for example, how long the shock is stalled. More exotic features of the collapse may be observable in the neutrino flux as well, such as possible transitions to quark matter or to a black hole. (An observation in conjunction with a gravitational wave detection would be especially interesting.)

To correctly interpret the neutrino signal, one needs to take into account neutrino flavor oscillations. Over the last decades, the oscillations have been firmly established in solar neutrinos and a variety of terrestrial sources, which means that including them in the supernova case is no longer optional. As it turns out, however, the physics of the oscillations in the supernova environment is much richer than in any of the cases measured to date. Neutrinos travel through the changing profile of the explosion, with stochastic density fluctuations behind the expanding shock. Their flavor states are also coupled due to their coherent scattering off each other. The net result is a problem that requires supercomputers, as well as state-of-the-art analytical models, to understand.

The effort to understand this complicated evolution has its reward: the oscillation patterns come out very different for the normal and inverted mass hierarchies. There are also several smoking gun signatures one can look for: for example, the expanding shock and turbulence leave a unique imprint in the neutrino signal. The supernova signal also has a very high sensitivity to values of θ_{13}, down to the levels inaccessible in any laboratory experiment. Additional information on oscillation parameters, free of supernova model-dependence, will be available if Earth matter effects can be observed in detectors at different locations around the Earth [20, 21]. The observation of this potentially copious source of neutrinos will also allow limits on coupling to axions, large extra dimensions, and other exotic physics (*e.g.* [22, 23]).

Two observations need to be made at this point. First, it would be extremely valuable to detect both the neutrinos and antineutrinos with high statistics, as the oscillations occur very different in the two channels. In fact, in the neutrino channel the oscillation features are in general more pronounced, since the initial spectra of ν_e and ν_μ (ν_τ) are always significantly different. Second, the problem is truly multidisciplinary and the neutrino physics and astrophysics go hand-in-hand. One needs to model both, and the payout one gets is simultaneous for both fields. For instance, one learns the sign of the neutrino hierarchy, the value of θ_{13}, the speed at which the shock expands, and the density profile of the star, "all in one package". The better one understands the astrophysics, the better the quality of information about neutrino physics, and vice versa. Hence it is essential to gather as much high-quality information as possible, and to optimize ability to disentangle the flavor components of the flux.

As a final note, because the neutrinos emerge promptly after core collapse, in contrast to the electromagnetic radiation which must beat its way out of the stellar envelope, an observed neutrino signal can provide a prompt supernova alert [24, 25]. This will allow astronomers to find the supernova in early light turn-on stages, which may yield information about the progenitor (in turn important for understanding oscillations). The LBNE detector(s) should be designed to allow prompt alert capability.

Several other experiments sensitive to supernova neutrinos will be online over the next few decades [16, 26]. However one should not consider these to be "competition" for LBNE: more experiments online during a supernova burst will only enhance the science yield from a supernova, and the ability to measure fluxes at different locations around the Earth will make the whole more than the sum of the parts [20].

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B. Sensitivity of Reference Configurations

The predicted event rate from a supernova burst may be calculated by folding expected neutrino differential spectra with cross-sections for the relevant channels, and with detector response. Although WCsim, the LBNE water Cherenkov simulation package, is nearly mature and can be used for some studies, LAr simulation packages are not yet ready for detailed studies of low energy response. Furthermore, neutrino interaction generators which properly handle products from interactions with nuclei in the tens-of-MeV range are currently lacking. For this reason, for this study we have chosen to do the event rate computation by using parameterized detector responses, making use of the GLoBES software [12]. We employ only the front-end rate engine part of GLoBES, and not the oscillation sensitivity part. GLoBES takes as input fluxes, cross-sections, "smearing matrices" and post-smearing efficiencies. The smearing matrices incorporate both interaction product spectra and detector response.

1. Supernova Neutrino Flux Models

We have examined several flux models. We assume fluxes at 10 kpc, which is just beyond the center of the Galaxy: event rates just scale as $1/D^2$.

