Supernova neutrino detection

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Supernova neutrino detection

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Abstract. When a massive star collapses at the end of its life, nearly all of the gravitational binding energy of the resulting remnant is released in the form of neutrinos. The burst of neutrinos from a Galactic core collapse supernova will be detected in neutrino detectors worldwide. This talk will cover supernova neutrino detection techniques in general, current supernova neutrino detectors, and prospects for specific future experiments.

1. Neutrinos from core collapse supernovae
A core collapse supernova will produce a burst of neutrinos of all flavors with energies in the few tens of MeV range. References [1, 2, 3] describe some of the expected features of a core collapse neutrino signal. Because of their weak interactions, the neutrinos are able to escape on a timescale of a few tens of seconds after core collapse (the promptness enabling a supernova early warning for astronomers [4]). An initial sharp “neutronization burst” of $\nu_e$ (representing about 1% of the total signal) is expected at the outset, from $p + e^- \rightarrow n + \nu_e$. Subsequent neutrino flux comes from NC $\nu\bar{\nu}$ pair production. Electron neutrinos have the most interactions with the proto-neutron star core; $\bar{\nu}_e$ have fewer, because neutrons dominate in the core; $\nu_\mu$ and $\nu_\tau$ have yet fewer, since NC interactions dominate for these. The fewer the interactions, the deeper inside the proto-neutron star the neutrinos decouple; and the deeper, the hotter. So one expects generally a flavor-energy hierarchy, $\langle E_{\nu_{\mu,\tau}} \rangle > \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$.

Neutrino oscillations can strongly affect the neutrino fluxes. Matter oscillation effects that come into play as the neutrinos traverse dense stellar matter leave imprints on the spectra. In addition, “collective oscillations” are likely important: in the extreme hot and dense protoneutron star environment, interactions of neutrinos with neutrinos become important, and the resulting non-linear Hamiltonians give rise to a complex phenomenology of the neutrino fluxes (e.g. [5, 6]). To probe experimentally these effects, both for core collapse physics studies and to learn about neutrino properties, measurements giving information about the neutrino spectra for different flavors are essential.

So far the only supernova neutrino observation is from SN1987A [7, 8, 9, 10], and we expect enormously enhanced information from the next nearby observation.

2. Supernova neutrino detection
From a neutrino experimentalist’s point of view, the basic strategy is to prepare to collect as many neutrino events as possible, of as many flavors as possible. A back of the envelope calculation shows that one typically gets a few hundred neutrino interactions per kton of detector material for a core collapse event at 10 kpc, just beyond the center of the Milky Way. For a
successful observation, the detector background rate must not exceed the supernova signal rate in a 10 second burst: this criterion is easy to satisfy for underground detectors, and is even thinkable for many near-surface detectors. One would like to have event-by-event timing resolution, ability to measure neutrino energies, and if possible, ability to use the neutrino information to point back to the supernova. Sensitivity to all flavors of the burst is extremely desirable: $\nu_\mu$ and $\nu_e$ flavors comprise two-thirds of the burst’s energy, but because supernova neutrino energies rarely exceed a few tens of MeV, these components of the flux are overwhelmingly below charged current (CC) interaction threshold, and neutral current (NC) sensitivity is required to detect them. It will be especially valuable for detectors to have ability to tag interactions as $\nu_e$, $\bar{\nu}_e$, and $\nu_{\mu,\tau}$ as well as just to collect them.

Currently the world’s primary sensitivity to supernova neutrinos is via inverse beta decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$. In this reaction, the produced positron has the energy of the neutrino, less 1.8 MeV; the positron’s energy loss is the primary means of detection. There are furthermore two possible tags of IBD: a prompt positron annihilation produces two 0.511 MeV $\gamma$ rays, and the neutron may also be observable via its time-delayed capture on a nucleus. In any detector with lots of free protons, IBD typically dominates by orders of magnitude.

Elastic neutrino-electron scattering (ES), $\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$, which occurs via both CC and NC channels, has a relatively small cross-section: the rate is a few percent of the IBD rate in scintillator and water Cherenkov detectors. Nevertheless the ES component of the supernova neutrino signal will be especially interesting, because it is directional. It is in fact the best way of using a neutrino detector to point back to the supernova’s location [11].

