Detection possibility of the pair-annihilation neutrinos from the neutrino-cooled pre-supernova star

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Abstract

The signal produced in neutrino observatories by the pair-annihilation neutrinos emitted from a 20 $M_\odot$ pre-supernova star at the silicon burning phase is estimated. The spectrum of the neutrinos with an average energy $\sim$2 MeV is calculated with the use of the Monte Carlo method. A few relevant reactions for neutrinos and anti-neutrinos in modern detectors are considered. The most promising results are from $\bar{\nu}_e + p \rightarrow n + e^+$ reaction. During the Si-burning phase we expect 1.27 neutrons/day/kiloton of water to be produced by neutrinos from a star located at a distance of 1 kpc. Small admixture of effective neutron-absorbers as e.g. NaCl or GdCl$_3$ makes these neutrons easily visible because of Cherenkov light produced by electrons which were hit by $\sim$8 MeV photon cascade emitted by Cl or Gd nuclei. The estimated rate of neutron production for SNO and Super-Kamiokande is, respectively, 2.2 and 41 events per day for a star at 1 kpc. For future detectors UNO and Hyper-Kamiokande we expect 5.6 and 6.9 events per day even for a star 10 kpc away. This would make it possible to foresee a massive star death a few days before its core collapse. Importance of such a detection for theoretical astrophysics is discussed.

Key words: Massive stars; Neutrino detection; Pre-supernova evolution
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1 Introduction

The detection of solar neutrinos by the R. Davis’s chlorine detector and supernova 1987A neutrinos by the Kamiokande water Cherenkov observatory are milestones of modern science, Nobel Prize honored in 2002. Currently built and operating neutrino detectors are larger, much more efficient and are able to detect all neutrino species in a wide range of energy. There are already proposed new experiments with next-generation megaton-scale detectors, like Hyper-Kamiokande [1] and UNO [2].

Solar neutrinos were detected with sub-kiloton detectors, because of relatively small distance to the Sun and continuous emission. Supernova neutrinos carry enormous energy of $10^{53}$ ergs released in gravitational collapse of the stellar core. This makes their detection possible from quite large distances, but such events are rare. We consider here the feasibility of detection of another giant astrophysical sources of neutrinos, namely massive ($M > 8 M_\odot$) stars at late stages of their evolution. Such stars, during C, Ne, O and Si burning phases, emit neutrinos copiously and are referred to as neutrino-cooled stars ([3], Sect. 10) or pre-supernova stars [4]. The structure of such evolutionary advanced stars is different from main sequence stars like the Sun. The most important differences relevant to the neutrino detection possibility are summarized in Table 1.

The solar neutrino luminosity is $7.8 \cdot 10^{31}$ erg/s [5]. The maximum neutrino luminosity during Si burning exceeds $3 \cdot 10^{45}$ erg/s ([6], [7]) – a value larger by a factor of $3.85 \cdot 10^{13}$. The neutrino energy flux at Earth from such a star and from the Sun are equal for a star $\sqrt{3.85 \cdot 10^{13}} = 6.2 \cdot 10^6$ AU, i.e. 30 pc away. This indicates that neutrino-cooled stars could be detected at astronomical distances. Actually, because of a different spectrum (cf. Fig. 2) and the presence of anti-neutrinos (cf. Table 3), we are able to detect them

|                          | The Sun | Neutrino-cooled phase of 20 M_\odot star |
|--------------------------|---------|------------------------------------------|
| Lifetime                 | $10^{10}$ years | 300 years |
| Photon luminosity        | $L_\odot$ | $10^5 L_\odot$ |
| Maximum $\nu$ luminosity | 0.02 $L_\odot$ | $10^{12} L_\odot$ |
| Average neutrino energy  | 0.3 MeV | 0.7-2 MeV |
| Total $\nu$ energy released | $10^{49}$ erg | $10^{51}$ erg |

Table 1
Differences between the Sun (main sequence star) and the neutrino-cooled 20 M_\odot star ([6], Table 1). Approximate values (orders of magnitude) are given. The total energy carried by neutrinos for a 20 M_\odot neutrino-cooled star corresponds only to late stages of nuclear burning (without supernova neutrinos).
Massive (neutrino-cooled) stars are believed to end as core-collapse supernovae. SN 1987A confirmed this theory. This close connection may be used to estimate chance of neutrino-cooled stage observation. If some of massive stars die other way, rate of neutrino-cooled events may be higher than of SNe, but it is reasonable to use estimates made for supernovae. At least three different methods exist there: historical records & remnants counts [8], extragalactic observations [9] and population synthesis (i.e. simulated stellar evolution of the Galaxy) methods [10]. Only first method gives local rate directly: time between events less than 5kpc away is estimated to be 175 years [11]. Two other methods give rate for entire Galaxy. Extragalactic counts give 40...200 years [9] of average time interval between supernova explosions. Population Synthesis give 10 years [10]. To compare local rates we may use Galaxy model of e.g Bahcall&Soneira [12]. For the solar neighbourhood we found 0.5%, 10% and 50% of disc stars closer than 1kpc, 5kpc and 10kpc respectively. Assuming that the Sun is not in privileged position close to e.g. giant star forming region, we get time between supernovae closer than 5kpc from 100 (Population Synthesis) to 400...2000 (extragalactic counts) years. Apparent disagreement between these two methods is usually explained by a large number of unobserved events. Clouds of interstellar gas and dust obscuring optical detection are obviously transparent for neutrinos, so we may conclude that neutrino-cooled events closer than 5kpc may be observed even more frequent than one per century. Close candidates for such a detection apparently do exist, with Betelgeuse (β Ori) being the most popular example [13]. In Sect. 5 we combine rates discussed above with our results to estimate a chance of successful detection.