We consider here the "Livermore" model [27], and the "Kneller" model [28]. The Livermore model was digitized using Fig. 1 of reference [27], assuming spectra given by eqn 10 of that reference. The model is somewhat out of date; however it is one of the few fluxes available for the full burst time interval, and it appears frequently in the literature, so it is considered for comparison purposes. The "Kneller" flux, provided by Jim Kneller, includes shock and collective effects. We consider also "Duan" fluxes [29, 30] for which different oscillation hypotheses have been applied: see sectionIV B 4. The "Duan" flux represents only a single late time slice of the supernova burst and not the full flux.

2. Event Rates in Water

Detector response assumptions for water are described in Appendix **??**.

The cross-sections for relevant interactions in water are shown in Fig. **??**. Some of these cross-sections– in particular, inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ (IBD) and elastic scattering (ES) of neutrinos on electrons $\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$ (both NC and CC) are known to few percent or better level. In contrast, others have relatively large uncertainties, and have never been measured in the few tens-of-MeV energy range.

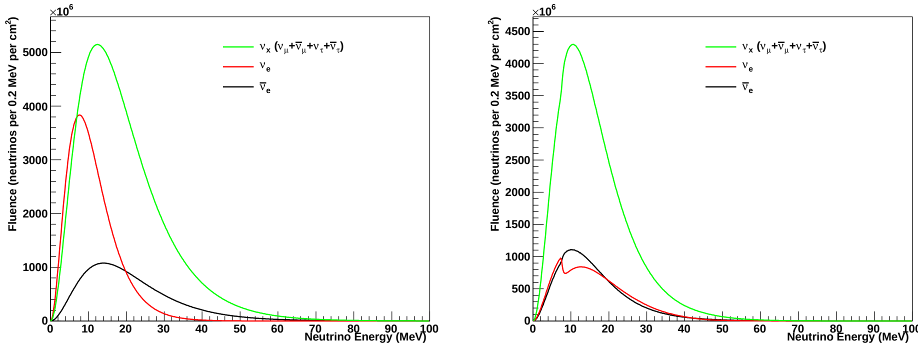

FIG. 1: Flavor components of the fluxes used for this study: red is ν_e, black is $\bar{\nu}_e$ and green is the sum of all other flavors. The left plot shows the "Livermore" model, integrated from $t = 0$ to $t = 14$ seconds. The right plot shows the "Kneller" model, integrated over 10 seconds.

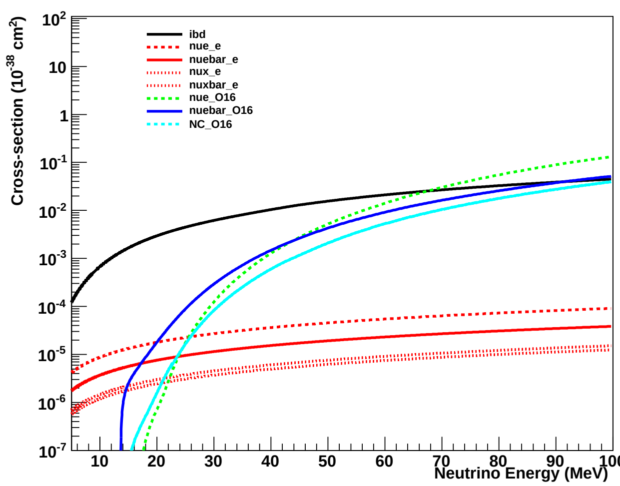

FIG. 2: Cross-sections for relevant processes in water.

In particular, interactions on oxygen, $\nu_e +^{16} \mathrm{O} \rightarrow e^- +^{16} \mathrm{F}$, $\bar{\nu}_e +^{16} \mathrm{O} \rightarrow e^+ +^{16} \mathrm{N}$, have diverse final states, including ejected nucleons and deexcitation gammas. For this study, we are considering only the lepton in the final state response for the CC interactions, taking into account the energy threshold. For the NC interaction with ^{16}O, $\nu_x +^{16} \mathrm{O} \rightarrow \nu_x +^{16} \mathrm{O}^*$, we are using a simplified model of the resulting deexcitation gammas by assuming relative final energy levels according to reference [31]. Because the reference does not provide differential final state information, we assume the distribution of these levels is independent of neutrino energy (which is an incorrect assumption, but probably not a terrible approximation). The resulting gamma cascade was simulated using relative probabilities of the transitions for a given excited state; the resulting gamma spectrum was then run through WCsim detector simulation. We found rather poor efficiency for detecting these gammas, in contrast to the results in reference [32], due to the fact that gammas frequently scatter electrons below Compton threshold.

