SN-Detection in LAr-TPC and the quest for (ν-Ar) Cross Sections

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Abstract. Neutrino-nucleus cross sections are of relevance to supernova astrophysics. These cross-sections can be grouped into three categories, those that affect supernova dynamics, supernova nucleosynthesis, and terrestrial supernova neutrino detection, each of which would benefit from experimental study. In this report only the relevance of an accurate knowledge of neutrino-target nucleus cross sections for SN detection will be discussed, in particular for the case of Argon, the active target material of LAr-TPC detectors currently under construction or proposed for future very massive underground experiments.

Keywords: Neutrino Absorption Reaction, SuperNova neutrino Detection, Liquid Argon Detector
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IMPORTANCE OF SN ELECTRON NEUTRINO SIGNAL

The absorption reaction of electron neutrinos on Argon nuclei ($^{40}\mathrm{Ar}_{18}$):

$$\nu_e + \mathrm{Ar} \rightarrow \mathrm{K}^* + e^- \tag{1}$$

has been proposed since 1986 [1, 2] as an alternative signature for real-time observation of low-energy astrophysical neutrino sources (solar neutrinos and neutrino bursts from gravitational collapse of massive stars) w.r.t. the traditional signatures like the elastic (e,ν_e) scattering in light or heavy water with electron detection by Cherenkov method, or like the (ν_e,d) capture also using Cherenkov detection of the final state electron in heavy water.

In these original studies [1, 2] only the (main) inverse β^- decay of ^{40}Ar ($J^\pi = 0^+, T = 2$) to the excited isobaric analog state at 4.38 MeV in ^{40}K ($J^\pi = 0^+, T = 2$, SuperAllowed Fermi transition) has been considered. The leading electron detection with LArTPC technology can be accomplished by a distinctive γ-rays (delayed) coincidence signature from ^{40}K de-excitation, with powerful background rejection.

Successively, shell-model calculations [3] (valid for ν-energy up to about 15-20 MeV, i.e. for the high energy component of the solar neutrino spectrum) showed that including several Gamow-Teller transitions to low-lying $J^\pi = 1^+, T = 1$ states of ^{40}K with excitation energies between 2.29 to 4.79 MeV leads to a significant enhancement of the overall absorption cross section. The GT matrix elements pertinent to ^{40}Ar neutrino absorption were experimentally confirmed [4] from measurement of branching ratios of the β-decay of ^{40}Ti to levels in ^{40}Sc (the mirror nucleus of ^{40}K).

In a further work [5] the Fermi and Gamow-Teller transition strengths have been measured leading to excited states up to 6 MeV in $^{40}\mathrm{K}^*$ and obtained the neutrino absorption cross section in ^{40}Ar extended into the supernova neutrinos range.

The detection and analysis of supernova neutrinos with LAr detectors requires knowledge of the neutrino-induced cross sections on ^{40}Ar for neutrinos (and antineutrinos) with energies up to about 100 MeV, with daughter nucleus excitations at high energies. An appropriate shell model calculation which describes GT strength at these energies is currently not available. However, (continuum) random phase approximation (RPA) for forbidden transitions of the $^{40}\mathrm{Ar}(\nu_e,e^-)^{40}\mathrm{K}$ reaction have been performed [6] considering allowed and forbidden multipoles up to $J = 6$. GT transitions dominate the (ν_e,e^-) cross section for neutrino energies $E_\nu < 50$ MeV; at higher energies forbidden (in particular spin-dipole) transitions cannot be neglected. These are dominated by the collective response to giant resonance, so that the RPA model [6] is usually considered sufficient to describe these non-allowed contributions.

A more recent, independent calculation done for the neutrino absorption cross sections [7] makes use of the local density approximation (LDA) taking into account the nuclear medium effects. The Coulomb distortion of the electron wave function in the field of the final nucleus is treated with the Fermi function as well as in the modified effective momentum approximation (MEMA).

The results from this model are compared with the other results cited above [3, 5, 6] for the total absorption cross section $\sigma(E_\nu)$ as a function of neutrino energy E_ν. The respective cross sections are shown in Fig.1.