As an example we consider a 20 M⊙ star model with properties reported in Table 1 of Ref. [6], with explicite given total neutrino luminosities of various stages of nuclear burning. As our scope here is to study the feasibility of neutrino detection, not to find state-of-art details of emission\textsuperscript{1}, we assume that the entire neutrino flux is resulting from e\textsuperscript{+}e\textsuperscript{−} annihilation. The values from Table 2 of the temperature, density and the electron chemical potential at the stellar center are assumed to approximate conditions in the stellar core. For simplicity we treat neutrino propagation without oscillation, however the effect of neutrino oscillations may change significantly the number of observed events in a given experiment [16]. To calculate the relevant neutrino cross sections the standard Weinberg-Salam theory [17] is used.

\textsuperscript{1} Detailed picture of late stages of nuclear burning is still a subject of active research as there are unanswered questions about e.g. hydrodynamical nature of nuclear burning [14]. Neutrinos itself are still enigmatic objects and e.g. the role of spin-flip interactions and the influence of right-handed neutrinos [15] is investigated.
Table 2

Properties of a 20 M⊙ star according to Ref. [6]. We have calculated the total energy radiated in neutrinos as a product $\tau L_\nu$. Actually, the neutrino emission is expected to be a function of time.

In Sect. 2 we calculate the neutrino spectrum with the use of Monte Carlo method, in Sect. 3 we briefly present neutrino-induced reactions and outline of selected detectors. Sect. 4 contains the expected neutrino signal from a star located at a distance of 1 kpc. In Sect. 5 astrophysical implications of the pre-supernova neutrino detection are discussed.

2 The spectrum of pair-annihilation neutrinos

Neutrinos produced by thermal processes are the most important part of the neutrino flux balancing the nuclear energy generation in the central region of massive (M>$8\,M_\odot$) stars at late phases of nuclear burning, i.e. from carbon burning up to silicon burning. For simplicity, we have assumed that the entire neutrino flux is produced by pair annihilation. Actually, so-called photoneutrinos and neutrinos from plasmon decay (cf. [19], Fig. 1) may contribute to the total neutrino flux [18], depending on physical conditions. This assumption is valid up to the silicon burning. After this phase the amount of neutrinos produced by weak nuclear reactions (beta decays, electron capture) increases, and finally dominates the neutrino flux [4].

Pair annihilation neutrinos are produced in the reaction ([20], p. 171)

$$e^+ + e^- \rightarrow \nu_x + \bar{\nu}_x$$ (1)

A high temperature ($T>10^9\,K$) is required to produce enough $e^+e^-$ pairs. Usually, in the local thermodynamical equilibrium, these pairs annihilate back into photons, but sometimes the reaction (1) occurs. Neutrinos produced by

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2 Inspection of Fig. 3, 4, 8, 9, 12, and 13 from Itoh et. al. [18] together with the values of electron fraction, $Y_e = 0.5$, central temperature, $T_c$, and density, $\rho_c$, from Table 2 shows that the annihilation neutrinos are dominant.
Burning phase $\nu_e$ $\bar{\nu}_e$ fraction $\nu_{\mu,\tau}/\nu_e$ ratio Average $\nu_x$ energy

|   |   |   |   |
|---|---|---|---|
| C | 42.5 % | 1:11.4 | 0.71 MeV |
| Ne | 39.8 % | 1:7.8 | 0.99 MeV |
| O | 38.9 % | 1:6.9 | 1.13 MeV |
| Si | 36.3 % | 1:5.4 | 1.85 MeV |

Table 3
Fraction of given neutrino flavor emitted by pair-annihilation, used in formula (9). One can notice increasing with temperature fraction of muon and tau neutrinos.

The reaction (1) escape freely from the central region of a star. In reaction eq. (1) the fluxes of neutrinos and anti-neutrino are the same.

We calculate the spectrum of neutrinos produced in reaction (1) with the Monte Carlo method of Ref. [21]. Both, electrons and positrons are described by Fermi-Dirac (FD) distributions. Conditions in the central region of the 20 M$_\odot$ star which define FD distribution parameters are summarized in Table 2.