Figure 37 shows the resulting differential energy spectra for the different channels. The plot on the left shows the interaction rates as a function of neutrino energy. The plot on the right shows the distribution of observed event energies in the detector. Table IV shows the breakdown of detected event channels, for two different specific supernova models.

These results show that IBD is overwhelmingly dominant: water Cherenkov is primarily sensitive to the $\bar{\nu}_e$ component of the flux. However there are non-negligible contributions from other channels. IBD positrons are emitted nearly isotropically; however, because ES and CC interactions on oxygen have anisotropic angular distributions, one

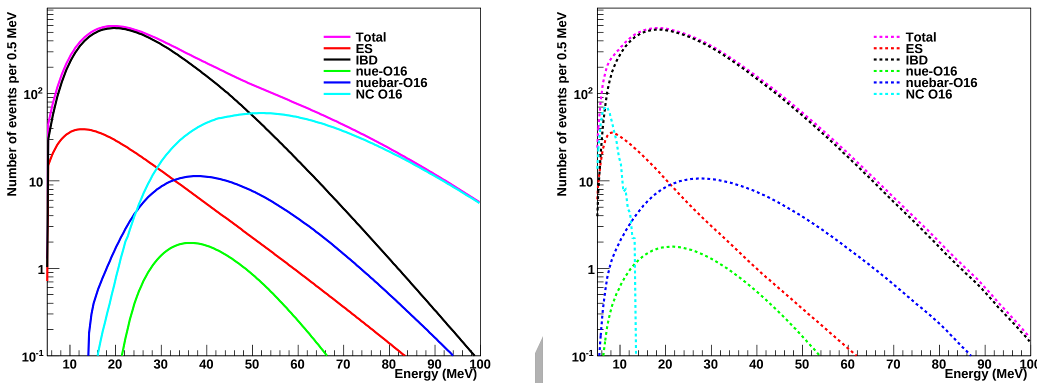

FIG. 3: Event rates in water, for the Livermore model and 30% coverage (events per 0.5 MeV).

Channel	Events, "Livermore" model	Events, "Kneller" model
$\bar{\nu}_e + p \rightarrow e^+ + n$	27116	16210
$\nu_x + e^- \rightarrow \nu_x + e^-$	868	534
$\nu_e +^{16}\mathrm{O} \rightarrow e^- +^{16}\mathrm{F}$	88	378
$\bar{\nu}_e +^{16}\mathrm{O} \rightarrow e^+ +^{16}\mathrm{N}$	700	490
$\nu_x +^{16}\mathrm{O} \rightarrow \nu_x +^{16}\mathrm{O}^*$	513	124
Total	29284	17738

TABLE I: Event rates for different models in 100 kt of water, for the 30% coverage reference configuration.

may be able to use the reconstructed Cherenkov angular information to help disentangle the flavor component. (Or, if the direction of the supernova is unknown, which is likely at early times, the angular information can be used to point to it [38, 39].)

We also note that different flux models can give substantially different event rates. In particular, because of the thresholds of the ^{16}O interactions, the rates of the CC interactions on oxygen are quite sensitive to the ν_e and $\bar{\nu}_e$ spectra.

Figure 38 shows the difference in observed event rates between the 15% and 30% reference configurations. For the 15% configuration, one loses about 9% of self-triggered events below ~10 MeV. The loss includes most of the NC excitation events.

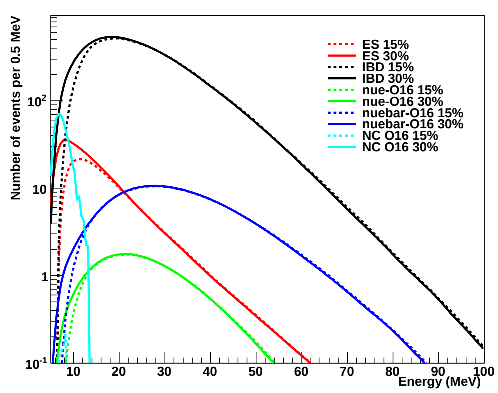

FIG. 4: Comparison of event rates for 15% and 30% PMT coverage configurations in 100 kt of water.

