Supernova Neutrinos\textsuperscript{a}

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ABSTRACT

I describe how the signals corresponding to the supernova $\nu_e$ and $\bar{\nu}_e$ (charged current reactions) as well as all active neutrinos (neutral current reactions) can be separately observed in various existing detectors. These observations would make it possible to determine the flux and average energy (or temperature) for each of these three neutrino signal components. I argue that all these quantities are needed in order to understand the interplay between the so far poorly known supernova neutrino emission process and the neutrino oscillations.

1. Introduction

Supernovae are fascinating objects. The core collapse represents one of the most energetic events known and the explosion that propels the envelope into the interstellar space and ultimately causes the visible effects noted already in historic times is poorly understood. But most of the gravitational energy of the collapse is not emitted as the kinetic energy of the outward explosion, and even less as the visible light. Instead, it is carried away by neutrinos. In fact, it is curious to note that, when averaged over a sufficiently long time ($>100$ years), the energy of the emitted neutrinos is comparable to the electromagnetic energy emitted by the whole galaxy over that time.

It is also likely that the hot nucleon gas pushed away by the neutrinos from the newly born proto-neutron star is the site of the $r$-process where roughly half of the heavy elements are produced. Understanding the neutrino emission process following the core collapse is thus a necessary step for the understanding of the $r$-process nucleosynthesis.

At the same time observation of supernova neutrinos represents probably the longest baseline neutrino oscillation experiment possible. Neutrinos emitted from the proto-neutron star might undergo matter oscillations while passing through the atmosphere and envelope of the star, and vacuum oscillations on the way to Earth. Finally, before reaching the detector they might be influenced by the passage through Earth. Thus, the detected neutrinos are potentially a complicated convolution of the primary fluxes reflecting the initial production inside the star, and the modifications due to oscillations on their way to the detectors.

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It is therefore obvious that observation of neutrinos emitted by a future supernova in our galaxy is going to be a goldmine of useful information. However, supernovae in our galaxy are very rare events, and supernova neutrino fluxes are observable for less than a minute per century (duty cycle of about $10^{-8}$). It is therefore important to anticipate what might happen, and make every effort to maximize the information gleaned from such a rare occasion. Each physicist will have, at best, only one chance to observe neutrinos from the galactic supernova during his or her scientific career. (Unfortunately, the present or planned neutrino detectors are unable to observe neutrinos with non-negligible statistics associated with supernovae even in the nearest galaxy, Andromeda, about 700 kpc away.)

As “guiding principles” for the modelling of the neutrino emission following the core collapse we will use four rules:

1. Essentially all gravitational binding energy, $E_B \sim G_N M_\odot / R$ ($G_N$ is the gravitational constant, $R \sim 10$ km is the neutron star radius), is emitted in neutrinos. For application we use $E_B = 3 \times 10^{53}$ ergs, and the distance of 10 kpc (about half of the stars in our galaxy are within that distance).

2. The characteristic neutrino emission time, related to the neutrino diffusion time, is $\sim 10$ seconds.

3. ‘Equal luminosity rule’ states that the total emitted energy is equally shared by all six neutrino flavors. Thus, the typical luminosity of each neutrino flavor is $\sim 5 \times 10^{51}$ erg/s.

4. ‘Temperature hierarchy rule’ states that, as a consequence of different cross sections for $\nu_e, \bar{\nu}_e$ and $\nu_x \equiv \nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$, the average energies are not equal and the hierarchy $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$ is expected. For applications we use the values $\langle E_{\nu_e} \rangle = 11$ MeV, $\langle E_{\bar{\nu}_e} \rangle = 16$ MeV, $\langle E_{\nu_x} \rangle = 25$ MeV.

Supernova neutrinos, presumably only $\bar{\nu}_e$, were detected so far only once, 26 years ago, when the neutrino signal of SN1987A was observed. That signal, taking into account its limited statistics, confirmed some of the rules above, but naturally told us nothing about the fluxes and average energies of the unobserved neutrino flavors.

The above rules, in particular the items 3) and 4) are based on simulations of the neutrino emission process. However, recent studies point out that these rules are highly model dependent, and that relatively large deviations from both of them might be expected.

Supernova neutrinos can be detected on Earth using three reaction types. The charged current reactions with the production of $e^+$, changing a free or bound proton into a free or bound neutron, are sensitive only to the $\bar{\nu}_e$ component. Similarly, the charged current reactions with the production of $e^-$, changing a bound neutron into a free or bound proton, are sensitive only to the $\nu_e$ component. Finally, the
neutral current reactions are sensitive to all active neutrino flavors. (Neutrino-electron scattering is caused by a combination of the charged and neutral current reaction amplitudes. Observationally, one cannot distinguish the initial neutrino flavor in that case.)