In the simulation we pick up electron and positron four-momenta from FD distributions, transform to the center-of-mass frame, distribute neutrino momentum directions randomly, and convert neutrinos energy back to the rest frame. Every single event is binned and counted as $|M|^2$, where our annihilation matrix is proportional to:

$$|M|^2 \propto (C_A - C_V)^2(p_e^- \cdot q_{\nu_x})(p_e^+ \cdot q_{\bar{\nu}_x}) + (C_A + C_V)^2(p_e^+ \cdot q_{\nu_x})(p_e^- \cdot q_{\bar{\nu}_x}) + m_e^2(C_V^2 - C_A^2)q_{\nu_x} \cdot q_{\bar{\nu}_x}$$

Here $p$ and $q$ are four-momenta, $m_e$ is the electron mass and:

$$C_V = \frac{1}{2} \pm 2 \sin^2\theta_W, \quad C_A = \frac{1}{2},$$

where $\theta_W$ is the Weinberg angle and $\sin^2\theta_W = 0.2224$. The ‘+’ sign refers to electron neutrinos, while the ‘−’ sign is for $\mu$ and $\tau$ neutrinos. The relative number of events from two simulation runs (one for the ‘+’ sign, the other one for the ‘−’ sign) has been used to determine the $\nu_{\mu,\tau}/\nu_e$ ratio.

The resulting anti-neutrino spectrum is presented in Fig. 1. We have used this spectrum together with the neutrino luminosity from Table 2 and the flavor fractions given in Table 3 to find the detector response.
Fig. 1. Normalized spectrum of pair-annihilation anti-neutrinos emitted by 20 $M_\odot$ star during carbon (dashed line), neon (dotted line), oxygen (short-dashed line) and silicon (solid line) burning stage. The spectrum shape for all flavors of neutrinos and anti-neutrinos is very similar. However, relative fluxes of given neutrino flavors (cf. Table 3) are different. There is equal amount of neutrinos and anti-neutrinos. The average anti-neutrino energy is 1.80 MeV, 1.11 MeV, 0.97 MeV, 0.71 MeV for Si, O, Ne, and C burning stage, respectively. As we expect, for $T \to 0$ the spectrum shape approaches the $E_{\bar{\nu}} = m_e = 0.51$ MeV annihilation line.

3 Neutrino reactions and cross-sections in modern neutrino detectors

3.1 Brief description of selected experiments

Super-Kamiokande [22] and SNO [23] are the largest present supernova neutrino detectors. Super-Kamiokande contains about 32,000 tons of water in the inner volume. The SNO detector consists of 1,000 tons of ultra-pure heavy water and about 1,700 tons of light water. Both the light and heavy water form active detector volumes for supernova neutrino detections, providing proton and deuteron targets for neutrino interactions.

Because of low, due to large distance, neutrino flux from candidate stars undergoing advanced stages of nuclear burning, very large detectors are needed
in order to detect the signal. Fortunately, there are proposals of two next generation water Cherenkov detectors for proton decay searches, UNO [2] and Hyper-Kamiokande [1], with 440,000 and 540,000 tons of water in fiducial volumes, respectively. We consider here also two detectors employing liquid scintillator (LS) that will be capable of detecting supernova neutrinos. These are KamLAND [24], already operating, and Borexino [25], to be operating soon. The low energy threshold for recoil electrons and the scintillation light are their most important advantages over water Cherenkov detectors.

3.1.1 Water Cherenkov detectors

Water Cherenkov detectors have good efficiency of detection of recoil electrons with energy above a rather high threshold (about 5 MeV). Recoil electrons are produced mainly in NC/CC interactions between neutrinos and electrons. However, almost all interesting events will be produced in CC interactions between electron anti-neutrinos and protons (inverse $\beta$ decay). The neutrino/anti-neutrino spectrum is closely related to the electron/positron spectrum. Pair-annihilation neutrinos from considered last stages of pre-supernova star cannot be detected because of their low energy. We want, however, to point out that despite this high energy threshold problem, we may detect the signal from capture of neutrons produced in inverse $\beta$ decay, if some neutron absorbent material will be added to the pure water. The salt phase of the SNO experiment proves that this is feasible. SNO detects $^{36}\text{Cl}$ de-excitation via an 8.6 MeV total energy gamma-ray cascade which is distinguishable from CC (single energetic particle Cherenkov) events by angular isotropy measures.

The remaining flavors, $\nu_\mu$, $\nu_\tau$, $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$, interact only by neutral-currents, i.e. only elastically scatter off electrons.