The addition of Gd to a water detector will not substantially change event rates, but will enhance ability to determine the flavor composition of an observed signal by allowing tagging of IBD events (although note that interactions on

^{16}O may produce ejected neutrons as well).

Because all of the supernova burst events arrive in a time window of a few tens of seconds, background is a much less serious issue than for relic supernova neutrino searches. For water detectors, it should be nearly negligible for Galactic bursts. To estimate it, we scale from Super-K [33, 34]: the rate in 22.5 kt with loose selection cuts is about 3×10^{-2} Hz at a 7 MeV threshold. Scaling by mass, this gives only about 4 background events in a 30 second burst. For a distant supernova search, background becomes more important and limits the distance sensitivity.

3. Event Rates in Argon

Detector response assumptions for LAr are described in Appendix **??**.

The cross-sections for interactions in argon [36, 37], are shown in Fig. 39. The uncertainties for the recent calculations are at around the 10% level. For the CC channels we have included energy deposition of the leading lepton; in the detector response, we also incorporate additional visible energy from deexcitation gammas (these gammas may also possibly help to tag the ν_e or $\bar{\nu}_e$ channels). We found no information in the literature about resulting excited levels for the NC interactions, so for the moment this channel is not included in the study, although event rates may be fairly large.

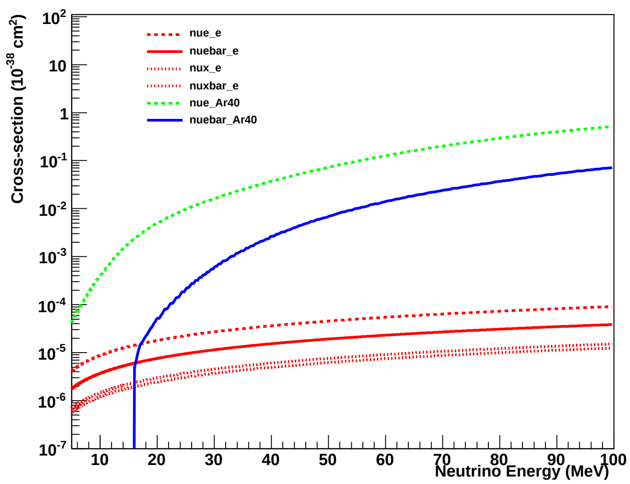

FIG. 5: Cross-sections for relevant processes in argon.

Figure 40 shows resulting interaction rates as a function of neutrino energy (left) and distribution of observed energies (right) in argon, for the "Livermore" model. Table V gives a table of event rates for two models. Note here that primary sensitivity is to the ν_e component of argon.

Channel	Events, "Livermore" model	Events, "Kneller" model
$\nu_e +^{40}\mathrm{Ar} \rightarrow e^- +^{40}\mathrm{K}^*$	1154	1424
$\bar{\nu}_e +^{40}\mathrm{Ar} \rightarrow e^+ +^{40}\mathrm{Cl}^*$	97	67
$\nu_x + e^- \rightarrow \nu_x + e^-$	148	89
Total	1397	1580

TABLE II: Event rates for different models in 17 kt of LAr.

For liquid argon, we have little information about backgrounds at the time of this writing, although again we can assume that they will be less of an issue for burst than for relic supernova neutrinos; furthermore backgrounds will be well known and can be statistically subtracted from a burst signal. We can assume that cosmic ray muons will be easily identifiable as long tracks, and Michel electrons can be tagged in association with muons. Backgrounds for supernova neutrinos in the range from 5-100 MeV will include events from radioactive products associated with muon spallation (some of which can be substantially delayed with respect to their parent muon). The distribution of spallation products in argon is currently unknown; however, most radioactive decays will deposit less than about

