Supernovae and SNO+

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Abstract. At the end of a massive star’s life, a violent explosion known as a supernova occurs and releases 99% of the star’s gravitational binding energy in the form of neutrinos. Although the explosion generates a huge burst of neutrinos, the large distance to earthbound detectors, low cross sections, and flavour changing oscillations can make detection and analysis challenging. Only one neutrino burst from a supernova has ever been detected, but neutrino detectors have been waiting patiently for another. The SNO+ detector at SNOLAB can be used as a supernova detector during both regular operation and calibrations by measuring the burst of neutrinos from a supernova. We present the neutrino detection method and analysis of potential galactic supernova with the SNO+ detector.

1. Introduction
A core-collapse supernova (CCSN) marks the end of a massive (M \gtrsim 8 \, M_\odot) star’s life. Unable to burn anymore fuel, the outward pressure from fusion reactions now fails to hold the star up against its own gravity and the iron core rapidly compresses (if M \sim 8 - 10 \, M_\odot, rapid electron capture converts the collapsing O-Ne-Mg core to Fe [1]). Photodissociation of the iron core generates large amounts of \nu_e, and the rapid production of neutrons through the electron capture of protons generates additional \nu_e, all of which leave the core freely until the density exceeds about 3 \times 10^{11} \, g/cm^3. Once the SN shock wave reaches this density (shock breakout), the trapped \nu_e escape (neutronization burst), and under the extreme SN conditions neutrinos of all flavours are expelled due to processes such as nucleon-nucleon and electron-nucleon bremsstrahlung, electron-positron annihilation, plasmon decay, and photoannihilation. An estimated 99.9 % of the star’s gravitational binding energy (3 \times 10^{53} \, erg) is released in the form of neutrinos. The entire burst of neutrinos is expected to take no longer than 10 seconds, with half of the neutrinos emitted within the first second [2].

Despite the enormous burst of neutrinos, only one CCSN has been observed via neutrinos: SN 1987A, which yielded only 24 events from \bar{\nu}_e interactions in a total of 3 detectors worldwide [3]. All other SN have only been observed optically, a probe which is unable to delve deep into the inner mechanisms of the supernova. Neutrinos interact only weakly, thus their travel is unimpeded from the core of the supernova to underground particle detectors on Earth. Observing neutrinos from a SN burst will provide possibilities to study a multitude of SN and neutrino properties, including the explosion mechanism, shock breakout, black hole formation, progenitor star information, collective neutrino oscillation effects, or even resolve the still-unknown neutrino mass hierarchy. Decoding the information provided by neutrinos is challenging and complex, as the neutrino signal can be influenced by a large degree of poorly known parameters, including the equation of state of the protoneutron star, progenitor star properties,
and MSW and collective neutrino oscillation effects. These effects are nontrivial, and due to a lack of consistent analytical treatment of these effects on the neutrino spectra, here we discuss only the detection of unoscillated neutrinos and will consider oscillated neutrinos in the future. It should also be noted that in conjunction with photons and neutrinos, observing gravitational waves from a CCSN will permit a multi-messenger approach to the study of supernovae.

2. Fluence Modeling

There are two ways SN neutrino models are generated: either through analytic numerical expressions or via complex computer simulations. In both cases, however, the muon and tau neutrinos are grouped together ($\nu_x = \nu_\mu + \nu_\tau + \bar{\nu}_\mu + \bar{\nu}_\tau$) due to their identical behaviour within a SN and in neutrino detectors.

For the analytic model we consider the following parameters. The total energy released is assumed to be distributed equally amongst the 6 flavours (denoted $\alpha$); $\epsilon_{\nu\alpha} \sim 5 \times 10^{52}$ erg, and average neutrino energies are typically taken to be $\langle E_{\nu_e}\rangle = 12.0$ MeV $\lesssim \langle E_{\bar{\nu}_e}\rangle = 15.0$ MeV $\lesssim \langle E_{\nu_x}\rangle = 18.0$ MeV [4], which are generic mean SN energies [5] consistent with SN 1987A. Two expressions are common in analytical SN expressions: a Fermi-Dirac spectrum and a power law spectrum, the latter is arguably more flexible when describing the high-energy tail in the spectra [6]. Using the power-law spectrum with the shaping parameter $\beta_{\nu_e} \sim \beta_{\bar{\nu}_e} \sim \beta_{\nu_x} = 3$ provides a simpler variation of the power law spectrum as described by [4], where $d$ is the distance to the CCSN:

$$\frac{d\Phi}{dE} = \frac{2.35 \times 10^{13}}{\text{cm}^2 \text{ MeV}} \sum_{\alpha} \epsilon_{\alpha} \frac{E^3}{\langle E_{\alpha}\rangle^5} e^{-4E/\langle E_{\alpha}\rangle}$$  \hspace{1cm} (1)