3.1.2 Liquid scintillator detectors

The primary goal of the Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND) experiment is a search for the oscillation of $\bar{\nu}_e$'s emitted from distant power reactors [24]. The inverse $\beta$ decay reaction is utilized to detect $\bar{\nu}_e$'s with energies above 1.8 MeV in 1,000 tons of liquid scintillator (LS). The detection of the $e^+$ and the 2.2 MeV gamma-ray from neutron capture on proton in delayed coincidence is a powerful tool for reducing background.

The Borexino experiment main physics goal is the detection of the 0.86 MeV $\nu_e$'s from electron-capture decay of $^7\text{Be}$ in the Sun [25]. The central volume of the detector contains 300 tons of liquid scintillator. Neutrinos from the last stages of nuclear burning will interact in the LS via electron scattering and the inverse $\beta$-decay.
3.2 Reactions & Cross-sections

3.2.1 The $\bar{\nu}_e + p \rightarrow e^+ + n$ reaction

Neutrino-proton scattering (often referred to as quasi-elastic neutrino-proton scattering) is historically called inverse beta decay. The structure of nucleon in neutrino-proton scattering at MeV energies is not important, because the momentum transfer between the two nucleons is small. We may approximate the vector and axial-vector form factors with two constants: $F_V(0) = g_V = 1$ and $F_A(0) = g_A = 1.27$. The value of $g_A/g_V$ is determined from the measured lifetime of the neutron.

Electron antineutrino quasi-elastic scattering on proton turns a proton into a neutron and produces positron of $E_{e^+} = E_\nu - \Delta$ energy (at zeroth order in $1/M$), where $\Delta = M_n - M_p$ is the mass difference between the proton and neutron. The momentum of produced positron is $p_{e^+} = \sqrt{E_{e^+}^2 - m_e^2}$.

The standard expression for the total cross section is,

$$
\sigma_{tot} = \sigma_0 \left( g_V^2 + 3g_A^2 \right) E_{e^+}p_{e^+} = 0.0952 \left( \frac{E_{e^+}p_{e^+}}{1 \text{ MeV}^2} \right) \times 10^{-42} \text{ cm}^2. \tag{4}
$$

The constant $\sigma_0$ includes the energy-independent inner radiative corrections [26] :

$$
\sigma_0 = \frac{G_F^2 \cos^2 \theta_C}{\pi} (1 + \Delta_{inner}^R), \tag{5}
$$

where $\Delta_{inner}^R \simeq 0.024$, and the Cabbibo angle $\cos \theta_C = 0.974$.

The inverse neutron $\beta$-decay, $\bar{\nu}_e + p \rightarrow e^+ + n$, is the reaction giving the largest yield for the detection of pre-supernova neutrinos. The large cross section, low energy threshold, delayed coincidence between positron’s annihilation and neutron capture signals, abudance of target protons makes this reaction the most promising.

We calculate the signal, which is the number of produced neutrons from this reaction in all the considered experiments.
3.2.2 Neutrino-Electron Scattering

Neutrino-electron scattering produces recoil electrons with kinetic energy from zero up to the kinematic maximum. The laboratory differential cross section for the $\nu_x e^-$ scattering is of the form:

$$
\frac{d\sigma}{dT_e'} = \frac{2G_F^2 m_e}{\pi} \left[ c_L^2 + c_R^2 \left( \frac{E_\nu - T_e'}{E_\nu} \right)^2 - c_L c_R m_e T_e' E_\nu \right]
$$

where $T_e' = E_e' - m_e$ is the recoil electron kinetic energy.

In our rate calculation we approximate by integrating eq. (6) over all electron recoil energies. The total cross section is

$$
\sigma = \int_0^{T_{max}} \frac{d\sigma}{dT_e'} dT_e' = \frac{2G_F^2 m_e E_\nu}{\pi} \left[ c_L^2 + \frac{1}{3} c_R^2 - \frac{1}{2} c_L c_R m_e E_\nu \right]
$$

where $c_L, c_R$ coefficients depend on the neutrino species considered (Table 4). Total scattering cross section is calculated without radiative corrections.

The elastically-scattered electrons will have kinetic energies of a few MeV. These relativistic electrons will be difficult to detect in any Cherenkov detector, because of high energy threshold. However, the next-generation liquid-scintillator Borexino detector will have low target threshold of approximately 0.25 MeV, mainly due to progress in radiopurity research [28]. It is possible that KamLAND experiment will improve radiopurity to detect low energy recoil electrons in future, so we calculate signal from elastic processes in both detectors.
3.2.3 Interactions with heavy water

The Sudbury Neutrino Observatory (SNO) employs inelastic neutrino-deuteron scattering to study the solar neutrino flux. The total $^8B$ solar neutrino flux is determined from observation of the following reactions:

$$\nu_e + d \to p + p + e^- \quad (CC),$$
$$\nu_x + d \to p + n + \nu_x \quad (NC),$$
$$\nu_x + e^- \to \nu_x + e^- \quad (ES),$$

where $x = e, \mu$ or $\tau$. The pre-supernova anti-neutrinos of all flavors can interact with deuterons and electrons through the following additional reactions:

$$\bar{\nu}_e + d \to n + n + e^+ \quad (inverse \beta),$$
$$\bar{\nu}_x + d \to p + n + \bar{\nu}_x \quad (NC),$$
$$\bar{\nu}_x + e^- \to \bar{\nu}_x + e^- \quad (ES).$$