In the ideal situation one would be able to determine separately and with sufficient statistical accuracy the rate of each of these reactions. Moreover, spectroscopic information (at least the extraction of the average energy or equivalently temperature) should be possible. And, still in the ideal situation, all this information should be extracted as a function of time.

In a less ideal and a bit more realistic case, an average over time of the six quantities, the fluxes and average energies of the three components, should be extracted from observations.

There are, at present, several operational detectors of a sufficient size to detect the galactic supernova neutrino signal (SuperKamiokande, SNO, KamLAND, LVD, AMANDA, and MiniBoone; see other talks at this conference for the description of these detectors). Several other detectors are being built or are planned (e.g. Borexino, OMNIS, LAND, Nestor, Antares, IceCube). All, or most, of these detectors were or are going to be built for a different purpose; observation of supernova neutrinos will be in a parasitic mode. Most of them have a ‘Supernova trigger’, i.e. a piece of software and/or hardware that is designed to warn the observers that a signal resembling a supernova was detected, and possibly switching thresholds etc. to maximize that signal. There is an international collaboration of supernova neutrino detectors (SNEWS, SuperNova Early Warning System, see e.g. 6) to provide, with high confidence, an early alert from the coincidence of neutrino signals in several detectors.

In the following I concentrate on three existing detectors: SuperKamiokande is a 32 kton water Čerenkov detector with a detection threshold of about 5 MeV, SNO is a 1 kt heavy water Čerenkov detector, again with a threshold of about 5 MeV, and KamLAND is again a 1 kt but liquid scintillator detector with a much lower threshold, of only few hundred keV.

In each of these detectors supernova neutrinos will be observed in several ways. Below I will explain how the combination of these signals, with the proper arrangements of the triggers, should be able to determine, with a reasonable accuracy, the six parameters described above, i.e. the flux and temperature of the three expected components of the core collapse supernova neutrino signal.

2. Charged current reactions

Detecting $\bar{\nu}_e$ neutrinos is relatively easy. All considered detectors contain free protons, and the inverse neutron beta decay

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (1)$$
has large and well understood cross section \( \sigma \) (accuracy of \( \sim 0.2\% \)). By measuring the positron energy one can deduce the incoming \( \bar{\nu}_e \) energy, since

\[
E_{\bar{\nu}_e} \simeq E_{e^+} + M_n - M_p .
\]  

In SuperKamiokande one expects about 8000 events of this type from the ‘standard’ supernova. Thus, it would be possible to determine the flux and average energy of this component with a good accuracy in several time bins.

The other considered detectors, SNO and KamLAND, will detect several hundred events of this type each (in SNO due to the light water part of the detector). In addition, in SNO, the reaction

\[
\bar{\nu}_e + d \rightarrow e^+ + n + n
\]  

will have about 80 events. Their identification depends on the way and efficiency of the neutron detection at SNO employed at the time of the supernova detection.

It is more difficult to detect \( \nu_e \). Since there are no free neutrons, the detection reaction must be based on neutrons bound in a nucleus. The corresponding cross sections are smaller than for the inverse neutron beta decay, eq.(1). Moreover, with few notable exceptions (deuteron, reaction on \( ^{12}\text{C} \) populating the ground state of \( ^{12}\text{N} \)), these cross sections have not been measured and thus their value is based on calculations involving nuclear models. That introduces some uncertainty into the deduced quantities.

In SNO the deuteron disintegration

\[
\nu_e + d \rightarrow e^- + p + p
\]  

will result also in about 80 events. They have to be distinguished, by their lack of neutrons, from the corresponding reaction with \( \bar{\nu}_e \), eq.(3).

In KamLAND there will be a handful of clean events of the type \( \nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{N}_{gs} \). Such events are easy to recognize since \( ^{12}\text{N}_{gs} \) decays by the \( \beta^+ \) emission with half-life of 11 ms back to carbon. If, as a result of oscillations, the \( \nu_e \) average energy is considerably larger than our guess, there will be correspondingly larger number of such events. However, it might be difficult to separate them from the mirror reaction \( \bar{\nu}_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{B}_{gs} \) with a similar signature and yield.

In SuperKamiokande the reaction \( \nu_e + ^{16}\text{O} \rightarrow e^- + ^{16}\text{F}^* \) results in only about 20 events when the ‘standard’ \( \nu_e \) average energy is assumed. However, again if through oscillations the effective \( \nu_e \) temperature would increase to \( T_{\nu_e} = 8 \text{ MeV} \), the yield would increase dramatically, to \( \sim 860 \) events. The angular distribution of these electrons is rather different than the distribution of positrons from the inverse neutron beta decay. This feature could be used in order to separate these two channels.

