Predictions for Spectral Distortions, Event Rates and D-N Asymmetries for the Super - Kamiokande Detector

Michele Maris a,b), Serguey T. Petcov a,c)

a) Scuola Internazionale Superiore di Studi Avanzati, Trieste, Italy.
b) INFN - Sezione di Pavia, Pavia, Italy.
c) INFN - Sezione di Trieste, Trieste, Italy.

Abstract

Day - Night asymmetries and electronic spectra distortions for the Super - Kamiokande detector are computed for the transition $\nu_e \rightarrow \nu_\mu (\tau)$ and for a set of neutrino parameters. The results show the possibility to enhance up to a factor six the Day - Night asymmetry selecting neutrino events induced by neutrinos which cross the Earth core. This should increases the sensitivity of the Super - Kamiokande detector to the Day - Night effect for $\sin^2 2\theta \nu < 0.01$ and $5 \times 10^{-6} \text{ eV}^2 < \Delta m^2 \lesssim 10^{-5} \text{ eV}^2$.

1 Introduction

In [1] the probabilities for the MSW conversion in Sun and Earth for solar neutrinos $P_\oplus (\nu_e \rightarrow \nu_\mu (\tau))$ were computed for the Super - Kamiokande experiment with a 1% accuracy. Probabilities were computed separately for the day, the night and for the sample of neutrino events which are induced by neutrinos whose trajectories cross the Earth core. In this way the probability for the Earth effect is enhanced up to a factor six for $\sin^2 2\theta \nu \leq 0.01$. In the present paper electronic spectra and event rates are predicted for the Super - Kamiokande detector from the probabilities presented in [1]. Spectra and event rates are computed for the same set of neutrino parameters $\Delta m^2$ and $\sin^2 2\theta \nu$ considered in [1]. This short communication reports the main results from these calculations, and it is preliminary to a more detailed paper which presently is under writing [2].

2 Formalism

In [1] neutrino events are classified in four classes or “samples” in accord with their detection time. The samples are labelled: Day, Night, Core and Mantle; where Day and Night samples are composed by those neutrino events detected during the day or the night, while the other samples are composed by those neutrino events which are detected at night and which are produced by neutrinos which cross the Earth core (Core) or does not cross it (Mantle).

---

1 Also at: Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria.
Since this classification, all the quantities defined in this paper (probabilities, spectra, event rates, asymmetries, etc) must be referred to one of these four samples. For this reason each quantity will be denoted by an apex \( s = D, N, C, M \) where these letters are for Day, Night, Core and Mantle samples respectively. In this way electronic spectra are denoted by: \( S^D_e(T_e), S^N_e(T_e), S^C_e(T_e), S^M_e(T_e) \) while event rates are denoted by: \( R^D_E, R^N_E, R^C_E, R^M_E \). The symbols \( S_{\nu,0}(T_e) \) and \( R_{E,0} \) are for electronic spectra and event rates computed for massless neutrinos and the Solar Standard Model (SSM). Few formulae connect these quantities to cross sections, neutrino spectra and probabilities. For spectra:

\[
S_{\nu,0}(T_e) = \int_{T_e(1+\frac{m_e}{2T_e})}^{+\infty} dE_\nu \, S_{\nu,0}(E_\nu) \frac{d\sigma_{\nu_e}(T_e, E_\nu)}{dT_e},
\]

and

\[
S^s_e(T_e) = \int_{T_e(1+\frac{m_e}{2T_e})}^{+\infty} dE_\nu \, S_{\nu,0}(E_\nu) \left[ \frac{d\sigma_{\nu_e}(T_e, E_\nu)}{dT_e} P^s_{\nu_e \rightarrow \nu_\mu(\tau)} \left( \frac{E_\nu}{\Delta m^2} \right) + \frac{d\sigma_{\nu_{\mu(\tau)}}(T_e, E_\nu)}{dT_e} \left( 1 - P^s_{\nu_e \rightarrow \nu_\mu(\tau)} \left( \frac{E_\nu}{\Delta m^2} \right) \right) \right],
\]

with \( s = D, N, C, M \) and where \( E_\nu \) is the incoming neutrino energy, \( T_e \) is the emerging electron kinetic energy, \( m_e \) is the electron mass, \( S_{\nu,0}(T_e) \) is the SSM spectrum for \( ^8\text{B} \) neutrinos, \( P^s_{\nu_e \rightarrow \nu_\mu(\tau)} \) is the transition probability for Day, Night, Core and Mantle.

