Solar neutrino interactions: Using charged currents at SNO to tell neutral currents at Super-Kamiokande

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Abstract

In the presence of flavor oscillations, muon and tau neutrinos can contribute to the Super-Kamiokande (SK) solar neutrino signal through the neutral current process $\nu_{\mu,\tau} e^- \rightarrow \nu_{\mu,\tau} e^-$. We show how to separate the $\nu_e$ and $\nu_{\mu,\tau}$ event rates in SK in a model independent way, by using the rate of the charged current process $\nu_e d \rightarrow p p e^-$ from the Sudbury Neutrino Observatory (SNO) experiment, with an appropriate choice of the SK and SNO energy thresholds. Under the additional hypothesis of no oscillations into sterile states, we also show how to determine the absolute $^8$B neutrino flux from the same data set, independently of the $\nu_e$ survival probability.

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I. INTRODUCTION

The Super-Kamiokande (SK) experiment [1] is measuring the rate $R_{SK}$ of electrons produced by $^8$B solar neutrinos [2] through the scattering process

$$\nu_e e^- \rightarrow \nu_e e^-, \hspace{1cm} (1)$$

in a fiducial mass of 22.5 kton of water and above a threshold $T_{SK} = 6.5$ MeV $- m_e$ for the measured electron kinetic energy [3]. There are good prospects for lowering $T_{SK}$ to $\sim 5$ MeV in the near future [4].

In the presence of flavor oscillations, as suggested by various solutions to the solar neutrino problem [5], also muon and tau neutrinos can contribute to $R_{SK}$ through neutral current interactions

$$\nu_{\mu,\tau} e^- \rightarrow \nu_{\mu,\tau} e^-, \hspace{1cm} (2)$$

although it is not possible to separate the contribution of reaction (2) from reaction (1) within the SK experiment itself.

In this work we show how to separate in a model independent way the $\nu_e$ and $\nu_{\mu,\tau}$ event rates in the SK experiment, by means of the Sudbury Neutrino Observatory (SNO) [6] measurement of the total electron rate ($R_{SNO}$) from the charged current process

$$\nu_e d \rightarrow p p e^-, \hspace{1cm} (3)$$

provided that the corresponding electron energy threshold $T_{SNO}$ is chosen appropriately. No other experimental information or theoretical assumption is required.

More precisely, we show that the response functions of the SK and SNO detectors happen to be approximately equal for suitably chosen values of $T_{SK}$ and $T_{SNO}$, within errors much smaller than the uncertainties associated to the cross section for reaction (3). This lucky circumstance makes our approach truly model independent: no prior assumption is required on the absolute $^8$B neutrino flux $\Phi_B$, on the energy (in)dependence of the oscillation probability, or on the presence of possible sterile neutrinos. Furthermore, if only active neutrinos are considered, the absolute value of $\Phi_B$ can also be determined from the same data ($R_{SK}$ and $R_{SNO}$).

The plan of the paper is as follows. In Section II we set the notation. In Section III we study the response functions of SK and SNO and show that they can be equalized to a good approximation by tuning the energy thresholds. In Section IV we work out the consequences of this empirical equality. We draw our conclusions in Sec. V.

We conclude this Section by estimating the rate of solar-neutrino induced electrons $R_{SK}$ actually occurring in the SK detector. The rate of observed events above $T_{SK} \approx 6$ MeV is $0.60 \pm 0.01$ (stat) $\pm 0.02$ (syst) events/kton/day [3]. However, this number is expected to be smaller than the actual rate of $\nu e$ interactions, due to inefficiencies in the data reduction chain. The total signal efficiency $\varepsilon$ appears to be dominated by three cuts: (1) Noise cut, $\varepsilon_n = 94.2\%$ [1]; (2) Spallation cut, $\varepsilon_s = 80\%$ [3]; and gamma ray cut, $\varepsilon_\gamma = 92.2\%$ [3]. Then we get $\varepsilon = \varepsilon_n \varepsilon_s \varepsilon_\gamma = 70\%$, in agreement with the signal efficiency quoted in [7]. Therefore, we estimate the total number of $\nu e$ interactions (detected and undetected) occurring in SK as:
\[ R_{SK}(T_{SK} = 6 \text{ MeV}) = 0.60 \pm 0.01 \pm 0.02 \cdot \varepsilon^{-1} \]
\[ \simeq 0.86 \pm 0.03 \text{ events/kton/day} . \]
\[ R_{SK}(T_{SK} = 7 \text{ MeV}) \simeq 0.61 \pm 0.025 \text{ events/kton/day} . \]

