Effect of Flavour Oscillations on the Detection of Supernova Neutrinos

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Abstract:Neutrinos and antineutrinos of all three flavours are emitted during the post bounce phase of a core collapse supernova with $\nu_\mu/\nu_\tau(\bar\nu_\mu/\bar\nu_\tau)$ having average energies more than that of $\nu_e(\bar\nu_e)$. They can be detected by the new earth bound detector like SNO and Super-Kamiokande which are sensitive to neutrinos of all three flavours. In this letter we consider the effect of flavour oscillations on the neutrino flux and their expected number of events at the detector. We do a three-generation analysis and for the mass and mixing schemes we first consider the threefold maximal mixing model consistent with the solar and the atmospheric neutrino data and next a scenario with one $\Delta m^2 \sim 10^{-11} eV^2$ (solar range) and the other $\Delta m^2 \sim 10^{-18} eV^2$, for which the oscillation length is of the order of the supernova distance. In both these scenarios there are no matter effects in the resultant neutrino spectrum and one is concerned with vacuum oscillations. We find that though neutrino oscillations result in a depletion in the number of ν_e and $\bar\nu_e$ coming from the supernova, the actual signals at the detectors are appreciable enhanced.

The question whether neutrinos are massive or not has been answered. After 537 days of data on atmospheric neutrinos the Super-Kamiokande has finally confirmed the existence of non-zero oscillations and hence mass for the muon neutrinos [1]. The Super-Kamiokande (SK) data confirmed the depletion in the atmospheric muon neutrino flux which the Kamiokande, IMB and the Soudan experiments had observed before. At 90% C.L. the mixing parameters allowed by all the atmospheric neutrino experiments combined are [2] $5 \times 10^{-4} eV^2 \leq \Delta m^2 \leq 6 \times 10^{-3} eV^2$, $sin^2 2\theta \geq 0.8$ for the $\nu_\mu - \nu_\tau$ channel and $10^{-3} \leq \Delta m^2 \leq 7 \times 10^{-3} eV^2$, $sin^2 2\theta \geq 0.8$ for the $\nu_\mu - \nu_s$ ($\Delta m^2 > 0$) oscillation mode, while the oscillation parameter region for the $\nu_\mu - \nu_e$ mode is completely ruled out by the data from the CHOOZ experiment [3]. The other puzzle which has warranted neutrino oscillations as a possible solution is the solar neutrino deficit problem. The three solar neutrino detectors, the Homestake, Kamiokande and Gallex (also Sage) have been observing neutrino flux far less than that predicted by the standard solar model [4]. This deficit can be explained by neutrino oscillations in vacuum for $\delta m^2 \sim 0.615 \times 10^{-10} eV^2$ and $sin^2 2\theta \sim 0.864$ [5] or by MSW resonant flavour conversions [6] for $\Delta m^2 \sim 5.4 \times 10^{-6} eV^2$ and $sin^2 2\theta \sim 7.9 \times 10^{-3}$ (non-adiabatic solution) and $\Delta m^2 \sim 1.7 \times 10^{-5} eV^2$ and $sin^2 2\theta \sim 0.69$ (large angle solution) [7]. The first results from the SK solar neutrino flux measurements favor the long wavelength vacuum oscillation solution with large angle mixing [8]. When the SK solar ν data is combined with the earlier data then the corresponding values are $\Delta m^2 \sim 6.5 \times 10^{-11} eV^2$, $sin^2 2\theta \sim 0.75$ for vacuum oscillations and $\Delta m^2 \sim 5 \times 10^{-6} eV^2$, $sin^2 2\theta \sim 5.5 \times 10^{-3}$ for non-adiabatic MSW resonant flavour conversion [9]. The threefold maximal mixing model [10, 11] can explain both the solar and the atmospheric neutrino data simultaneously [12]. In a recent paper [13] it has been shown that the maximal mixing model can account for both the SK atmospheric data and the CHOOZ data provided the relevant Δm^2 is in the range $4 \times 10^{-4} eV^2 \leq \Delta m^2 \leq 1.5 \times 10^{-3} eV^2$, along with the solar ν data. One hopes to find a definite solution to the solar neutrino problem once the Sudbury Neutrino observatory (SNO) which is the first heavy water detector becomes operational [14]. Though one of the principal motivation for these two detectors was to throw light on the solar neutrino problem but they are equally useful for detecting the neutrinos from a nearby supernova event.