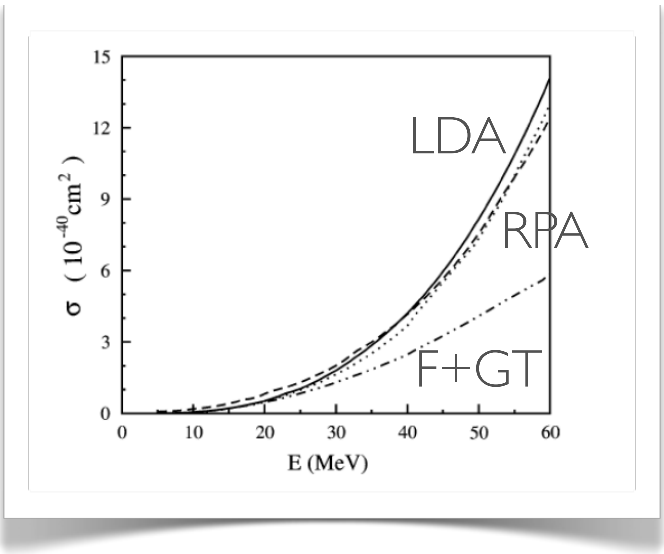

FIGURE 1. *Total cross section σ_{ABS} vs. E_ν for $\nu_e + \mathrm{Ar} \rightarrow \mathrm{K}^* + e^-$ reaction for LDA [7] with Fermi function (solid line) and with modified effective momentum approximation (dashed line), Shell Model [3] (dashed-double dotted line) and RPA [6] (dotted line). The plot is taken from [7].*

At this conference the latest result neutrino-Ar absorption cross sections from theoretical calculations, based on a Hybrid Model [Shell-Model (F+GT) + Random Phase Approximatiom] have been presented [T. Suzuki [8], these Proceedings] and agree well with the RPA calculation of [6].

The results show that the theoretical uncertainty due to nuclear model dependence in predicting the total event rates for argon based detector is not too large.

In summary, the absorption reaction of electron neutrinos on Argon nuclei from recent theoretical calculations, was found to be large (and much larger than previously estimated) in the energy range of interest for SN neutrinos, with low Q-value of few MeV to the lowest-lying levels of the final nuclear state. It should be also noticed however, that no direct measurements of $\nu_e(^{40}\mathrm{Ar},^{40}\mathrm{K}^*)e^-$ cross section have ever been performed in this energy range.

GALACTIC SN-ν DETECTION WITH LIQUID ARGON DETECTORS

The large absorption reaction of electron neutrinos on Argon nuclei, theoretically calculated with different methods by various authors, opens up interesting perspectives for galactic SN-ν detection with liquid argon detectors even at moderate mass scale.

In the range of the hundreds tons (e.g. for the MicroBooNE Experiment at FNAL with about 100 t of LAr) up to some tens of ν_e events per 100 t of (active) mass can be expected in case of a 10 kpc galactic SN event.
This rate largely depends however on the choice of the astrophysical parameters - neutrino temperature, pinching factor, partition,.. in the SN model as well as on the neutrino physical parameters (θ_{13} - recently determined to be large - and mass hierarchy) and the way neutrino oscillation through the dense stellar medium during the SN explosion phases are accounted for. How the number of events changes, with reasonable changes of the input parameters, has been evaluated in [9] and reported here. The percentage variation $100 \times \delta N/N$ of the number of absorbed ν_e under a number of alternative hypotheses is shown in the Table below:

$T+\Delta T$	$T-\Delta T$	$f \rightarrow 1/8$	$\eta \rightarrow 2$	$P_{ee} \rightarrow 0.3$
+51 %	−45 %	−25 %	+15 %	−16 %

The first two columns show the effect of changing the temperature by $\Delta T = \pm 1.3$ MeV; the third column, describes the effect of non-equipartitioned fluxes; the fourth one, the effect of having a pinched (‘non-thermal’) spectrum.

The last column assumed that $\nu_e \to \nu_2$ due to very small θ_{13}. This hypothesis (and related uncertainty) is now washed out from the recent indications of the large θ_{13} value that implies $P_{ee} = 0$. This shows that the present uncertainty in the temperature has a big impact on the expected signal, about 50 %. It shows also that a *mixture* of various phenomena can affect the flux at the $\sim$ 20 % level. To separate these effects clearly, it will be important to study several properties of the neutrino signal, like distributions in time and energy and use several reactions with different detectors.