Analogously, and by cutting the electron energy spectrum \[3\] at \( T_{SK} = 7 \text{ MeV} \), we obtain
\[ R_{SK}(T_{SK} = 7 \text{ MeV}) \simeq 0.61 \pm 0.025 \text{ events/kton/day} . \]

Our estimates (3,4) are tentative and will be used only for some numerical examples, the main idea of this work being independent on the specific value of \( R_{SK} \). It is understood that, when the SNO data will become available and will be compared with the SK data, one should use both rates \( R_{SK} \) and \( R_{SNO} \) as corrected for efficiency effects by the experimental collaborations themselves.

II. NOTATION

We denote the absolute flux of \(^8\)B solar neutrinos by \( \Phi_B \) and its energy spectrum \[8\] by \( \varphi(E_\nu) \),
\[ \Phi_B = \int dE_\nu \varphi(E_\nu) , \]
\( E_\nu \) being the neutrino energy. We do not assume any prior estimate of \( \Phi_B \) from standard solar models \[2,9\] in this work.

In the presence of neutrino oscillations, we denote the \( \nu_e \) oscillation probabilities into other states (\( \nu_\mu, \nu_\tau, \) or sterile \( \nu_s \)) as
\[ P_{e\alpha}(E_\nu) = P(\nu_e \rightarrow \nu_\alpha) \quad (\alpha = e, \mu, \tau, s) , \]
subject to the unitarity constraint \( \sum_\alpha P_{e\alpha} = 1 \). No assumption is made on the functional form of \( P_{e\alpha}(E_\nu) \).

The neutrino cross sections for the reactions (1), (2), and (3) are indicated as \( \sigma_e, \sigma_{\mu\tau}, \) and \( \sigma_{CC} \), respectively. It is understood that each cross section \( \sigma_X(X = e, \mu\tau, \text{CC}) \) is corrected for the energy threshold and resolution effects appropriate to the the SK and SNO detectors,
\[ \sigma_X(E_\nu, T_{\text{min}}) = \int_{T_{\text{min}}} dT \int dT' r(T, T') \frac{d\sigma_X(E_\nu, T')}{dT'} , \]
where \( T' \) and \( T \) are the true and measured electron kinetic energies, respectively, \( T_{\text{min}} \) is the energy threshold (equal to \( T_{SK} \) for \( \sigma_e \) and \( \sigma_{\mu\tau} \) and to \( T_{SNO} \) for \( \sigma_{CC} \)) \[\int d\sigma_X/dT' \] is the differential cross section, and \( r(T, T') \) is the energy resolution function
\[ r(T, T') = \frac{1}{\sqrt{2\pi} \Delta T'} \exp \left( \frac{-(T - T')^2}{2\Delta T'^2} \right) , \]
\(^1T_{SK} \) and \( T_{SNO} \) are data analysis thresholds that can be chosen freely, provided that they are greater than the detector trigger thresholds.
with a one-sigma width $\Delta_T'$ scaling as

$$\Delta_T' = \Delta_{10} \sqrt{\frac{T'}{10 \text{ MeV}}} ,$$  \hspace{1cm} (11)$$

$\Delta_{10}$ being equal to 1.5 MeV for SK [3,4] and to 1.4 MeV for SNO [10]. The differential cross sections are taken from [11] for reactions (1,2) and from [12] for reaction (3).