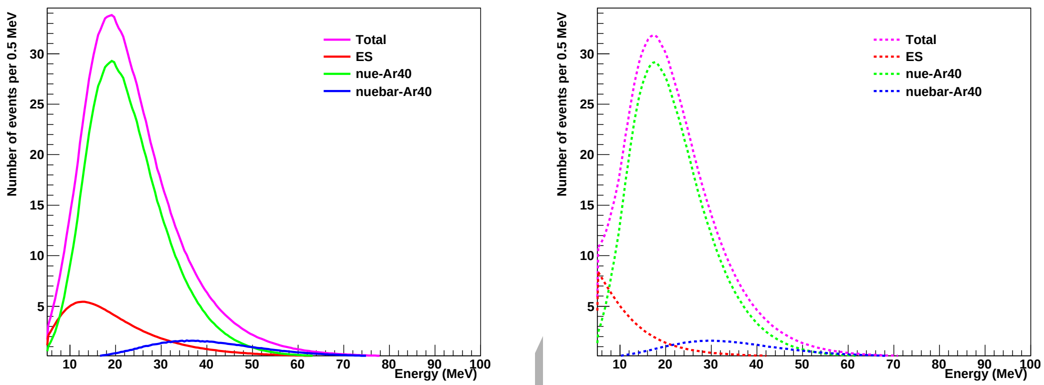

FIG. 6: Event rates in 17 kt of argon (events per 0.5 MeV).

10 MeV. At the 300 ft level, the muon rate in the detector will be about 1 kHz; at 800 ft it is about 100 Hz. Assuming that the fraction of muons producing radioisotopes which decay in the supernova neutrino range of interest (and which cannot be vetoed using space and time correlation information) is less than ~ 0.01, we can assume that this background will not be overwhelming during a nearby supernova burst, even at 300 ft.

4. Comparing Oscillation Scenarios

As described in the introduction to this section, there will likely be significant and observable imprints of oscillation parameters on the observed spectrum of burst supernova neutrino events. For oscillation sensitivity, ability to measure and tag the different flavor components of the spectrum is essential.

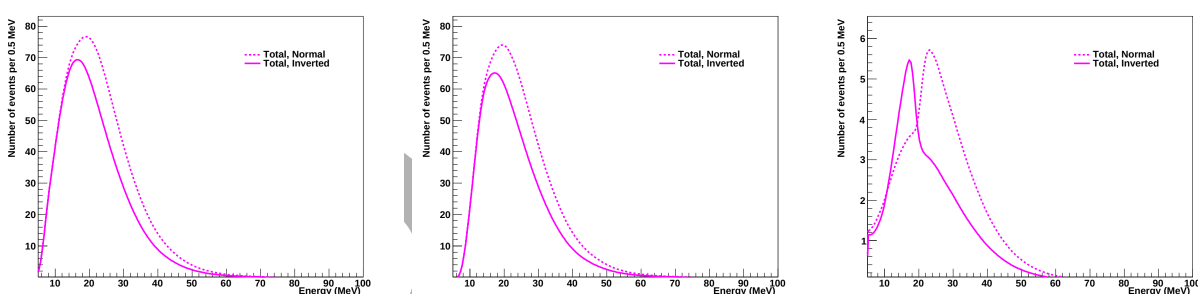

FIG. 7: Comparison of total event rates for normal and inverted hierarchy, for the Duan flux (a late time slice, not the full flux) , for WC 30% (left), WC 15% (center) and 17 kt LAr (right) configurations, in events per 0.5 MeV.

Figure 41 compares event rates for normal and inverted hierarchy, for a particular spectrum (a late time slice, not the full flux) provided by Huaiyu Duan [29]. While information about the hierarchy is clearly present in the water spectrum, which is mostly $\bar{\nu}_e$, the difference between the hierarchies is most dramatic in the observed mostly-ν_e argon spectrum.

We have attempted a simple quantification of the relative sensitivity of the different single detector configurations to mass hierarchy. Because fluxes with oscillation signatures are at this time only available representing a fraction of the total flux, we cannot evaluate the full statistical sensitivity. However we have done the following: we have determined the minimum statistics for which normal hierarchy is distinguishable from inverted hierarchy, for the Duan single-angle spectrum [29]. For water Cherenkov (either 15% or 30% coverage), approximately 3500 events are required to distinguish the hierarchy at 3σ; 15% and 30% PMT coverage configurations are equally sensitive, because the differences occur at relatively high energy. For LAr, about 550 events are required. Figure 42 shows examples of observed spectra for the different configurations and hierarchies, for statistics near distinguishability.