Finally, I should mention plans to develop a supernova lead based neutrino detector. In it, one would count either the number of neutrons emitted in the charged
or neutral current reactions leading to the continuum in the final nuclei; or observe the electrons from the charged current reactions as well. Several recent publications have been devoted to the theoretical prediction of the corresponding cross sections \cite{10,11,12,13}. The spread between these calculated cross sections illustrates the difficulties encountered when dealing with the neutrino induced reactions on complex nuclei.

Even though the relation between the incoming $\nu_e$ energy and the outgoing electron energy is not as simple as in eq.\((2)\) since one has to take into account the spread of energies of the final nuclear system, it is reasonable to assume that one or several of the above ways of detecting the $\nu_e$ signal would make it possible to check the ‘hierarchy rule’ stated above, or to conclude that, presumably due to neutrino oscillations, the $\nu_e$ component on Earth has considerably higher energy than usually expected.

3. Neutral current reactions

Neutral current reactions measure the flux of all active neutrinos. Typically, neutral current cross section are increasing functions of energy. Thus, if the ‘temperature hierarchy’ and ‘equal luminosity’ rules are valid, one expects that the yield of the neutral current reactions will be dominated by the $\nu_x$ neutrinos. (These neutrinos are in that case responsible for 4/6 of the total luminosity, and have higher energy, and hence bigger yield per particle.) Thus, in some sense, the yield of the neutral current reaction is a measure of the contribution of the $\nu_x$ neutrinos to the supernova luminosity.

There are several observable neutral current reactions in the considered detectors:

1. Neutrino-electron scattering has observable rate in all detectors. However, as mentioned earlier, it is difficult to separate the neutral current part, since the charged current is usually dominating.

2. In water one can observe the $\gamma$ rays following the inelastic scattering of neutrinos on oxygen \cite{14}.

3. In heavy water (SNO) the neutral current deuteron disintegration, $\nu + d \rightarrow \nu + p + n$, can be detected by counting the number of singly produced neutrons. SNO collaboration has demonstrated that they mastered this technique \cite{15}.

4. Inelastic neutrino scattering on a heavy nucleus often results in excitation of the continuum, followed by the emission of one or more neutrons, e.g. $\nu + ^{208}\text{Pb} \rightarrow \nu' + ^{207}\text{Pb} + n$. Again, the detection will be based on counting the number of produced neutrons.

5. In a liquid scintillator detector, which contains carbon, the excitation of the $T = 1, I^\pi = 1^+$ state in $^{12}\text{C}$ results in the emission of the clearly recognizable $\gamma$ line at 15.11 MeV.
6. In a detector with sufficiently low thresholds (KamLAND, Borexino) the elastic scattering on protons $\nu + p \rightarrow \nu' + p'$ can be observed by detecting the recoiling protons.

It is important to note that the neutral current reactions in items 2-5 have no spectral information. One measures simply the number of events

$$N_{nc} \sim \frac{1}{D^2 \langle E_\nu \rangle} \int f(E_\nu) \sigma(E_\nu) dE_\nu,$$

where $D$ is the supernova distance, $f(E_\nu)$ is the neutrino spectrum, and $\sigma(E_\nu)$ is the cross section. Thus, there is a parameter degeneracy. Higher average energy and correspondingly lower flux can produce the same number of events. It is difficult to overcome this problem.

The detection of the neutral current inelastic scattering on $^{16}\text{O}$ deserves an explanation. The principle is illustrated in Fig. 1. When neutrinos of a sufficient energy inelastically scatter on $^{16}\text{O}$, the resulting excited state decays by nucleon emission, leading to the ground or excited states of $^{15}\text{N}$ (proton emission) or $^{15}\text{O}$ (neutron emission). These mirror nuclei have only bound excited states with energies between 5 and 10 MeV. Thus, every time the excited state in one of these two nuclei is reached (branching of $\sim 30\%$) a photon of energy of at least 5 MeV, detectable in SK, is emitted. The yield of this reaction is particularly sensitive to the high energy tail of the neutrino spectrum, i.e. to the deviation (pinching) from the Fermi-Dirac shape.