The core of a massive star ($M \geq 8M_\odot$) starts collapsing once it runs out of nuclear fuel. The collapse continues to densities beyond the nuclear matter density after which a bouncing of the in falling matter takes place leading to supernova explosion and the formation of a protoneutron star. Only a small fraction of the huge gravitational energy released in the process goes into the explosion and all the rest of the energy is carried away by neutrinos and antineutrinos of all three flavours. These neutrinos for galactic supernova events can be detected by detectors like the SNO and SK. In contrast to the solar, the atmospheric as well as the accelerator/ reactor neutrinos where one has neutrino flux of a single flavour at the source, postbounce supernova neutrinos (antineutrinos) start from the source in all three flavours but with ν_μ/ν_τ ($\bar\nu_\mu/\bar\nu_\tau$) having average energies more than that of $\nu_e(\bar\nu_e)$ and it is an interesting problem to study whether their flux and their signal at the terrestrial ν detectors get appreciably altered in reaching the earth if neutrinos do oscillate. In this work we give quantitative predictions for the number of neutrino events coming from a typical type II supernova at a distance of 10kpc in both SNO and SK and show how the number of events for each detection process would change in case oscillations do take place.

There have been various attempts before to estimate the effect of non-zero neutrino mass and mixing on the expected neutrino signal from a galactic supernova. Matter enhanced resonant flavour conversion has been observed to have a large effect on the ν_e signal [15, 16, 17]. The $\bar\nu_e$ events of course remain unchanged in this case. With vacuum oscillations we can expect an increase in both the ν_e and $\bar\nu_e$ signal. Burrows *et al.* [16] have considered for SNO, the effect of vacuum oscillations as well and have found that with two-flavours the effect of vacuum oscillations on the signal is small, using their model predictions for the different ν luminosities.

We have considered a three-generation mixing scheme and have calculated the effect of neutrino oscillations on the signal from a 20 $M_\odot$ supernova model developed recently [19]. First we do our calculations for the threefold maximal mixing model consistent with the solar ($\Delta m^2 \sim 10^{-11} eV^2$) and the atmospheric neutrino data ($\Delta m^2 \sim 10^{-3} eV^2$). For $\Delta m^2 \sim 10^{-3} eV^2$ normally we expect matter enhanced resonance in the supernova. But for the particular case of maximal mixing it has been shown before, both numerically [20] and analytically [21], that there are absolutely no

matter effects in the resultant neutrino spectrum on earth. Though the arguments in both these previous papers are for solar neutrinos, extension to the case of supernova neutrinos is straightforward. Hence in this scheme we are concerned with vacuum oscillations. We also consider a second scenario where we take one of the mass square differences in the solar vacuum oscillation solution range while the other is $\sim 10^{-18}eV^2$ where the oscillations wavelength $\lambda \sim L$, the distance of the supernova from the earth and hence oscillations are observable in the neutrino spectrum. In this scenario of course there is no chance of a MSW resonance and we have vacuum oscillations. We find appreciable enhancement in the expected ν_e and $\bar{\nu}_e$ charge current events for both SNO and SK in both scenarios even with vacuum oscillations.