By observing the charged-current interactions (CC and inverse $\beta$ decay) only electron neutrino (anti-neutrino) flux is measured. The NC reaction of any flavour neutrino on deuteron breaks up the deuterium and produces a proton and a neutron. The NC cross-section is the same for all neutrino flavours, thus one can determine the total flux of all active neutrino and anti-neutrino flavors above an energy threshold of 2.2 MeV. The cross sections for $\nu$-d reactions are of primary importance in the analysis of SNO data, it is motivation for theoretical calculations employing nuclear physics and effective field theory. We use in our paper the cross section values for the deuteron break-up interactions from the tables provided by Kubodera and Nozawa [29]. In all cases of anti-neutrino reactions with light or heavy water only the neutron is detected in the final state. The ES reaction produces low energy recoil electron mainly below energy threshold, so we do not consider further this reaction.

3.2.4 Averaged cross section

The spectrum-averaged cross section is

$$\bar{\sigma}_\alpha = \int_0^\infty \sigma(E)\lambda_\alpha(E)dE$$

where $\lambda_\alpha(E)$ is the normalized spectrum for neutrinos produced by the pair-annihilation in pre-supernova star at C, Ne, O and Si burning phase ($\alpha = C,$
Table 5

| Reaction                  | $E_{th} [MeV]$ | $\bar{\sigma}_{Si} [cm^2]$ | $\bar{\sigma}_{O} [cm^2]$ | $\bar{\sigma}_{Ne} [cm^2]$ | $\bar{\sigma}_{C} [cm^2]$ |
|---------------------------|---------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| $\bar{\nu}_e + p \rightarrow e^+ + n$ | 1.8           | $6.80 \cdot 10^{-44}$       | $3.74 \cdot 10^{-45}$       | $9.07 \cdot 10^{-46}$       | $4.88 \cdot 10^{-49}$       |
| $\bar{\nu}_e + d \rightarrow e^+ + n + n$ | 4.0           | $1.22 \cdot 10^{-46}$       | $4.38 \cdot 10^{-50}$       | $4.64 \cdot 10^{-52}$       | —                           |
| $\nu_x + d \rightarrow \nu_x + p + n$ | 2.2           | $1.68 \cdot 10^{-45}$       | $1.64 \cdot 10^{-47}$       | $1.63 \cdot 10^{-48}$       | $4.76 \cdot 10^{-54}$       |
| $\bar{\nu}_x + d \rightarrow \bar{\nu}_x + p + n$ | 2.2           | $1.41 \cdot 10^{-45}$       | $1.20 \cdot 10^{-47}$       | $1.19 \cdot 10^{-48}$       | $3.27 \cdot 10^{-54}$       |
| $\nu_e + e^- \rightarrow \nu_e + e^-$ | 0.0           | $1.76 \cdot 10^{-44}$       | $1.04 \cdot 10^{-44}$       | $9.07 \cdot 10^{-45}$       | $6.40 \cdot 10^{-45}$       |
| $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$ | 0.0           | $6.79 \cdot 10^{-45}$       | $4.05 \cdot 10^{-45}$       | $3.49 \cdot 10^{-45}$       | $2.45 \cdot 10^{-45}$       |
| $\nu_{\mu,\tau} + e^- \rightarrow \nu_{\mu,\tau} + e^-$ | 0.0           | $3.07 \cdot 10^{-45}$       | $1.95 \cdot 10^{-45}$       | $1.72 \cdot 10^{-45}$       | $1.26 \cdot 10^{-45}$       |
| $\bar{\nu}_{\mu,\tau} + e^- \rightarrow \bar{\nu}_{\mu,\tau} + e^-$ | 0.0           | $2.63 \cdot 10^{-45}$       | $1.68 \cdot 10^{-45}$       | $1.49 \cdot 10^{-45}$       | $1.10 \cdot 10^{-45}$       |

Spectrum-averaged cross sections for interactions of pre-supernova neutrinos in the light- and heavy-water Cherenkov detectors and liquid scintillator detectors. $E_{th}$ is the neutrino energy threshold for a given reaction; $\nu_x$ stands for $\nu_e$, $\nu_\mu$ and $\nu_\tau$; $\bar{\nu}_x$ stands for $\bar{\nu}_e$, $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$.

Ne, O & Si). The integration over the spectrum of incoming neutrino energies, $E$, was performed numerically and the results are shown in Table 5. We use the total cross sections $\sigma(E)$ for the most important interactions in considered detectors as described in previous sections.