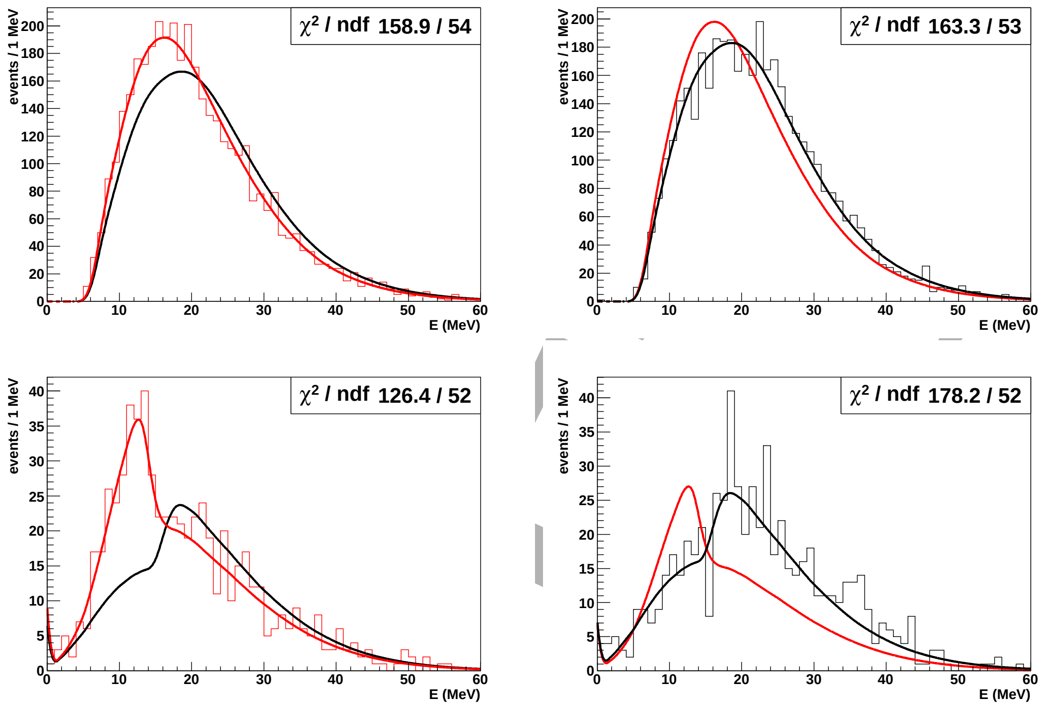

FIG. 8: Example fits to the expected spectral shapes for normal and inverted hierarchies for the Duan model. Top plots: 100 kt water, 30% PMT coverage, assuming 4000 events. Bottom plots: 17 kt argon, assuming 630 events observed. Left plots: true hierarchy is inverted. Right plots: true hierarchy is normal. The χ^2/dof is given for the fit to the "wrong" hierarchy.

Since number of events scales as inverse square of the distance to the supernova, we convert this to a *relative* figure of merit based on the distance at which hierarchy is distinguishable: assigning a value of 1 to the distance sensitivity of one 17 kt module of LAr, we assign relative distance sensitivity of other single-detector configurations according to $D_{\rm max}$(detector configuration)/$D_{\rm max}$(17 kt LAr). The results are reported in the last column of Table **??**. We assume that Gd loading will improve the sensitivity by enhancing the flavor tagging capability; a "+" is added if Gd is present. Although we have not yet made a quantitative evaluation of both LAr and water running simultaneously, it is certain that configurations for which two kinds of detectors are in operation (allowing sensitivity to both ν_e and $\bar{\nu}_e$ components of the flux) will be superior, and such configurations have an additional "+" added to their entry in the last column.

Although this study was done for one specific model, the relative evaluation of the configurations based on statistical reach can be considered reasonably robust.