The differential number of neutrino events at the detector for a given reaction process is

$$\frac{d^2S_\nu}{dEdt} = \frac{n}{4\pi L^2}N_\nu(t)\sigma(E)f_\nu(E) \tag{1}$$

One uses for the number of neutrinos produced at the source $N_\nu(t) = L_\nu(t)/\langle E_\nu(t)\rangle$ where $L_\nu(t)$ is the neutrino luminosity and $\langle E_\nu(t)\rangle$ is the average energy. In (1) $\sigma(E)$ is the reaction cross-section for the neutrino with the target particle, L is the distance of the neutrino source from the detector(10kpc), n is the number of detector particles for the reaction considered and $f_\nu(E)$ is the energy spectrum for the neutrino species involved. For the neutrino luminosity and average energy we use the values of Totani et al. [19] for a 20 $M_\odot$ type II supernova model based on the hydrodynamic code developed by Wilson and Mayle. Though in their paper Totani et al. observe that the neutrino spectrum is not a pure black body, but we as a first approximation use a Fermi-Dirac spectrum for the neutrinos, charaterised by the ν temperature alone for simplicity. The effect of a chemical potential is to cut the high energy tail of the neutrino spectrum and we also study it's effect on the the ν signal and on the enhancement of the signal when oscillations are introduced. We find the ν signal for the various detection processes as a function of energy by integrating out time from (1). By integrating (1) over energy as well we get the total number of events for the reaction concerned. These are the expected number of events.

In the presence of oscillations of massive neutrinos more energetic $\nu_\mu(\bar{\nu}_\mu)$ and $\nu_\tau(\bar{\nu}_\tau)$ get transformed into $\nu_e(\bar{\nu}_e)$ which modifies the numbers that we obtain using (1). The

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general expression for the probability that an initial ν_α gets converted to a ν_β after traveling a distance L in vacuum is

$$P_{\nu_\alpha \nu_\beta} = \delta_\alpha \beta - 4 \sum_{j>i} U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} sin^2 \frac{\pi L}{\lambda_{ij}} \tag{2}$$

where $\alpha = e, \mu, \tau, ..$ and $i, j = 1, 2, 3, ..$

- $\lambda_{ij} = 2.5 \times 10^{-3} km \frac{E}{MeV} \frac{eV^2}{\Delta m_{ij}^2}$

- $\Delta m_{ij}^2 = m_j^2 - m_i^2$

$U_{\alpha i}$ are the components of the mixing matrix. For the mass and mixing parameters we consider two scenarios.

- **scenario 1:** Here we consider threefold maximally mixed neutrinos with the mass spectrum $\Delta m_{13}^2 \approx \Delta m_{23}^2 \sim 10^{-3} eV^2$ corresponding to the atmospheric range while $\Delta m_{12}^2 \sim 10^{-11} eV^2$ in accordance with the solar neutrino problem. The oscillations due to all the mass differences are averaged out to $1/2$ as $\lambda << L$, and hence the expression for the various probabilities in this case relevant for us are [11, 12]

$$P_{\nu_e \nu_e} = \frac{1}{3} \tag{3}$$

$$P_{\nu_\mu \nu_e} + P_{\nu_\tau \nu_e} = 1 - P_{\nu_e \nu_e} \tag{4}$$

We call this Case 1.

- **scenario 2:** Here we set $\Delta m_{12}^2 \sim 10^{-18} eV^2$ for which $\lambda \sim L$ and the oscillation effects are observable while $\Delta m_{13}^2 \approx \Delta m_{23}^2 \sim 10^{-11} eV^2$ (solar range). If we consider the Maiani parametrisation of the mixing matrix U [22] then the expression for the probabilities are

$$P_{\nu_e \nu_e} = 1 - sin^2 2\theta_{12} cos^4 \theta_{13} sin^2 \frac{\pi L}{\lambda_{12}} - \frac{1}{2} sin^2 2\theta_{13} \tag{5}$$

$$P_{\nu_\mu \nu_e} + P_{\nu_\tau \nu_e} = 1 - P_{\nu_e \nu_e} \tag{6}$$

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For this case the oscillations due to Δm_{13}^2 and Δm_{23}^2 are averaged out as the neutrinos travel to earth but those due to Δm_{12}^2 survive. For θ_{13} we consider two sets of values allowed by the solar ν data. We have done our calculations for $\sin^2 2\theta_{13} = 1.0$ (the maximum allowed value) and with $\sin^2 2\theta_{13} = 0.75$ (the best fit value) [9]. The first set is called Case 2a while the second is called Case 2b. Since nothing constrains Δm_{12}^2 in this scenario we can vary θ_{12} and study it's effect on the ν signal. We have tabulated our results for $\sin^2 2\theta_{12} = 1.0$ since it gives the maximum increase in the signal from the no oscillation value.