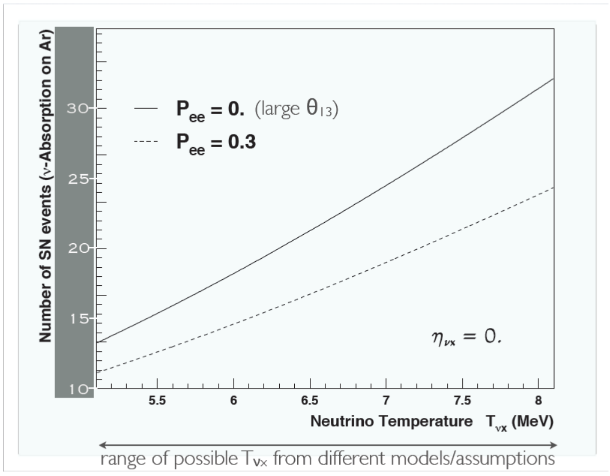

FIGURE 2. *Number of expected ν_e events as a function of the effective temperature. A reference 100 t detector mass (corresponding to $1.5 \cdot 10^{30}$ Ar targets) is considered. (for simplicity, an ideal detector without threshold on the final state electron energy and full detection efficiency is assumed). The cross-section 'hybrid model' for ν_e-absorption on Argon is used (shell model [3] for allowed transitions, and RPA [6] for forbidden transitions). Neutrino fluence is taken with T free to vary and pinching parameter set at $\eta = 0$. The other SN parameters are: $D = 10$ kpc, $f = 1/6$ (strict equipartition), and $\mathscr{E}_B = 3 \times 10^{53}$ erg. Oscillation are separately accounted: full line corresponds to the large, now well established value of θ_{13}.*

In Fig. 2 we show the calculated number of expected events for a 100t of LAr mass (on the scale of the MicroBooNE detector) for a wide range of values of the effective temperature.

The distinctive feature of the Ar target relies on the sensitivity to the electron-neutrino component of the SN-ν flux, opposite the the “traditional" WC or scintillator detector primarily sensitive to the electron-antineutrino component. Combined information from neutrino and antineutrino detection can provide important additional hints about the SN explosion mechanism but also about the neutrino intrinsic properties.

ABSORPTION CROSS SECTION DIRECT MEASUREMENT AT ν-SNS

Direct measurement of the $\nu_e(^{40}\text{Ar},^{40}\text{K}^*)e^-$ cross section at p-beam dump facilities has been repeatedly advocated by many among the authors [1, 6, 7, 8] of the theoretical calculations here referenced. Electron neutrino reactions in ^{40}Ar can be experimentally studied with the muon decay at rest (DAR) neutrinos, whose energy spectrum, with maximum energy E_ν^{max}=53 MeV, is similar to the SN neutrinos spectrum.

Opportunities for Neutrino Physics at the Spallation Neutron Source (ν-SNS) of the Oak Ridge National Laboratory, including measurement of the $\nu_e(^{40}\text{Ar},^{40}\text{K}^*)e^-$ cross section with LArTPC detectors, have been recently reviewed and reported in [10].

Neutrinos fluxes at the Oak Ridge ν-SNS facility [10, 11] , with a nominal (time integrated) ν_e Fluence $F_{\nu e} = 6 \times 10^{14} \nu/cm^2$ at D=20 m, allows the collection of a large number of absorption events of the order of $N_{evt} \simeq 1800$ per ton of LAr per yr (assuming the theoretical cross section from [7] or [6] or [8]).

A $1 \times 1 \times 2$m^3 (3 t) LArTPC detector looks thus definitively adequate, considering that for LArTPCs the detection efficiency ε_{Det} can be assumed close to 1 and the fiducial volume cut for containment of the final state event topology should be small ($V_{Fid} \simeq V_{Active}$).

The neutron background (faking the ν_e absorption signature) is small, due to the high rejection capability of the imaging LArTPC technology. Cosmic ray background and trigger efficiency need however to be understood and carefully evaluated (LArTPC is a “slow" read-out detector - e.g. 600 μs for 1 m drift).

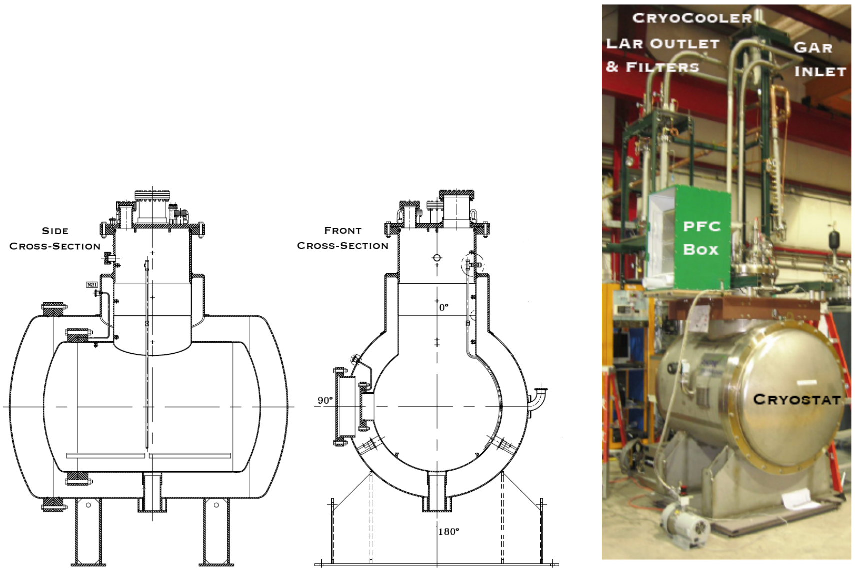

FIGURE 3. *[Left] Side and Front Cross-Section views of the* ArgoNeuT *cryostat. The inner and outer vessels, the chimney on the top and the removable end-caps at one side are visible in the drawings. [Right] Picture taken during assembly with details of the cooling and recirculation system (the 4-pipe pathways of the recirculation circuit and the cold head of the cryocooler located inside a vacuum-insulated containment vessel).*