CC interactions can occur for bound as well as free nucleons. Reactions of both $\nu_e$ and $\bar{\nu}_e$ can occur, with the production of an electron or positron: $\nu_e + (N,Z) \rightarrow (N-1,Z+1) + e^-$; $\bar{\nu}_e + (N,Z) \rightarrow (N+1,Z-1) + e^+$. Cross-sections are typically smaller for bound than for free nucleons, but can nevertheless be non-negligible. The charged lepton is usually observable, and CC interactions sometimes can be tagged in other ways, e.g. via detection of ejected nucleons or nuclear de-excitation $\gamma$ rays. Various NC interactions on nuclei also have cross-sections that yield reasonable rates, and as for the CC case, sometimes a nice tag is possible via ejected nucleons or de-excitation $\gamma$’s. Furthermore, NC coherent scattering on protons [12] or nuclei [13] is possible and measurable by detectors with sufficiently low energy threshold. Only the $\nu_e$ and $\bar{\nu}_e$ components of the supernova neutrino signal are accessible via CC interactions. Because NC interactions are flavor-blind, they measure the total flux, including the $\nu_\mu$ and $\nu_\tau$ components. Both CC and NC cross-sections and the nature of the observables are dependent on the nuclear physics of the specific nucleus involved, and in many cases there are large theoretical uncertainties and no measurements.

Specific detector types include water Cherenkov detectors (e.g. Super-Kamiokande [14]) which exploit primarily IBD; tagging may be enhanced by Gd-doping [15]. Interactions on oxygen also make up some of the signal [16], especially if low energy threshold can be attained [17]. Planned future large water Cherenkov detectors include LBNE [17], Hyper-K [18], and MEMPbHYS [19]. The use of water Cherenkov detectors for supernova neutrino detection can be extended to detectors like IceCube that are made of long strings of sparsely distributed photomultiplier tubes embedded in ice or water, which may be able to observe a coincident increase in single count rates from many phototubes due to a large number of IBD-induced Cherenkov photons in the surrounding ice or water [20, 21].

Hydrocarbon-based (usually scintillator) detectors also exploit primarily IBD (e.g. Baksan [22], LVD [23], KamLAND [24], Borexino [25], and even surface detectors such as Mini-BooNE [26] and NO$\nu$A [27].) Scintillation detectors can often achieve quite low (sub-MeV) energy thresholds, and therefore have potential for neutron capture and/or $\gamma$ tagging, as well as detection of $\nu p$ elastic scattering. However because scintillation light is emitted isotropically, pointing capability is generally poor. In scintillator 15.5 MeV de-excitation $\gamma$-ray tags the NC
excitation of $^{12}\text{C}^\ast$, $\nu_e + ^{12}\text{C} \rightarrow \nu_x + ^{12}\text{C}^\ast$. The SNO+ [28] detector is now under construction. Proposed large future detectors include HanoHano [29] and LENA [30].

A particularly nice tagged $\nu_e$ channel is available in argon, $\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^\ast$; the $^{40}\text{K}^\ast$ de-excitation $\gamma$’s would be observable in liquid argon time projection chamber detectors (e.g. Icarus [31]), assuming suitable triggering is implemented. Proposed large liquid argon detectors are LBNE [17], GLACIER [32] in Europe, and detectors in Japan [33].

A particularly promising future possibility for supernova neutrino detection is a lead-based neutrino detector, for which the cross-section is high for NC as well as CC channels. For either $\nu_e + ^{208}\text{Pb} \rightarrow e^- + ^{208}\text{Bi}^\ast$ or $\nu_x + ^{210}\text{Pb} \rightarrow \nu_x + ^{210}\text{Pb}^\ast$, the lead nucleus subsequently emits one or two neutrons [34, 35]. The relative rates for the different channels in lead depend on neutrino energy, which promises some spectral and flavor information from a supernova burst observation. The new HALO detector [36] is under construction, which makes use of the $^3\text{He}$ neutron counters from SNO.