4 The event rate and the background signal in selected detectors

The number of incoming particles interacting (per day) with the target is equal to the product of the spectrum averaged cross section $\bar{\sigma}_\alpha$, the number $N$ of target atoms or electrons, the total intensity of the flux per day $\phi_\alpha$, and the fraction $f$ of total flux that is interacting with a given target. The reaction rate $r$ per day is written as:

$$r [day^{-1}] = f \cdot \bar{\sigma}_\alpha [cm^2] \cdot N \cdot \phi_\alpha [cm^{-2} day^{-1}].$$ (9)

For anti-neutrinos from silicon burning stage in 1kt water Cherenkov detector we have: $\bar{\sigma}_{Si} = 6.8 \cdot 10^{-44} [cm^2], N = 6.69 \cdot 10^{31}, \phi_{Si} = 7.6 \cdot 10^{11} [cm^{-2} day^{-1}]$ and, from Table 3, $f = 0.363$.

The number of target particles is easy to calculate if the mass and the chemical composition of material in the fiducial volume are known. We obtain the total flux per day from the pre-supernova star 1 kpc away by dividing the luminosity $L_\nu$ (Table 2) by the average neutrino energy (Table 3) and the surface area of a R=1 kpc radius sphere. The spectrum of the total neutrino flux from the
To make detection of pre-supernova anti-neutrinos feasible we propose to supplement the existing and future water Cherenkov detectors with some addi-
Fig. 2. The standard solar neutrino spectrum (BP2000, [5]) for pp fusion reactions in the Sun (solid lines) and the spectrum of pair-annihilation neutrinos emitted by a 20 M\(\odot\) star during silicon burning stage (dashed line). Star is located at a distance of 1 kpc.

The addition of NaCl or GdCl\(_3\) (see the proposition made by J.F. Beacom and M.R. Vagins *GADZOOKS!* [30]) to the water. Neutrons produced in inverse \(\beta\) decay are captured by Gd or Cl nuclei producing high energy (above 8 MeV) gamma cascades. The addition of neutron absorbers is very important, because in a pure light water neutrons are captured by protons and produce not detectable 2.2 MeV gamma cascades, e.g. energy threshold in SK is about 5 MeV. This modification has been proved to work in the salt phase of solar neutrino detection in the SNO detector. The addition of NaCl to the kiloton of heavy water increased the neutron capture efficiency and the associated Cherenkov light [31]. Neutron capture efficiency is different in every experiment and has to be calibrated with neutron source, as e.g. \(^{252}\text{Cf}\) in SNO.

Background neutron events are disturbing pre-supernova neutrino detection, and thus should be carefully studied in every detector before the addition of the neutron absorber. The average rate of background neutron production from activity in the D\(_2\)O region is 0.72 neutrons per day in the SNO detector [31]. These background events are produced mainly by deuteron photodisintegration (not relevant for a light water detectors) and due to the external-source neutrons. The background of neutrons in spallation products from energetic
muons can be suppressed by a veto following the muon [24]. Long-lived muon induced isotopes, which decay by the production of a neutron and a beta (e.g. $^{8}$He, $^{9}$Li and $^{11}$Li), can simulate the $\bar{\nu}_{e}$ coincidence signature. Thus, the study of muon induced spallation products in the neutron absorber nuclei is important. Other major sources of the neutron background are: $(\alpha,n)$ interactions, fission of radioactive impurities, interactions of atmospheric and fission antineutrinos (both natural and from reactors) with protons. The neutrino flux from nuclear power plants depends strongly on location of nearby ones, and this factor has to be included in projects of future pre-supernova detectors.

5 Importance of pre-supernova neutrinos detection

Our results for 20 $M_{\odot}$ pre-supernova star show that neutrinos (particularly $\bar{\nu}_{e}$) from last stages of nuclear burning in such a star are possible to detect. Future detectors (UNO, Hyper-Kamiokande) will be able to cover significant fraction of the Galaxy. However, when we take into account relatively low, from typical experiment lifetime point of view, local core-collapse SN rate, of 1 per $\sim$100 yrs or less (Table I of [33], [32] for overview, see however [34]), only projects of long standing, namely nucleon decay and neutrino observatories, have chance to be operating during such an event. At present it is difficult to reliably estimate probability of successful neutrino-cooled start detection because of (1) uncertainties of local supernova rate, (2) unexplored yet variety of massive stars and their models, (3) unknown details of detection technique, especially neutron background level. Making optimistic assumption of 10 events/day detectable and clearly distinguishable from background, we get (using Galaxy model [12] and Si burning event rate for 20 $M_{\odot}$ star from Table 6) 1.7% Galaxy coverage (i.e. up to 2 kpc from Earth) for Super Kamiokande. Next generation detectors UNO and Hyper Kamiokande cover significant fraction 30% (7.5 kpc) and 37% (8.2 kpc) of Galaxy disk stars, respectively. The highest Galaxy supernova rate estimate of 1 per 10 years [10] gives (under above assumptions) successful detection probability of 3% (SK), 60% (UNO) and 75% (HyperK) during 20 years of uninterrupted observation.