In principle, a smaller detector as the existing ArgoNeuT LArTPC detector [12][1] can also be used. The ArgoNeuT detector, shown in Fig.3, made of a 550 lt cryostat and a TPC of $40\ h \times 47\ w \times 90\ l$ cm^3, corresponding to about $\sim$170 liters of LAr active volume can detect about 350 evt/yr in ArgoNeuT at the ν-SNS, in case a suitable location at 20 m distance from the target is made available. Though the statistics is limited, a first direct measurement of the ν_e absorption reaction on Argon can be afforded.

The absorption reaction signature from ν-SNS (as well as from SN neutrinos) in a LArTPC detector is well defined. It consists of one primary, prompt energetic e-track (with el.m. shower activity when above 30 MeV, the critical energy in LAr) surrounded by a cluster of secondary e-tracks in a volume ($r \simeq 50$ cm) around the primary vertex in the MeV range and below from Compton conversion of K* de-excitation γ's (in LAr $X_0 = 14$ cm).
The energy of the prompt recoil electron yields the neutrino incident energy. The total energy of the secondary photons (partly prompt and partly delayed) corresponds, when all the Compton electrons were detected, to the K* level above ground state of the nuclear transition.

An event recorded by the ICARUS T600 detector during the commissioning test run on surface in 2001 has been shown [13]. Its topological signature, shown in Fig.4, with an e-like track and a couple of localized energy depositions in the surrounding volume, is similar to the expected signature for a SuperNova or ν-SNS neutrino interaction in LAr. The event was induced by cosmic ray interaction in the material surrounding the LAr volume.

With LArTPC detectors, only a modest cut of about E$^{thr} = 8$ MeV in the neutrino energy spectrum is required. This threshold is determined by a minimum energy around 5 MeV for the leading electron track identification, in addition to the Q-value of the (^{40}Ar,^{40}K*) nuclear transition (2.3 MeV to the lowest-lying GT level), but an accurate calibration of the detector energy response is necessary.

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[1] The ArgoNeuT detector is presently committed for an extended run at the Fermilab Test beam Facility (2012-14) - LArIAT Experiment. A subsequent transportation and use at the OakRidge Lab ν-SNS facility should be agreed with the Institutions who own different components of the detector and readout system.

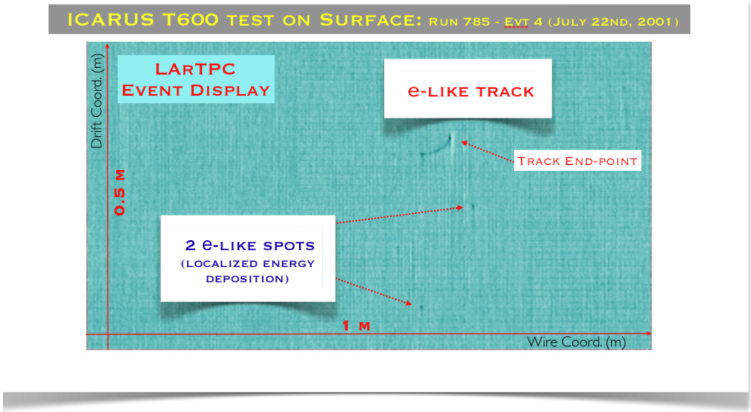

FIGURE 4. *Cosmic ray background induced event from ICARUS T600. An electron-like track of about 11 cm is visible, with two nearby el.m. spots.*

OUTLOOK

The Spallation Neutron Source facility at the Oak Ridge National Laboratory provides with an intense neutrino flux from muon DAR in a energy range (up to $m_\mu/2$) nicely overlapping the expected SN neutrino range. A LArTPC detector of modest mass, of the order of a ton (or even less) in suitable location at the shortest possible distance from the p-target (e.g. 20 m), can detect thousand events per year, allowing for a first and indispensable measurement of the so far unmeasured neutrino cross section of the absorption reaction, the relevant channel for SN detection with LAr based detectors. The experimental result in comparison with the theoretical results available form various models will be extremely helpful in understanding and constraining the theoretical uncertainties in the neutrino nuclear cross sections in the SN energy region.

The final goal of reducing the cross section uncertainty to the order of 10% (or less, possibly) would open the possibility to access the parameter space of the current SN models, in the lucky circumstance of a stellar core collapse event in our Galaxy detected by a large mass LArTPC detector at Earth.

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