The corresponding expressions for the antineutrinos will be identical. We note that because the energy spectra of the ν_μ and ν_τ are identical, we do not need to distinguish them and keep the combination $P_{\nu_\mu \nu_e} + P_{\nu_\tau \nu_e}$. We have made here a three-generation analysis where all the three neutrino flavours are active. Hence if both the solar ν problem and the atmospheric ν anomaly require ν oscillation solutions, then in the **scenario 2**, the atmospheric data has to be reproduced by $\nu_\mu - \nu_s$ oscillations. We are interested in this scenario as only with neutrinos from a supernova can one probe very small mass square differences $\sim 10^{-18} eV^2$. To find the number of events with oscillations we will have to fold the expression (1) with the expressions for survival and transition probabilities for the neutrinos for all the cases considered.

In Table 1 we report the calculated number of expected events for the main reactions in H_2O and D_2O. Column 2 of Table 1 gives the expected numbers for the model under consideration when the neutrino masses are assumed to be zero. Column 3,4,5 give the corresponding numbers for the two neutrino mixing scenarios that we have considered (see Table 1 for details). All the numbers tabulated have been calculated for 1 kton of detector mass. To get the actual numbers we have to multiply these numbers with the relevant fiducial mass of the detector. The efficiency of both the detectors (SNO and SK) is taken to be 1 [19, 23, 24]. The energy threshold is taken to be 5 MeV for both SK [23] and SNO [24]. For the cross-section of the $(\nu_e - d), (\bar{\nu}_e - d), (\nu_x - d)$ and $(\bar{\nu}_e - p)$ reactions we refer to [25]. The cross-section of the $(\nu_e(\bar{\nu}_e) - e^-)$ and $(\nu_x - e^-)$ scattering has been taken from [27] while the neutral current $(\nu_x - ^{16}O)$ scattering cross-section is taken from [23]. For the $^{16}O(\nu_e - e^-)^{16}F$ and $^{16}(\bar{\nu}_e, e^+)^{16}N$ reactions we refer to [26] where we have used the cross-sections for the detector with perfect efficiency. From a

comparison of the predicted numbers in Table 1, it is evident that neutrino oscillations play a significant role in supernova neutrino detection. For the neutral current sector the number of events remain unchanged as the interaction is flavour blind.

The 32 kton of pure water in SK detects neutrinos primarily through the capture of $\bar{\nu}_e$ on protons $(\bar{\nu}_e p \rightarrow n e^+)$ and $(\nu_e(\bar{\nu}_e) - e^-)$ scattering. The energy threshold for $^{16}O(\nu_e, e^-)^{16}F$ is 15.4 MeV and that for $^{16}O(\bar{\nu}_e, e^+)^{16}N$ is 11.4 MeV, hence these reactions are important only for very high energy neutrinos. The typical average energies of ν_e and $\bar{\nu}_e$ from a type II supernova is about 11 MeV and 16 MeV respectively, so we do not expect significant contribution from these two reactions. This is evident from Table 1 where the ^{16}O events are only 2.1% of the total charge current signal at SK. As a result of mixing the mu and tau neutrinos and antineutrinos oscillate (with average energy $\sim$ 25 MeV) into ν_e and $\bar{\nu}_e$ during their flight from the galactic supernova to the detector resulting in higher energy ν_e and $\bar{\nu}_e$ and the number of ^{16}O events are increased appreciably (for Case 1 $(\nu_e - ^{16}O)$ events go up by 13 times) so that after oscillations they are 7% (Case 1) of the total charge current events at SK. The effect of oscillations on the $(\bar{\nu}_e$-p$)$ capture is to enhance the expected signal by about 25% (Case 1). In all previous studies where the effect of MSW transition on the neutrino signal has been studied [15, 17], there is no enhancement in the number of expected events for the $(\bar{\nu}_e$-p$)$ sector while we do get a significant change in the expected signal with vacuum oscillations. For the $(\nu_e(\bar{\nu}_e) - e^-)$ scattering the effect of oscillation is very small.