Benefits given by the detection of the pre-supernova neutrino signal can be divided into two sets: (1) those related to possible prediction of subsequent supernova event and (2) insight into processes related to deep interior of massive stars prior to its death.
5.1 Supernova prediction?

Supernova event is an unpredictable phenomenon. Astronomers await nearby supernova for 400 years. Therefore, many of them speculate on the likely next Galaxy event. The list of candidates includes Betelgeuse, Mira Ceti, Antares, Ras Algheti, γ² Vel, Sher25 and Eta Carinae. Unfortunately, the surface of these stars is unaffected by (possibly) dramatic nuclear and hydrodynamical processes deep inside. This is effect of $\tau \sim 10000$ years timescale of hydrogen envelope [35]. No electromagnetic observation at any wavelength and resolution can help. Only neutrinos carry informations on the current state of the stellar core. That’s why only neutrinos could warn us before the supernova event. The case of SN1987A [6] unexpectedly revealed this fact. The silicon-burning neutrinos, although carry only about 1% energy compared to the main supernova neutrino burst, are possible to detect, as we showed in previous sections (cf. Table 6). The information about an incoming supernova is transmitted around 2 days\(^3\) earlier. The early warning would provide an additional time which may be crucial for preparation of all available observational techniques, including gravitational radiation detectors, and would allow us to be ready for the main neutrino burst from collapse and protoneutron star cooling.

In a very favorable case of a close star, much less than 1 kpc away\(^4\) with operating megaton-scale neutrino observatory modified by addition of appropriate neutron absorber, we could expect detection of oxygen- and neon-burning neutrinos a few months before the explosion. The detection, however, would be more difficult than silicon-burning neutrinos, mainly due to lower luminosities $L_\nu$ (Table 2), lower average energies $E_\nu$ (Fig. 1) and smaller cross-sections (Table 5).

Let’s note, that the above speculations are no longer valid if the neutrino detection is offline. Realtime (on-line) data analysis is strongly preferred from this point of view.

5.2 Astrophysical importance of Si burning neutrinos

The aim of our work is to show the feasibility of pair-annihilation neutrinos detection. We did not discuss the calculations of the neutrino luminosities, but actually the silicon burning is very complicated and "potentially numer-

\(^{3}\) For a 20 M$_\odot$ star. This time strongly depends on the stellar mass (cf. [35], Table I), and is in the range 0.7 - 18 days.

\(^{4}\) A 20 M$_\odot$ pre-SN star at Betelgeuse distance (Betelgeuse is actually a 15 M$_\odot$ red giant at a distance of 185 pc) which just entered the oxygen burning stage would produce in HyperK 45 neutrons/day during 6 months before its explosion.
ically unstable stage" ([35], sec. IV A-4) of stellar modeling, mainly due to similar timescales of nuclear burning and convection. The behaviour of spherically symmetric models employing the mixing-length convection appears to be completely different from 2D hydrodynamic models ([3], Epilogue). Thus any observational data, even few detected events may be very important to constrain theoretical models. In a favorable situation of a close star with new-generation observatories we should be able to constrain the time-dependence of the neutrino flux and of the spectrum.

The Si-burning neutrino emission precedes a subsequent explosion event independently of the actual stellar death scenario. The SN1987A confirmed standard supernova mechanism [36]. However, it is believed that at least some of the massive stars die in other ways. The most recent research is concentrated on GRB-SN connection [37], their relation to failed supernovae [38] and the core rotation [33]. It is not yet understood why some massive stars become supernovae, hypernovae or even GRBs. The detection of pre-supernova Si-burning neutrinos together with the following observations of optical, neutrino and gravitational signals from the supernova and the identification of the progenitor would establish the relation of pre-supernova conditions and the explosion dynamics. Let’s note, that in case of the supernova shrouded in interstellar clouds, Si burning neutrinos carry exclusive information on the progenitor.

5.3 Discussion

This article shows that detection of pre-supernova star neutrinos is a feasible new goal for neutrino astronomy. Our simplified analysis may be extended to stars of different masses. The constant neutrino flux can be replaced with more realistic time-dependent flux generated by stellar evolution codes. The simple spectrum of pair-annihilation neutrinos can be augmented with detailed plasma- and weak-nuclear-neutrinos spectra. These refinements could change the results somewhat, not affecting our predictions as to the detection feasibility considerably. Clearly, the most important circumstance is the distance to the next Galactic supernova. It is also, however, the most indeterminable one. Therefore, if we want to get results, we have to maximize our observation range. Detectors like Hyper-Kamiokande, UNO, or even better should be operating at the “time zero”.
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References

[1] M. Koshiba, Phys. Rep. 220 (1992) 229; K. Nakamura, *Neutrino Oscillations and Their Origin*, Universal Academy Press, Tokyo, 2000, p.359.