C. Conclusions

Table **??** shows overall evaluation of the different reference configurations.

Sensitivity to physics in a supernova burst is good for any of the configurations; it improves with larger active mass. The 15% coverage gives somewhat degraded performance with respect to the 30% coverage: about 10% of the total number of events are lost. All of the loss is below 10 MeV and includes a very large fraction of NC ^{16}O excitation events. The addition of Gd will improve flavor tagging. We can state with confidence that a combination of different detector types offers the best physics sensitivity, because of ability to distinguish different flavor components of the supernova burst flux.

D. Next Steps

We have made preliminary estimates of event rates and simple "anecdotal" evidence of observability of oscillation features for a supernova burst signal. There are several improvements and further studies in progress.

Number	Detector configuration	Events in water at 10 kpc	Events in argon at 10 kpc	Relative hierarchy sensitivity
1	3 100 kt WC, 15%	60,000	N/A	2.6
1a	3 100 kt WC, 30%	66,000	N/A	2.6
1c	3 100 kt WC, 30% with Gd	66,000; enhanced flavor ID	N/A	2.6+
2	3 17kt LAr, 4850 ft, γ trig	N/A	4500	1.7
2a	3 17kt LAr, 300 ft, no γ trig	N/A	4500	1.7
2b	3 17kt, LAr, 800 ft, γ trig	N/A	4500	1.7
3	2 100 kt WC, 15% + 1 17 kt LAr, 300 ft, no γ trig	40,000	1500	2.1+
3a	2 100 kt WC, 30% + 1 17 kt LAr, 300 ft, no γ trig	44,000	1500	2.1+
3c	1 100 kt WC, 30% with Gd + 1 17 kt LAr, 300 ft, no γ trig	22,000; enhanced flavor ID	1500	1.5++
4	2 100 kt WC, 15% + 1 17 kt LAr, 800 ft, γ trig	40,000	1500	2.1+
4a	2 100 kt WC, 30% + 1 17 kt LAr, 800 ft, γ trig	44,000	1500	2.1+
4c	1 100 kt WC, 30% with Gd + 1 17 kt LAr, 800 ft, γ trig	22,000; enhanced flavor ID	1500	1.5++
5	1 100 kt WC, 30% with Gd + 2 17 kt LAr, 300 ft, no γ trig	22,000; enhanced flavor ID	3000	1.5++
6	1 100 kt WC, 30% with Gd + 2 17 kt LAr, 800 ft, γ trig	22,000; enhanced flavor ID	3000	1.5++

TABLE III: Summary of supernova burst capabilities of the reference configurations. See text for explanation of the last column.

- We will refine the detector response parameterization as simulations improve.
- The information on products (especially deexcitation gammas and ejected nucleons) of interactions on ^{16}O and ^{40}Ar is quite sparse in the literature. We will work on improving our modeling of these interactions. Other isotopes of oxygen and argon, although making a small contribution to the total signal, should also be considered. We will also study the effect of systematic uncertainties (*e.g.* on the cross-sections) on the physics sensitivity.
- Angular distributions of products will provide valuable information. ES and CC interactions on oxygen have pronounced anisotropy (IBD is weakly anisotropic). These anisotropies can be exploited for pointing to the core collapse [38, 39] (for an early alert, or to aid in finding the remnant in the case of weak supernova signal), for disentangling flavor components, and for making more precise measurements of the neutrino energy spectrum. We will evaluate the angular distribution of the expected signal.
- In practice, given a burst signal, one would perform a multiparameter fit to all available energy, angle and flavor information in order to extract supernova and oscillation physics. We will develop such an analysis and explore the physics sensitivity given different models.
- Matter oscillations in the Earth may provide additional information about neutrino oscillation parameters. We will explore the potential to observe physics signatures, possibly in conjunction with other experiments likely to be running over the next decades.
- At the moment we have very little information on the nature of spallation background in argon, on the potential quality of signal tagging in LAr using gammas, and on background reduction in an LAr detector. These issues are critical for evaluation of relic supernova neutrino sensitivity, and they may also be relevant for burst supernova neutrinos, especially for low-statistics bursts for core collapses beyond 10 kpc. We will continue to investigate these issues.