The SNO is the world's first heavy water detector made of 1 kton of pure D_2O surrounded by ultra pure H_2O. There are 10^4 phototubes around this entire volume which can view only the inner 1.4 kton of water efficiently [24]. We find about 99% increase in $(\nu_e - d)$ events and about 46% increase in $(\bar{\nu}_e - d)$ events for the Case 1. From the column 2 of Table 1 we can see that there are more $(\bar{\nu}_e - d)$ than $(\nu_e - d)$ events even though there are more ν_e than $\bar{\nu}_e$ coming from the supernova. This is because the reaction cross-section $\sigma \sim E^{2.3}$ and the $\bar{\nu}_e$ spectrum is harder than the ν_e spectrum. This also results in a greater enhancement due to oscillations for the $(\nu_e - d)$ events, as the difference between the energies of the ν_e and $\nu_\mu(\nu_\tau)$ is greater than those between $\bar{\nu}_e$ and $\bar{\nu}_\mu(\bar{\nu}_\tau)$ and hence the effect on the ν_e events is more. As a result after

oscillations are switched on the number of $(\nu_e - d)$ events supersede the $(\bar{\nu}_e - d)$ events. We observe a similar effect for the ^{16}O events, where the $\bar{\nu}_e$ signal without oscillations is more than the ν_e signal, while the effect of oscillations is more for the latter. The effect is more magnified in this case due to the very strong energy dependence of the reaction cross-section and also due to the fact that the energy threshold for $(\bar{\nu}_e - ^{16}O)$ event is lower than for the $(\nu_e - ^{16}O)$ event. In Fig. 1 we plot the signal due to the $(\nu_e - d)$ events as a function of energy , without oscillations and with oscillations for the Case 1 and Case 2b. All the features mentioned are clearly seen. The plot for the Case 2b clearly shows oscillations.

In Fig. 2 we plot the cumulative fluence of the ν_e coming from the supernova at 10 kpc without oscillations and with oscillations for Case 1 and Case 2b. It is seen that the result of oscillation in fact is to reduce the total number of ν_e. Yet as seen from Table 1, we have obtained significant increase in the $(\nu_e - d)$ events and the $(\nu_e - ^{16}O)$ events. The solution to this apparent anomaly lies in the fact that the cross-section of these reactions are strongly energy dependent. As a result of oscillations the ν_e flux though depleted in number, gets enriched in high energy neutrinos. It is these higher energy neutrinos which enhance the ν signal at the detector. This also explains the difference in the degree of enhancement for the different processes. For the $(\nu_e - d)$ and $(\nu_e - ^{16}O)$ events, especially for the latter, the effect is huge while for the $(\nu_e - e^-)$ scattering it is negligible as it's reaction cross-section is only linearly proportional to E. Due to their high energy dependent σ the $^{16}O(\nu_e, e^-)^{16}F$ events turn out to be extremely sensitive to oscillations. A similar argument holds true for the case of the antineutrinos, only here the effect of oscillations is less than in the case for the neutrinos as the difference between the energies of the $\bar{\nu}_e$ and $\bar{\nu}_\mu/\bar{\nu}_\tau$ is comparatively less as discussed earlier.