[2] Chang Kee Jung, *International Workshop on Next Generation Nucleon Decay and Neutrino Detector (NNN 99)*, Stony Brook, New York, 23-25 Sep 1999. [hep-ex/0005046](http://arxiv.org/abs/hep-ex/0005046)

[3] D. Arnett, *Supernovae and Nucleosynthesis*, Princeton University Press, 1996.

[4] A. Heger & S. E. Woosley and G. Martinez-Pinedo & K. Langanke, Astrophys. J., 560 (2001) 307-325.

[5] John N. Bahcall, M. H. Pinsonneault, and Sarbani Basu, Astrophys. J. 555 (2001) 990-1012. [astro-ph/0010346](http://arxiv.org/abs/astro-ph/0010346)

[6] W. D. Arnett, J. N. Bahcall, R. P. Kirshner, S. E. Woosley, Ann. Rev. Astron. Astrophys. 27 (1989) 629.

[7] T. A. Weaver, G. B. Zimmerman and S. E. Woosley, Astrophys. J. 225 (1978) 1021.

[8] S. Van den Bergh, G. A. Tammann, Ann. Rev. Astron. Astrophys. 29 (1991) 368.

[9] E. Cappellaro, M. Turrato, Astrophys. Space Sci. Libr. 264 (2000) 321.

[10] J. N. Bahcall and T. Piran, Astrophys. J. Lett. 267 (1983) L77.

[11] R. G. Strom, Astron. Astrophys. 288 (1994) L1.

[12] J. N. Bahcall and R. M. Soneira, Astrophys. J. Lett. 238 (1980) L17.

[13] [http://antwrp.gsfc.nasa.gov/apod/ap990605.html](http://antwrp.gsfc.nasa.gov/apod/ap990605.html)

[14] S. M. Asida, D. Arnett, Astrophys. J. 545 (2000) 435.

[15] S. Ciechanowicz, M. Misiaszek, W. Sobków, [hep-ph/0305107](http://arxiv.org/abs/hep-ph/0305107) to appear in Eur. Phys. J. C (2003).

[16] I. Gil-Botella and A. Rubbia, J. Cosmol. Astropart. Phys. JCAP 10 (2003) 009.
[17] W. Greiner, B. Muller, *Gauge Theory of Weak Interactions*, 2nd Edition, Springer-Verlag Berlin Heidelberg New York, 2000.

[18] N. Itoh et. al., Astrophys. J. Supplement Series **102** (1996) 411.

[19] B. Aufderheide, Astrophys. J. **411** (1993) 813.

[20] R. Kippenhahn, A. Weigert, *Stellar Structure and Evolution*, Springer-Verlag 1994

[21] Xiangdong Shi & George M. Fuller, Astrophys. J. **503** (1998) 307.

[22] The Super-Kamiokande Collaboration, Phys. Rev. Lett. **90** (2003) 061101.

[23] The SNO Collaboration, Phys. Rev. Lett. **89** (2002) 011301.

[24] The KamLAND Collaboration, Phys. Rev. Lett. 90 (2003) 021802.

[25] The Borexino Collaboration, Astropart. Phys. **16** (2002) 205-234.

[26] P. Vogel and J. F. Beacom, Phys. Rev. D **60** (1999) 053003.

[27] M. Fukugita and T. Yanagida, *Physics of Neutrinos and Applications to Astrophysics*, Springer-Verlag Berlin Heidelberg New York, 2003.

[28] G. Zuzel et. al., Nucl. Instrum. Meth. **A498** (2003) 240-255.

[29] K. Kubodera and S. Nozawa, International Journal of Modern Physics **E3** (1994) 101-148.

[30] John F. Beacom, Mark R. Vagins, hep-ph/0309300 submitted to Phys. Rev. Lett.

[31] The SNO Collaboration, nucl-ex/0309004, submitted to Phys. Rev. Lett.

[32] J. F. Beacom, R. N. Boyd & A. Mezzacappa, Phys. Rev. D **63** (2001) 073011.

[33] A. Odrzywolek, M. Kutsche, M. Misiaszek & K. Grotowski, Acta Physica Polonica B, Vol. 34, No 5 (2003) 2791.

[34] A. Di Paola et. al., Astronomy & Astrophysics **393** (2002) L21.

[35] S. E. Woosley, A. Heger, T. A. Weaver, Rev. Mod. Phys. **74** (2002) 1015.

[36] H. A. Bethe, Rev. Mod. Phys. **62** (1990) 801.

[37] A. MacFayden, S. E. Woosley, Astrophys. J. **524** (1999) 262.

[38] Andrew Gould, Samir Salim, Astrophys. J. **572** (2002) 944.