In the calculation of event rates, the cross sections $\sigma_X$ always appear in the combination $\varphi \sigma_X$. It is then useful to define two quantities (related to $\varphi \sigma_X$) that characterize completely the detector response to a given neutrino reaction, namely, the energy averaged cross section $\overline{\sigma}_X$,

$$\overline{\sigma}_X(T_{\text{min}}) = \frac{\int dE_\nu \varphi \sigma_X}{\int dE_\nu \varphi} ,$$  \hspace{1cm} (12)$$

and the normalized response function $\varrho_X$,

$$\varrho_X(E_\nu, T_{\text{min}}) = \frac{\varphi \sigma_X}{\int dE_\nu \varphi \sigma_X} .$$  \hspace{1cm} (13)$$

($X = e, \mu \tau, CC$). We remark that both functions $\overline{\sigma}_X(T_{\text{min}})$ and $\varrho_X(E_\nu, T_{\text{min}})$ do not depend on the value of $\Phi_B$ nor on $P_{ee}(E_\nu)$; they are completely determined from detector properties, cross sections and $^8B$ decay spectrum.

Given the above definitions, the rate of electrons produced per unit time and target electron in Super-Kamiokande through reactions (1) and (2) can be generally written as

$$R_{e}^{\text{SK}}(T_{\text{SK}}) = \Phi_B \overline{\sigma}_e \int dE_\nu \varrho_e P_{ee}$$  \hspace{1cm} (14)$$

and

$$R_{\mu\tau}^{\text{SK}}(T_{\text{SK}}) = \Phi_B \overline{\sigma}_{\mu\tau} \int dE_\nu \varrho_{\mu\tau} (1 - P_{ee} - P_{es}) ,$$  \hspace{1cm} (15)$$

respectively, having in mind that the SK detector does not measure $R_{e}^{\text{SK}}$ and $R_{\mu\tau}^{\text{SK}}$ separately, but only their sum,

$$R_{\text{SK}} = R_{e}^{\text{SK}} + R_{\mu\tau}^{\text{SK}} .$$  \hspace{1cm} (16)$$

Analogously, the rate of electrons produced per unit time and target deuterons in the SNO detector through the charged current reaction (3) reads

$$R_{\text{SNO}}(T_{\text{SNO}}) = \Phi_B \overline{\sigma}_{CC} \int dE_\nu \varrho_{CC} P_{ee} .$$  \hspace{1cm} (17)$$

We stress that Eqs. (14–17) are written in the most general way and with no approximation.

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2 It is understood that the experimental rates to be compared with such equations must be corrected for the detector efficiencies, as also remarked in the Introduction.
A final remark about units. If $\Phi_B$ is given in cm$^{-2}$s$^{-1}$ and the cross sections in cm$^2$, then the rates $R$ are expressed in units of events per second per target particle (electrons in SK and deuterons in SNO), equivalent to $10^{36}$ generalized “Solar Neutrino Units” (SNU’s). Given that the molecular weight of water (heavy water) is 18 g/mol (20 g/mol), one SNU corresponds to 28.9 event/kton/day in SK (5.2 event/kton/day in SNO).

III. CROSS SECTIONS AND RESPONSE FUNCTIONS FOR SK AND SNO

Figure 1 shows the energy averaged cross sections $\sigma_e$ and $\sigma_{\mu\tau}$ as a function of the SK threshold $T_{SK}$, as well as $\sigma_{CC}$ as a function of the SNO threshold $T_{SNO}$. We remind that such cross sections include the effect of the detector energy resolution [see Eqs. (9,12)].

Figure 2 shows the normalized response functions of SK ($\rho_e$ and $\rho_{\mu\tau}$) and SNO ($\rho_{CC}$) as a function of the neutrino energy, for representative values of the detector thresholds. As shown in the previous Section, the quantities in Figs. 1 and 2 characterize completely the response of SK to $\nu_e$ scattering and of SNO to $\nu_e$ absorption.

From Fig. 2, one can see that the response functions $\rho_e$ and $\rho_{\mu\tau}$ are almost coincident; for any practical purpose, one can assume that

$$\rho_e(E_{\nu}, T_{SK}) = \rho_{\mu\tau}(E_{\nu}, T_{SK})$$

(18)

to a very good approximation. This is not surprising, since the cross sections for $\nu_e e$ and $\nu_{\mu,\tau} e$ scattering have a similar shape in the range probed by SK, up to an overall factor [13]. It is more intriguing to notice that the SK and SNO response functions in Fig. 2 happen to be very similar, provided that the SNO threshold is chosen about 2 MeV below the SK threshold. It appears that, using different thresholds and with the help of the energy resolution smearing, the differences in the SK and SNO cross sections (weighted by the $^8$B neutrino spectrum) can be largely compensated.