For the **scenario 2** we have studied the effect of the mixing angles on the signal. For a fixed θ_{13} the effect of oscillations is enhanced if we raise θ_{12}. The effect of θ_{13} is more subtle. The effect of oscillations increase with θ_{13} initially and then decrease. We have also checked the effect of a chemical potential μ on the neutrino signal. A non-zero μ cuts the high energy tail of the neutrino signal as a result of which the total signal goes down for both with and without oscillations, the effect being greater for the more energy sensitive reactions.

With the supernova model of Totani *et al.* [19], we have obtained oscillation effects in the expected ν signal which are significantly larger than those obtained by Burrows *et al.* [16, 18]. In the model that Burrows *et al.* use in their study, the ν luminosities L_ν are more than those for Totani *et al.* model, but the average energy is much smaller, particularly for the $\bar{\nu}_e$ and $\nu_{\mu,\tau}(\bar{\nu}_{\mu,\tau})$. Hence their ν_μ spectra lacks in high energy neutrinos which results in almost negligible effect of oscillations in their case. Again in the model of Burrows *et al.* the average energies decrease with time while in the model of Totani *et al.* not only the average energies but also the difference between the average energies of $\nu_e(\bar{\nu}_e)$ and $\nu_{\mu,\tau}(\bar{\nu}_{\mu,\tau})$ increases with time. The effect of all these is to magnify the effect of oscillations in our case.

In conclusion, we have shown that with the model of Totani *et al.* even with vacuum oscillations we obtain appreciable enhancement in the expected ν signal in SNO and SK even though the number of neutrinos arriving at the detector from the supernova goes down. In contrast to the case where we have MSW resonance in the supernova, with vacuum oscillations we get enhancement for both ν_e as well as $\bar{\nu}_e$ events. If we have a galactic supernova event in the near future and if we get a distortion in the neutrino spectrum and an enhancement in the signal, for both ν_e as well as $\bar{\nu}_e$ then that would indicate vacuum neutrino oscillations.

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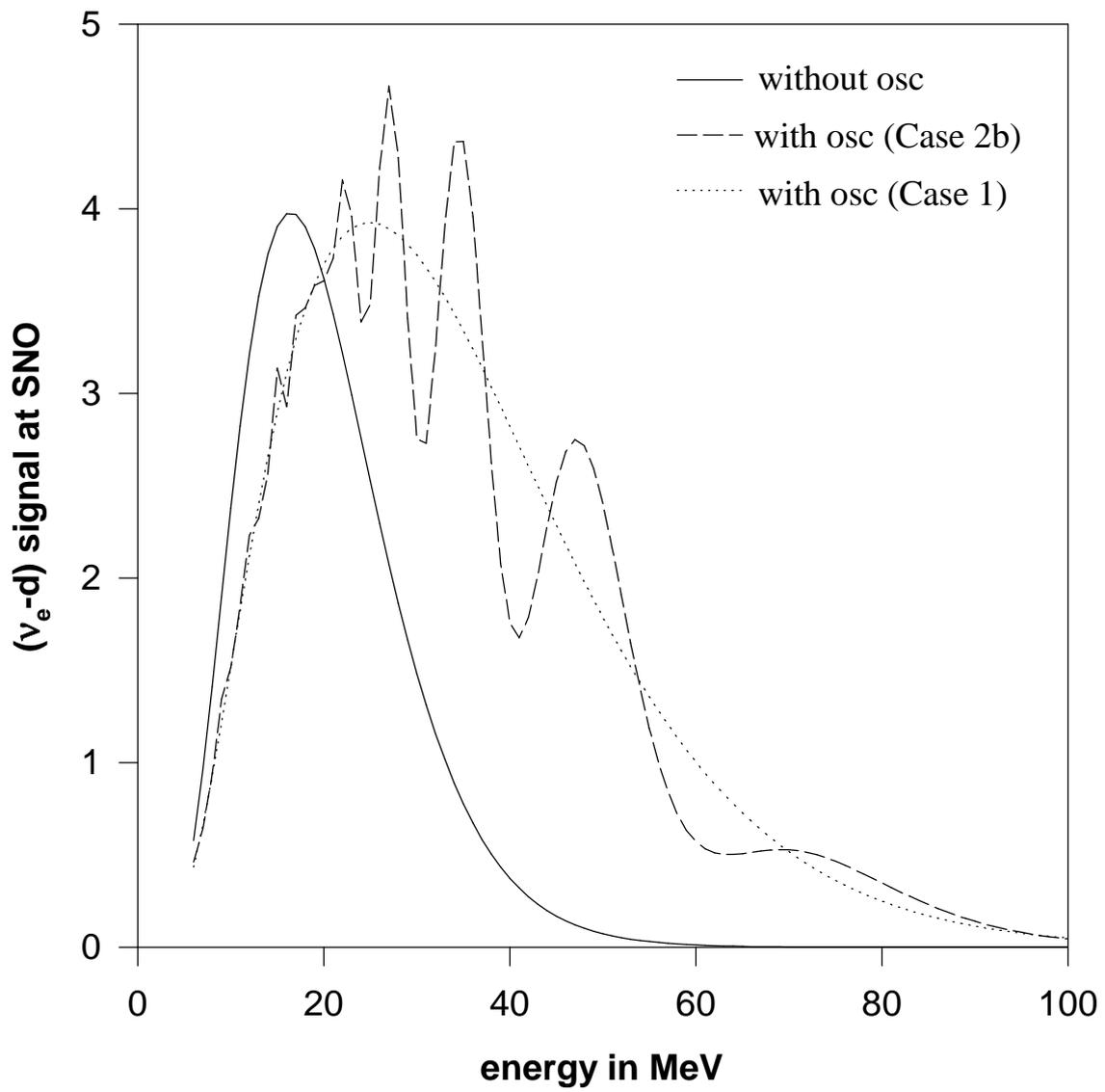
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Table 1 The expected number of neutrino events for a 1 kton water cerenkov detector