In comparison, simulations model the time-dependence of the neutrino properties, but are limited by computational power and therefore rarely extend beyond 1 second postbounce. Simulations provide $\langle E\rangle(t)$, $\beta(t)$, and neutrino luminosities $L(t)$, such that the flux is given by:

$$\Phi(t) = \frac{L(t)}{\langle E\rangle(t)}$$  \hspace{1cm} (2)

The power law distribution is then used to generate the neutrino spectrum. The time-dependent data SNO+ considered extends up to 0.5 seconds postbounce and was provided by the Garching group at MPA Garching with their 1D simulations using the PROMETHEUS-VERTEX code [7, 8].

In the future we will also explore a variety of alternate parameters within the analytical expressions. We will vary the average energies to simulate different phases of the supernova, as well as to study effects from different equations of state for the protoneutron star. Additionally, the shaping parameters do not remain constant over time, and exploring different luminosities also permits the simulation of various SN phases and extremes.

3. The SNO+ Detector

The suite of particle detectors which are capable of detecting a SN neutrino burst includes SNO+, which is described at length in [9]. Located 2 km underground in SNOLAB, the rock overburden (5890 $\pm$ 94 m.w.e.) reduces cosmic rays to only 63 muon interactions per day in the detector. A transparent 12 m diameter spherical inner vessel containing the detecting medium is surrounded by 9300 PMTs supported on a 17.8 m diameter geodesic sphere. 5300 tonnes of ultrapure water surrounds the outside of the geodesic sphere and shields the detector from external radiation from the surrounding rock, while an additional 1700 tonnes of ultrapure water shields the inner vessel from the PMTs and their support structure. The inner vessel will contain different media depending on the detector phase:

- 1 kt ultrapure water (water phase)
• 780 tonnes organic liquid scintillator (LS): linear alkylbenzene + PPO (scintillator phase)
• 780 tonnes LS + 3.0 tonnes natural tellurium (double beta phase)

The different interaction media are required for a broad physics program which includes:
• Neutrinoless double beta decay ($^{130}\text{Te}$ decay)
• Supernova neutrinos and anti-neutrinos (all phases)
• Reactor- and geo- anti-neutrinos
• Exotics (e.g. invisible nucleon decay, solar axions)
• Solar neutrinos (CNO, pep, $^8\text{B}$, and pp chains)

In each phase SNO+ is sensitive to a galactic core collapse supernova.

The inner vessel is currently filled with ultrapure water and official data taking for the water phase began on May 4th, 2017. Studies during this phase will focus on exotics such as invisible nucleon decay as well as supernova lifetime studies (SN watch), external background studies, and detector performance.

For the supernova watch, SNO+ has installed a pre-supernova monitoring GUI which takes the Kamland pre-supernova alert [10] and determines the significance of a CCSN occurring within the next 48 hours. If the significance is above a certain value, detector operators are to take all necessary action to keep the detector in a stable running state. This is a precaution to ensure the signal is as clear as possible, as SNO+ will remain sensitive to a SN neutrino burst even during detector calibration due to the high intensity and short time span of the burst. During regular running in water phase, a burst monitoring system will create a burst file when 30 events of energy 4 MeV occur in 10 seconds of each other, and stops recording when the rate drops below 10 Hz (averaged over 1 second). The burst monitoring system is useful for quick feedback, not only for a potential SN burst, but also for large bursts of background events (generally electronic noise) in the detector. Studies are underway to determine the parameters of the burst monitor during the various detector calibrations and during scintillator loaded phases, with the target of at least 1 burst file generated per day. In addition to the burst monitor, regular data taking occurs, with the current detector threshold in water phase set at 2 MeV.

During liquid scintillator loaded phases, the detector threshold is anticipated to be set at 200 keV, small enough for a large number of neutrino-proton elastic scattering ($\nu$-p ES) events to be observed as well as the inverse beta decay (IBD) events. The large quantity of these events while the detector contains scintillator will allow for robust SN studies, as this reaction occurs equally for all neutrino flavours.