For each fixed value of $T_{SK}$, we have then maximized the agreement between $\rho_e(E_{\nu}, T_{SK})$ and $\rho_{CC}(E_{\nu}, T_{SNO})$ by tuning $T_{SNO}$, so as to minimize the integral reminder

$$\delta = \int dE_\nu |\rho_e - \rho_{CC}|.$$  

(19)

The results are shown in Fig. 3 for some representative values of the thresholds. One sees that the two response functions $\rho_e$ and $\rho_{CC}$ can be equalized to a good approximation. Indeed, we find that the reminder $\delta$ is always $\lesssim 0.04$.

We find that the values of $(T_{SK}, T_{SNO})$ that minimize $\delta$ satisfy the approximate relation $T_{SNO} = 0.995 T_{SK} - 1.71$ (MeV), with an accuracy sufficient for practical purposes. Of course, if the true SNO energy resolution function turns out be different from our prospective shape [see Eqs. (10,11)], this relation can also change slightly. The comparison of the SK and SNO response functions should be finalized when the SNO detector will be operated and calibrated.

In short, in the calculations of the electron rates $R_{SK}$ and $R_{SNO}$ one can take

$$\rho_{\mu\tau}(E_{\nu}, T_{SK}) = \rho_e(E_{\nu}, T_{SK}) = \rho_{CC}(E_{\nu}, T_{SNO})$$

(20)
within an accuracy of a few percent or less, provided that the SK and SNO thresholds obey the empirical relation

$$T_{\text{SNO}} = 0.995 T_{\text{SK}} - 1.71 \text{ (MeV)}.$$ \hspace{1cm} (21)

The model-independent consequences of the two equations above will be worked out in the next Section.

We point out that the comparison of the response functions of solar neutrino experiments have always provided useful insights in the interpretation of the solar neutrino problem. For instance, an empirical equality between the response functions of the Homestake and Kamiokande experiments to the $^8\text{B}$ neutrino flux was used in [14] and later in [13] to make some model-independent statements on the $^8\text{B}$ flux suppression. An equality similar to Eq. (18) was used in [13] to derive a lower bound on the $^8\text{B}$ flux. Even inequalities between response functions have been used to study or constrain the neutrino oscillation probabilities [16]. However, to our knowledge, Eqs. (20,21) have not been derived prior to this work.

IV. MODEL INDEPENDENT RELATIONS

In this section we derive the model-independent consequences of the empirical equality (20), which holds with a precision of a few percent or less, when $T_{\text{SNO}}$ and $T_{\text{SK}}$ satisfy Eq. (21). We also discuss the associated uncertainties.

From Eqs. (14–17) and Eqs (20,21) one easily derives a first important relation,

$$\frac{R_{\mu\tau}^{\mu\tau}(T_{\text{SK}})}{R_{\text{SK}}(T_{\text{SK}})} = 1 - \frac{R_{\text{SNO}}(T_{\text{SNO}})}{R_{\text{SK}}(T_{\text{SK}})} \frac{\sigma_e(T_{\text{SK}})}{\sigma_{\text{CC}}(T_{\text{SNO}})}$$ \hspace{1cm} (22)

which allows to determine in a model independent way the fractional contribution of (purely neutral current) $\nu_{\mu,\tau}$ interactions to the total $\nu e$ scattering rate $R_{\text{SK}}^{\mu\tau}$ in Super-Kamiokande. We stress that the above equation \textit{does not depend} on either $\Phi_B$ or the probability functions $P_{e\alpha} = P_{e\alpha}(E_{\nu})$; in particular, it holds also for nonzero mixing with a sterile neutrino, $P_{e\alpha}(E_{\nu}) \neq 0$.