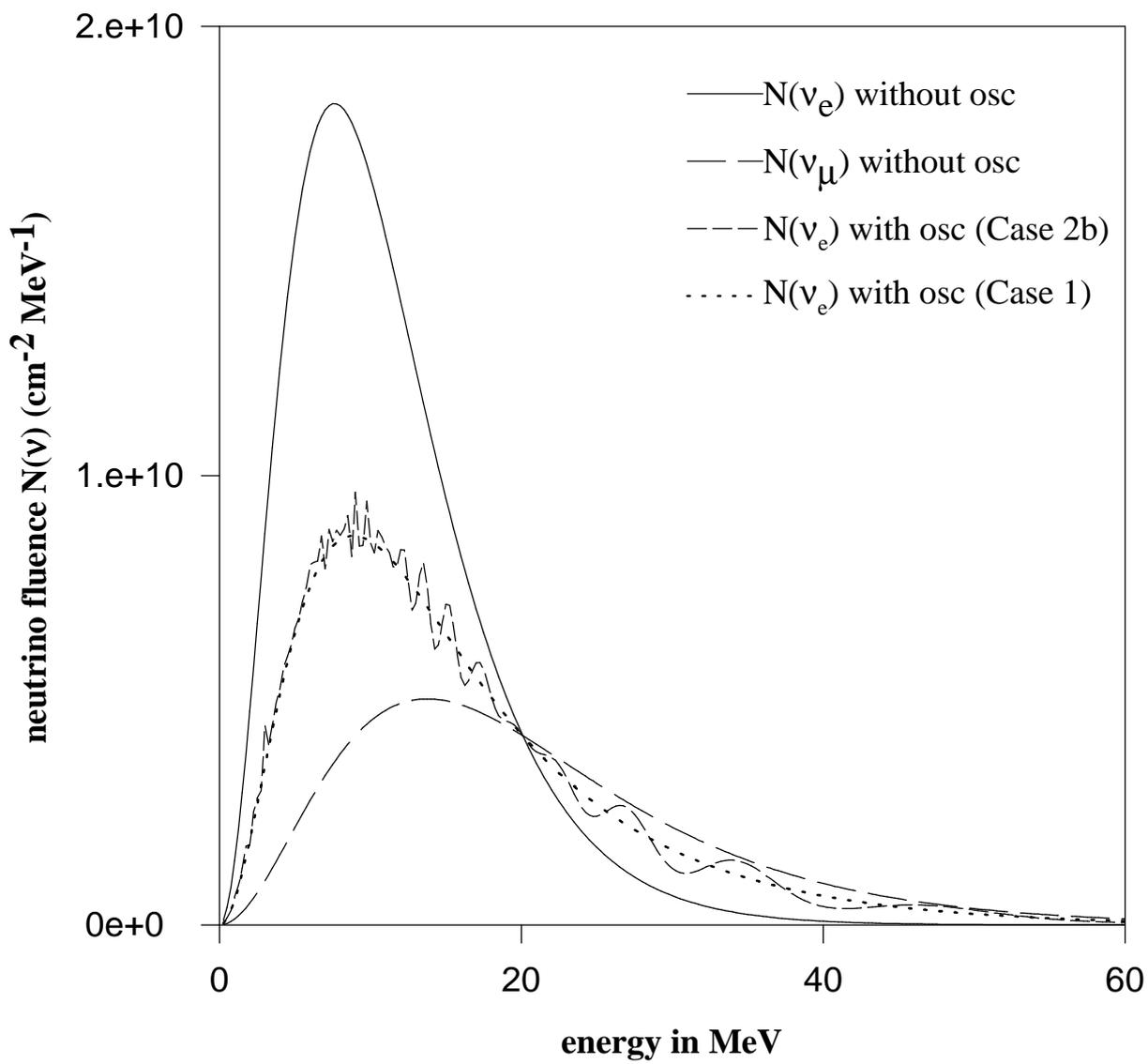| reaction	signal without oscillation	signal with oscillation		
		scenario 1	**scenario 2**	
		Case 1	Case2a	Case2b
$\nu_e + d \rightarrow p + p + e^-$	78	155	150	153
$\bar{\nu}_e + d \rightarrow n + n + e^+$	93	136	133	135
$\nu_x + d \rightarrow n + p + \nu_x$	455	455	455	455
$\bar{\nu}_e + p \rightarrow n + e^+$	263	330	326	329
$\nu_e + e^- \rightarrow \nu_e + e^-$	4.68	5.68	5.61	5.66
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	1.54	1.77	1.76	1.77
$\nu_{\mu,\tau}(\bar{\nu}_{\mu,\tau}) + e^- \rightarrow \nu_{\mu,\tau}(\bar{\nu}_{\mu,\tau}) + e^-$	3.87	3.55	3.50	3.53
$\nu_e + ^{16}O \rightarrow e^- + ^{16}F$	1.13	14.58	13.78	14.45
$\bar{\nu}_e + ^{16}O \rightarrow e^+ + ^{16}N$	4.57	10.62	10.23	10.53
$\nu_x + ^{16}O \rightarrow \nu_x + \gamma + X$	13.6	13.6	13.6	13.6

Figure Captions

Fig. 1 The $(\nu_e - d)$ signal at SNO vs neutrino energy without and with oscillations for the Case 1 and Case 2b

Fig. 2 The cumulative ν_e fluence as a function of the neutrino energy without and with oscillations for the Case 1 and Case 2b. Also shown is the ν_μ fluence for comparison.

Fig. 1

neutrino fluence $N(\nu)$ (cm^{-2} MeV^{-1})

2.e+10

1.e+10

0e+0

——— $N(\nu_e)$ without osc

— — $N(\nu_\mu)$ without osc

– – – $N(\nu_e)$ with osc (Case 2b)

· · · · $N(\nu_e)$ with osc (Case 1)

0

20

40

60

energy in MeV

Fig. 2