4. SN Interactions in SNO+

For first order sensitivities in SNO+, we use the SNOwGLoBES software package (see http://www.tapir.caltech.edu/~cott/CGWAS2013/snowglobes_1.1.pdf). The spectra for various interaction channels can be calculated as:

$$\frac{dN}{dE_\alpha} = N_t \int_0^\infty \sigma(E_\alpha) \frac{d^2\Phi_\alpha}{dt dE_\alpha} dt$$

(3)

- $N_t$ is the number of target particles
- $\sigma(E_\alpha)$ is the interaction cross section for neutrino energy $E_\alpha$
- $t$ is the time of the burst

The total number of interactions for a particular channel is thus:

$$N = \int_0^\infty \frac{dN}{dE_\alpha} dE_\alpha$$

(4)
Cross sections for the relevant processes in SNO+ are given by [11] for the neutrino-proton elastic scattering channel and by SNOwGLoBES software package for the rest. In the future, SNO+ will add cross sections for neutrino interactions on tellurium, as this will be an additional process during the double beta phase. The high cross sections of IBD and $\nu$-p ES for scintillator promise large interaction rates and high statistics for studies comparing $\bar{\nu}_e$ fluxes to the total $\nu$ flux. Although the $\nu$-p ES cross section is about a factor of three less than the IBD cross section, this reaction occurs for all 6 neutrino flavours, leading to comparable interaction rates. Here we focus on the observed spectra of these two major interaction channels.

Considering interactions as functions of detected energy is more realistic and requires a couple of considerations. The observed particles and their energies will differ from the incident neutrinos, requiring a conversion from incident neutrino energy to outputted particle energy. The detector response is then considered: first the energy smearing due to detector energy resolution, and finally a detection efficiency which is generally a function of energy. How these are applied is discussed below.

5. Inverse Beta Decay and neutrino-proton Elastic Scattering

In all phases, the detector is highly sensitive to $\bar{\nu}_e$ supernova neutrinos through the inverse beta decay mechanism:

$$\bar{\nu}_e + p \rightarrow n + e^+ \tag{5}$$

This reaction is followed by neutron capture on hydrogen:

$$n + p \rightarrow d + \gamma \ (2.2 \ MeV) \tag{6}$$

The incoming neutrino energy is directly related to the outgoing positron’s energy:

$$E_{e^+} = E_\nu - 1.3 \ MeV \tag{7}$$

In considering detector response, we use the SNOwGLoBES smearing matrices. For water Cherenkov detectors, these were incorporated using the LBNE package WCSim for energy smearing and efficiency. For liquid scintillator, the detector energy resolution was chosen (from [12]) to be $\sigma/E = 7%/\sqrt{E \ MeV}$. In comparison, SNO+ expects an energy resolution of $\sigma/E = 6%/\sqrt{E \ MeV}$, and this change will be added in the future. The detector efficiency for liquid scintillator is assumed to be 100%. This is suitable as the efficiency remains at 100% above an energy of 180 keV, and SNO+ expects a threshold of 200 keV during phases with liquid scintillator.

By optimizing the spatial and time difference between the positron’s prompt energy and the delayed neutron capture, the IBD events can be tagged. Studies are underway to quantify the tagging efficiency of the inverse beta decay process within SNO+, with the expectation that nearly all the inverse beta decay interactions will be observed and essentially be background-free during scintillator phases.

In comparison, neutrino-proton elastic scattering is not observable in water Cherenkov detectors and requires a liquid scintillator detector low in backgrounds to observe. The proton is highly ionizing in the medium, and the amount of observed energy is quenched. Birks’ law is used to convert the proton’s energy to effective (observed) energy:

$$T'(T) = \int_0^T \frac{dT}{1 + k_B(dT/dx)} \tag{8}$$

Birks’ constant, $k_B = 0.0098 \pm 0.0003 \ cm/MeV$, has been measured for SNO+ liquid scintillator [9]. The observed energy exists in the keV region, where many natural radioactive backgrounds exist. As there are no tagging opportunities, backgrounds must be minimized by a variety of techniques, including:
• Position, energy reconstruction
• Fiducial volume cut
• Threshold levels
• Ultrapure materials

The $^{14}$C decay rate in liquid scintillator (expected to be hundreds of Hz) is ultimately what limits the SNO+ threshold to 200 keV during these phases, and a spatial radius cut of 5 m will reduce the backgrounds coming from external sources, including those occurring on the surface of the inner vessel.

6. Conclusions
Preliminary studies indicate the observed interaction rates of IBD and $\nu$-p scattering in the liquid scintillator studies will be comparable and on the order of hundreds of events, if observation of $\nu$-p scattering is efficient. We are planning on studying the event ratio $N_{\text{IBD}}/N_{\nu\text{-p}}$ to categorize different SN explosions (e.g. equations of state, temperatures, etc.) and extend these to neutrino oscillation studies. For example, the energy-dependent ratios could resolve whether the neutrino mass hierarchy is normal ($m_1 < m_2 < m_3$) or inverted ($m_3 < m_1 < m_2$) [13].

In addition to these studies, SNO+ is developing a Monte Carlo generator which will be used in the future for full supernova studies. Future work will also include combined studies with a $\nu_e$ detector such as HALO [14] for an analysis of the three neutrino spectra: $\nu_e$, $\bar{\nu}_e$, and $\nu_x$.

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