![Figure 1: Schematic illustration of the detection scheme for the neutral current detection in water Čerenkov detectors.](image)

The elastic scattering of neutrinos on protons (item 6) above) is the only neutral current reaction that, at least in principle, can furnish spectroscopic information.
among the neutral current reactions considered above\textsuperscript{16}. (A complementary information could be, perhaps, extracted from the $\nu-e$ scattering data, after a statistical subtraction of the $\nu_e-e$ and $\bar{\nu}_e-e$ events.)

The cross section for $\nu-p$ elastic scattering is well understood. For $E_\nu \ll M_p$ it is given by ($T_p$ is the recoil proton kinetic energy)

$$
\frac{d\sigma}{dT_p} \approx \frac{G_F^2 M_p}{\pi} \left[ (c_A^2 + c_V^2) + (c_A^2 - c_V^2) \frac{T_p M_p}{E_\nu^2} \right], \quad c_V = 1/2 - 2 \sin^2 \theta_W, \quad c_A = 1.27/2.
$$

However, the proton recoil energy is quite small, restricted to $T_p < 2E_\nu^2/M_p$. The recoiling proton is obviously nonrelativistic, and can be detected only by its ionization. Moreover, in a liquid scintillator the light yield of heavy ionizing particles is reduced (quenched) when compared to the light yield of the electrons or photons. The cross section, integrated over the Fermi-Dirac energy distribution, is shown in Fig. 2. Note the steep dependence on the neutrino temperature.

![Figure 2: Cross section of the elastic neutrino scattering on protons for the indicated incoming neutrino temperatures. True proton recoil energy, without quenching, is used](image)

Obviously, only detectors with sufficiently low threshold ($\ll 1$ MeV) of the the ‘effective’ (i.e. quenched) proton recoil energy and correspondingly low background at those energies could be used. According to Ref.\textsuperscript{16} one expects about 300 events per kt above 200 keV. Thus, the background at these energies should be at most in
the few Hz range. Assuming that these extremely stringent conditions could be met (both KamLAND and Borexino plan to meet them), it would be possible not only to detect the recoil protons but to extract useful spectroscopic information out of that signal.

This is illustrated in Fig. 3 where it is demonstrated that the parameter degeneracy between the luminosity of the $\nu_x$ neutrinos and their temperature can be resolved. The values of the total energy of the $\nu_x$ neutrinos and their temperature were chosen for this illustration in such a way that the total number of events above threshold is the same.

4. Neutronization pulse

In the early stages of the core collapse electrons are captured on the core nuclei, and the resulting $\nu_e$ escape. Eventually the density of the core increases so much that the neutrinos are trapped. However, outside the outgoing shock the $\nu_e$ created by the electron captures still escape, forming a very narrow ($\sim 0.01$ s) and intense pulse. This pulse represents $2 - 5 \times 10^{51}$ ergs of energy, i.e. perhaps $5 - 10\%$ of the total energy of the $\nu_e$ neutrinos (see, e.g. Ref. 17).

Scaling the yield estimates in Ref. 18, I estimate that such a pulse could result in $\sim 10 \nu_e - e$ scattering events in SK, recognizable by their clustering in time, and by their characteristic narrow angular distribution. (Obviously, that yield estimate has a substantial error margin.)

Clearly, observation of the neutronization pulse would be valuable for understand-
ing the mechanism of the core collapse and bounce.

5. Relic supernova neutrinos

Neutrinos emitted by the core collapse supernovae move freely and accumulate over time. Eventually, they form a diffuse (in time and direction) neutrino flux, when averaged over $\sim 10^8$ galaxies ($10^8$ is the ratio of the time elapsed between supernovae per galaxy $\sim 30$ years, and the neutrino pulse duration $\sim 10$ seconds.) That diffuse flux is cut-off naturally at the redshift $z \sim 1$, since the neutrinos emitted at higher redshifts become unobservable due to their lower energy. Crude estimate of this diffuse flux suggests that its $\bar{\nu}_e$ component is $\sim 10\bar{\nu}_e/(\text{cm}^2 \text{ s})$ resulting in about 0.5 events per kt and year.

More detailed evaluations basically confirm that estimate. Observation of such diffuse flux would be a measure of the average SN rate over a substantial fraction of the Universe.

Clearly, the $\bar{\nu}_e$ component of the diffuse flux has the best chance to be seen. There is a ‘window of opportunity’ for its observation, above the energies of the reactor and solar neutrinos, and below the energy of the atmospheric neutrino signal. Both Kamiokande and SuperKamiokande reported limits on the diffuse flux. The much better SK limit, which is background limited, is approaching (but still well above) the theoretical estimate of this flux. It appears that one needs a much larger detector, with correspondingly smaller background per unit mass, to be able to positively identify this important quantity.

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7. References

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