3. Current and future supernova neutrino detectors

Table 1 summarizes existing and planned detectors. Currently running detectors have sensitivity primarily to the $\bar{\nu}_e$ component of the signal, via IBD $\bar{\nu}_e + p \rightarrow n + e^+$, which is the dominant component for water Cherenkov and scintillator. For supernova burst detection, one wants not only statistics but also diversity of flavor sensitivity: NC sensitivity, which gives access to the $\nu_\mu$ and $\nu_\tau$ components of the flux, and $\nu_e$ sensitivity are particularly valuable. Near future (within next five years or so) new argon, lead and scintillator detectors with supernova neutrino sensitivity should enrich the flavor sample. In the farther future, we can expect mega-detectors to provide huge statistics.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>Mass (kton)</th>
<th>Location</th>
<th>Events at 10 kpc</th>
<th>Live period</th>
</tr>
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<tbody>
<tr>
<td>Baksan</td>
<td>$^3\text{He}$</td>
<td>0.33</td>
<td>Caucasus</td>
<td>50</td>
<td>1980-present</td>
</tr>
<tr>
<td>LVD</td>
<td>$^3\text{He}$</td>
<td>1</td>
<td>Italy</td>
<td>300</td>
<td>1992-present</td>
</tr>
<tr>
<td>Super-K</td>
<td>$^3\text{He}$</td>
<td>32</td>
<td>Japan</td>
<td>8000</td>
<td>1996-present</td>
</tr>
<tr>
<td>KamLAND</td>
<td>$^3\text{He}$</td>
<td>1</td>
<td>Japan</td>
<td>300</td>
<td>2002-present</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>$^3\text{He}$</td>
<td>0.7</td>
<td>USA</td>
<td>200</td>
<td>2002-present</td>
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<tr>
<td>Borexino</td>
<td>$^3\text{He}$</td>
<td>0.3</td>
<td>Italy</td>
<td>100</td>
<td>2005-present</td>
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<tr>
<td>IceCube</td>
<td>Long string</td>
<td>0.6/PMT</td>
<td>South Pole</td>
<td>N/A</td>
<td>2007-present</td>
</tr>
<tr>
<td>Icarus</td>
<td>Ar</td>
<td>0.6</td>
<td>Italy</td>
<td>60</td>
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</tr>
<tr>
<td>HALO</td>
<td>Pb</td>
<td>0.08</td>
<td>Canada</td>
<td>80</td>
<td>Near future</td>
</tr>
<tr>
<td>SNO+</td>
<td>$^3\text{He}$</td>
<td>0.8</td>
<td>Canada</td>
<td>300</td>
<td>Near future</td>
</tr>
<tr>
<td>NO$\nu$A</td>
<td>$^3\text{He}$</td>
<td>15</td>
<td>USA</td>
<td>3000</td>
<td>Near future</td>
</tr>
<tr>
<td>LBNE LAr</td>
<td>LAr</td>
<td>34</td>
<td>USA</td>
<td>3400</td>
<td>Future</td>
</tr>
<tr>
<td>LBNE WC</td>
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<td>200</td>
<td>USA</td>
<td>44,000</td>
<td>Future</td>
</tr>
<tr>
<td>MEMPHYS</td>
<td>$^3\text{He}$</td>
<td>440</td>
<td>Europe</td>
<td>88,000</td>
<td>Future</td>
</tr>
<tr>
<td>Hyper-K</td>
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<td>540</td>
<td>Japan</td>
<td>110,000</td>
<td>Future</td>
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<tr>
<td>LENA</td>
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<td>50</td>
<td>Europe</td>
<td>15,000</td>
<td>Future</td>
</tr>
<tr>
<td>GLACIER</td>
<td>Ar</td>
<td>100</td>
<td>Europe</td>
<td>9,000</td>
<td>Future</td>
</tr>
</tbody>
</table>
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Figure 1. Event rates in 100 kton of water (left), 17 kton of liquid argon (center), and 50 kton of scintillator (right), as a function of observed energy, for various interaction channels and for the flux from reference [37], computed using SNOwGLOBES [38].