Under the hypothesis of no oscillations into sterile states, $P_{e\alpha} = 0$, a second important relation can be derived from Eqs. (14–17) and Eqs (20,21):

$$\Phi_B = \frac{1}{\sigma_{\mu\tau}(T_{\text{SK}})} \left[ R_{\text{SK}}(T_{\text{SK}}) - R_{\text{SNO}}(T_{\text{SNO}}) \frac{\sigma_e(T_{\text{SK}}) - \sigma_{\mu\tau}(T_{\text{SK}})}{\sigma_{\text{CC}}(T_{\text{SNO}})} \right].$$ \hspace{1cm} (23)

The above equation gives $\Phi_B$ independently of the functional form of $P_{e\alpha}(E_{\nu})$.

Equations (22) and (23) represent the main results of our work. A supplementary relation can be derived from Eqs. (14–16) and (18), under the hypothesis that $P_{e\alpha} = 0$ \textit{and} that the boron neutrino flux $\Phi_B$ is known independently (e.g., from standard solar models):

$$\frac{R_{\text{SK}}^{\mu\tau}}{R_{\text{SK}}} = 1 - \frac{\sigma_e}{\sigma_{\mu\tau}} \frac{R_{\text{SK}} - \Phi_B\sigma_{\mu\tau}}{R_{\text{SK}}},$$ \hspace{1cm} (24)

The above equation makes use of SK data only ($R_{\text{SK}}$) and does not depend on $P_{e\alpha}(E_{\nu})$; however, its usefulness is limited by the requirement of a prior knowledge of $\Phi_B$. Using
In a recent standard solar model calculation of $\Phi_B$ \[9\] and the latest SK data \[4\], the term subtracted from unity in Eq. (24) amounts to $\sim 0.79$. We will use this model-dependent value only for some prospective error estimates, as we discuss in the following.

In order to extract $R_{\mu\tau}^{SK}/R_{SK}$ by means of Eq. (22), one has to consider both theoretical and experimental errors.

Theoretical errors are of two different types: (i) Uncertainties in the cross section ratio $\sigma_{e}/\sigma_{CC}$; and (ii) Approximations implicit in Eq. (20). The first are dominated by the overall normalization of the CC cross section for $\nu_e d$ absorption, whose uncertainty is about $\pm 10\%$ \[12\]. Concerning the approximations implicit in Eq. (20) one should note that, if $\rho_{CC} - \rho_{e} \neq 0$, then the right-hand side of Eq. (22) acquires an additional “error term” equal to $\Delta = (\Phi_B \sigma_e / R_{SK}) \int dE_{\nu} P_{ee}(\rho_{CC} - \rho_{e})$. The integral reminder $\delta$ (see Eq. (19)) gives an upper limit to $\delta P = |\int dE_{\nu} P_{ee}(\rho_{CC} - \rho_{e})|$, as $P_{ee} \leq 1$. Actually, $\delta P$ is much smaller than $\delta$ in several oscillation cases of phenomenological interest (e.g., for both vacuum and matter enhanced solutions to the solar neutrino problem). We have checked that $\delta P \sim 6 \cdot 10^{-3}$ in the worst cases. If standard solar models are not too wrong, the factor $\Phi_B \sigma_e / R_{SK}$ in $\Delta$ is in the range $\sim 2 - 3$ (as the rate observed in SK is about 1/2 - 1/3 than rate expected). Therefore, we estimate that the approximations implicit in Eq. (20) introduce at most an error $\Delta \sim 0.02$ in equation Eq. (22). Being much smaller than the uncertainty (i), this error can be neglected. We also checked that this conclusion holds when allowance is made for variations of the SK (SNO) energy resolution function within the quoted \[4\] (prospected \[10\]) errors.

Concerning the experimental uncertainties in Eq. (22), they are associated with the term $R_{SNO}/R_{SK}$. The present fractional error of $R_{SK}$ is 3 - 4\% [Eq. (5,6)]. However, the fractional error for $R_{SNO}$ cannot be precisely evaluated before SNO starts operation and its background is measured. If we assume, conservatively, a total (SNO+SK) uncertainty of $\sim 10\%$ for $R_{SNO}/R_{SK}$, then the total fractional error of the subtracted term in Eq. (22) is $\sim 15\%$ (theoretical and experimental errors added in quadrature). Of course, the central value of the subtracted term (i.e., of the $\nu_e$ contribution to the total SK rate) can only be guessed at present. If we take the value $\sim 0.76$ from the discussion following Eq. (24), then $R_{\mu\tau}^{SK}/R_{SK} \simeq 1 - 0.79(1 \pm 0.15) \simeq 0.21 \pm 0.12$, implying that the $\nu_{\mu,\tau}$ signal can be extracted at $\sim 2\sigma$ from Eq. (22).