[1] Private collaboration document DUSEL/LBNE R&D Document 694-v2, http://nwg.phy.bnl.gov/DDRD/cgi-bin/private/ShowDocument?docid=694
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APPENDIX A: SUPERNOVA BURST PHYSICS SENSITIVITY ASSUMPTIONS

1. Assumptions for Event Rates in Water

We used WCsim to evaluate the detection response in water for the 15% and 30% PMT coverage configurations . At the moment, we do not yet have a perfect match between WCsim output in Super-Kamiokande mode and published SK detector parameters in the few to few tens of MeV range [40, 41]– the agreement is at about the 10% level. The resolution used as a function of electron energy is shown in Fig. **??**; it was scaled by a factor of 0.66 in order that WCsim SK-mode output match the resolution in reference [40] (in addition to minor simulation mismatch, we do not have all SK software tools for energy response reconstruction at our disposal for WCsim output, which likely accounts for some of the discrepancy).

Trigger efficiency is shown in Fig. **??** for the different configurations; this assumes a trigger requirement of 33 hits in 300 ns for the 15% PMT coverage configuration and 39 hits in 300 ns for the 30% configuration. (Note that we are assuming supernova neutrino events in water are self-triggered; one can imagine a configuration in which all digitized PMT hits are saved in the event of a high rate, which could improve efficiency.) These efficiencies are slightly worse than SK I [40] and SK II [41] efficiencies.

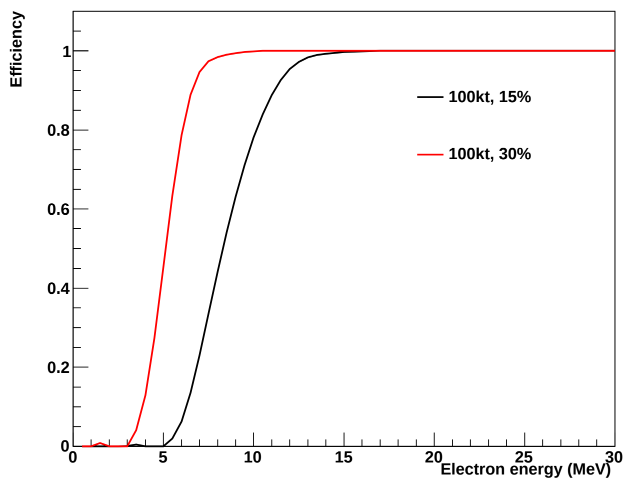

FIG. 9: Trigger efficiency as a function of electron energy, for 30% and 15% PMT coverages.

2. Assumptions for Event Rates in Argon

For event rate estimates in liquid argon, we are assuming a detection threshold of 5 MeV. We are assuming also that a photon trigger is not required for detection of supernova events; we assume that suitable triggering will be provided either from charge collection or from some external trigger. The energy resolution used is from reference[42], $\frac{\sigma}{E} = \frac{11\%}{\sqrt{E}} + 2\%$.

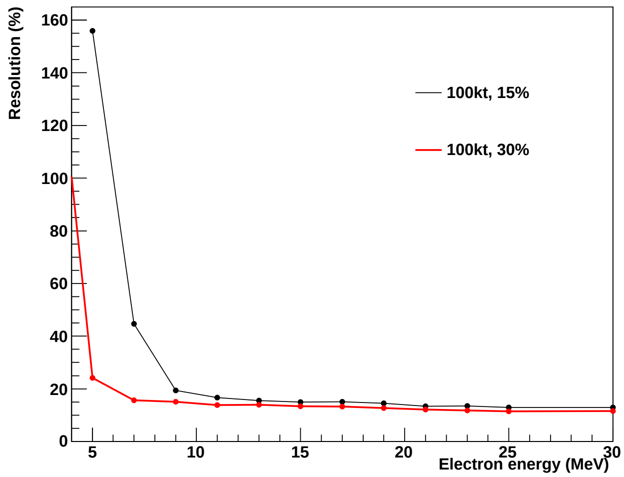

FIG. 10: Energy resolution as a function of electron energy, for 30% and 15% PMT coverages.