Concerning the estimate of $\Phi_B$ from Eq. (23), one expects an uncertainty of about 20\% from the same arguments. This value is comparable to the uncertainty affecting the theoretical estimates of $\Phi_B$ from solar models \[4,9\] and to the expected error of the neutral current event rate in SNO \[8\] (which also provides $\Phi_B$ in the absence of sterile neutrino oscillations \[17\]). Therefore, Eq. (23) provides us with a competitive, independent estimate of the boron neutrino flux. Of course, all these error estimates should be finalized when the actual data from SK and SNO will be compared.

Finally, we remind that Eqs. (22,23) hold when the cross sections are expressed in cm$^2$, the rates in events per target particle per second, and $\Phi_B$ in cm$^{-2}$s$^{-1}$. We think it useful to rewrite and summarize our results by using also the following units: $[R_{SK}] = [R_{SNO}] = \text{kton}^{-1}\text{d}^{-1}$, $[\Phi_B] = \text{cm}^{-2}\text{s}^{-1}$, and $[\sigma_X] = \text{cm}^2$. Then, independently of the functional form of the oscillation probabilities $P_{ee}(E_{\nu})$, one has:
for any $\Phi_B$ and $P_{es}$,
\[ \frac{R_{\mu\tau}^{SK}}{R_{SK}} = 1 - 5.56 \frac{R_{SNO}}{R_{SK}} \frac{\sigma_e}{\sigma_{CC}}, \] (25)

and

for $P_{es} = 0$,
\[ \Phi_B = \frac{10^{-36}}{\sigma_{\mu\tau}} \left( \frac{R_{SK}}{28.9} - \frac{R_{SNO}}{5.2} \frac{\sigma_e - \sigma_{\mu\tau}}{\sigma_{CC}} \right), \] (26)

provided that the SK and SNO thresholds obey the empirical Eq. (21). For these joint values of thresholds, we have tabulated the relevant cross sections in Table I.

We conclude with a numerical example. Choosing a threshold $T_{SK} \simeq 7.0$ MeV for SK, the corresponding observed event rate $R_{SK}$ is estimated to be 0.61 events/kton/day [Eq. (6)]. The SNO threshold appropriate for comparison with SK is $T_{SNO} = 5.25$ MeV [see Eq. (21)]. If SNO measures, say, 8 events/kton/day above such threshold, then one obtains, using the cross sections in Table I, $R_{\mu\tau}^{SK}/R_{SK} \simeq 0.29$ [for any $P_{es}$, Eq. (25)] and $\Phi_B \simeq 6.6 \cdot 10^6$ cm$^{-2}$ s$^{-1}$ [for $P_{es} = 0$, Eq. (26)].

V. CONCLUSIONS

We have found that an approximate equality holds between the Super-Kamiokande and SNO (charged current) response functions [Eq. (21)], provided that their thresholds $T_{SK}$ and $T_{SNO}$ are chosen appropriately [Eq. (21)]. We have taken advantage of this property, by showing that one needs only two data (the total electron rates $R_{SK}$ and $R_{SNO}$) to determine, in a model independent way, two important quantities: (a) The $\nu_{\mu,\tau}$ contribution to the SK signal, even in the presence of additional mixing with a sterile neutrino [Eq. (25)]; and (b) The absolute boron neutrino flux, in the absence of oscillations into sterile states [Eq. (26)]. Therefore, the measurement of the total charged current event rate in SNO appears to be very interesting and informative in itself, and not only in relation with the neutral current measurement to be performed in the same experiment.

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TABLE I. Values of the SK cross sections $\sigma_e(T_{SK})$ and $\sigma_{\mu\tau}(T_{SK})$ and of the SNO cross section $\sigma_{CC}(T_{SNO})$, for kinetic energy thresholds satisfying the relation $T_{SNO} = 0.995T_{SK} - 1.71$ MeV.

| $T_{SK}$ (MeV) | $T_{SNO}$ (MeV) | $\sigma_e$ \((10^{-44} \text{ cm}^2)\) | $\sigma_{\mu\tau}$ \((10^{-45} \text{ cm}^2)\) | $\sigma_{CC}$ \((10^{-42} \text{ cm}^2)\) |
|----------------|-----------------|-------------------------------|-------------------------------|-------------------------------|
| 6.0            | 4.26            | 1.238                         | 1.918                         | 0.999                         |
| 6.2            | 4.46            | 1.147                         | 1.772                         | 0.971                         |
| 6.4            | 4.66            | 1.060                         | 1.634                         | 0.942                         |
| 6.6            | 4.86            | 0.977                         | 1.504                         | 0.911                         |
| 6.8            | 5.06            | 0.899                         | 1.381                         | 0.879                         |
| 7.0            | 5.25            | 0.825                         | 1.265                         | 0.845                         |
| 7.2            | 5.45            | 0.755                         | 1.156                         | 0.811                         |
| 7.4            | 5.65            | 0.690                         | 1.054                         | 0.776                         |
| 7.6            | 5.85            | 0.628                         | 0.959                         | 0.740                         |
| 7.8            | 6.05            | 0.571                         | 0.870                         | 0.703                         |
| 8.0            | 6.25            | 0.517                         | 0.787                         | 0.666                         |
| 8.2            | 6.45            | 0.467                         | 0.710                         | 0.629                         |
| 8.4            | 6.65            | 0.421                         | 0.639                         | 0.592                         |
| 8.6            | 6.85            | 0.378                         | 0.573                         | 0.555                         |
| 8.8            | 7.05            | 0.339                         | 0.513                         | 0.519                         |
| 9.0            | 7.25            | 0.302                         | 0.457                         | 0.483                         |
| 9.2            | 7.44            | 0.269                         | 0.406                         | 0.447                         |
| 9.4            | 7.64            | 0.239                         | 0.360                         | 0.413                         |
| 9.6            | 7.84            | 0.211                         | 0.318                         | 0.380                         |
| 9.8            | 8.04            | 0.186                         | 0.280                         | 0.347                         |
| 10.0           | 8.24            | 0.163                         | 0.245                         | 0.316                         |
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FIGURES

FIG. 1. Upper panel: The effective cross sections for $\nu_e e \rightarrow \nu_e e$ and $\nu_{\mu,\tau} e \rightarrow \nu_{\mu,\tau} e$ scattering, $\sigma_e$ and $\sigma_{\mu\tau}$, as a function of the electron kinetic energy threshold in the SK experiment. Lower panel: The effective cross section $\sigma_{CC}$ for the charged current process $\nu_e d \rightarrow p p e$, as a function of the electron kinetic energy threshold in the SNO experiment.

FIG. 2. The normalized response functions of SK and SNO to $^8$B neutrinos, for representative values of the detector thresholds. See the text for details.

FIG. 3. Examples of the approximate equality of the SK and SNO response functions for selected values of the detector thresholds $T_{SK}$ and $T_{SNO}$. Such values obey approximately the relation $T_{SNO} \approx 0.995 T_{SK} - 1.71$ (MeV).
FIG. 1. Upper panel: The effective cross sections for $\nu_e e \to \nu_e e$ and $\nu_{\mu,\tau} e \to \nu_{\mu,\tau} e$ scattering, $\sigma_e$ and $\sigma_{\mu\tau}$, as a function of the electron kinetic energy threshold in the SK experiment. Lower panel: The effective cross section $\sigma_{CC}$ for the charged current process $\nu_e d \to pp e$, as a function of the electron kinetic energy threshold in the SNO experiment.
FIG. 2. The normalized response functions of SK and SNO to $^{8}$B neutrinos, for representative values of the detector thresholds. See the text for details.
FIG. 3. Examples of the approximate equality of the SK and SNO response functions for selected values of the detector thresholds $T_{SK}$ and $T_{SNO}$. Such values obey approximately the relation $T_{SNO} = 0.995 T_{SK} - 1.71$ (MeV).