The cross sections for elastic neutrino scattering over electrons are: \( \frac{d\sigma_{\nu_e}(T_e, E_\nu)}{dT_e} \) for \( \nu_e \) and \( \frac{d\sigma_{\nu_{\mu(\tau)}}(T_e, E_\nu)}{dT_e} \) for \( \nu_\mu, \nu_\tau \). The formulae for these cross sections are reported in [3, 4].

Event rates are obtained from:

\[
R_{E,0}(T_{e,th}) = \int_{T_{e,th}}^{+\infty} dT_e \, S_{e,0}(T_e),
\]

\[
R^s_E(T_{e,th}) = \int_{T_{e,th}}^{+\infty} dT_e \, S^s_e(T_e).
\]

Here it is assumed that event rates are computed for an electron kinetic energy threshold \( T_{e,th} \) of 5 MeV, while event rates are expressed in units of the SSM prediction so that \( R_{E,0} \equiv 1 \).

Spectra and event rates may be combined to produce various indicators useful for the experimental data analysis. Three indicators are considered here: spectral distortion, spectral D - N asymmetry and event rates D-N asymmetry. The spectral distortion compares the predicted electronic spectra for the MSW effect (or the measured one) with the spectra predicted for the SSM and the massless neutrino. It is defined as:

\[
\delta S^s_e(T_e) = \frac{S^s_e(T_e)}{S_{e,0}(T_e)}, \quad s = D, N, C, M.
\]
In absence of any systematical effect this index has a simple interpretation: if $\delta S_s^e(T_e) \equiv 1$ there is no MSW effect and the SSM is correct, if $\delta S_s^e(T_e)$ is a constant but it is different from 1 then there is an energy independent neutrino effect or the SSM is wrong. At last, if $\delta S_s^e$ changes with the energy then an energy dependent neutrino effect occurs, which should be a sign of a new physics. The spectral D-N asymmetry is an indicator of the D-N effect. It is defined as:

$$A_s^e(T_e) = 2 \frac{S_s^e(T_e) - S_d^p(T_e)}{S_s^e(T_e) + S_d^p(T_e)}$$  \hspace{1cm} s = N, C, M, \tag{5}$$

a zero asymmetry is an indication of no-Earth effect. Finally, the Event Rate D-N asymmetry (or shortly the asymmetry) is defined as:

$$A_s^R = 2 \frac{R_s^e - R_d^p}{R_s^e + R_d^p}$$ \hspace{1cm} s = N, C, M. \tag{6}$$

3 Results

Figure 1, Figures from 2.1 to 2.18 and table I shows the predictions for spectra, event rates and related distortions and asymmetries for the selected set of neutrino parameters $\Delta m^2$ and $\sin^2 2\theta_V$. Since the MSW effect in the Earth is not large, its influence on the electronic spectra are better illustrated by spectral distortions and asymmetries than by the electronic spectra itself. So, in the present paper, only one set of spectra is reported in Fig. 1 for $\sin^2 2\theta_V = 0.01$ and $\Delta m^2 = 5 \times 10^{-5} \text{ eV}^2$. In the figure the upper full - line is the SSM spectra while $S_d^p(T_e)$, $S_N^e(T_e)$, $S_C^e(T_e)$ and $S_d^p(T_e)$ are represented respectively by the long - dashed line, the short - dashed line, the lower full line and the dotted line.

Figures from 2.1 to 2.18 reports the spectral distortions (upper frame of each figure) and the spectral D-N asymmetries (lower frame of each figure) predicted for each combination of the MSW parameters $\Delta m^2$ and $\sin^2 2\theta_V$ listed in Tab. I. The enhancement in the spectral distortions and in the D-N asymmetries introduced by the Core sample is fairly evident, especially for $\sin^2 2\theta_V < \sim 0.01$. The magnitude of the effect is sensitive to $\Delta m^2$. Figures from 2.1 to 2.18 depict also many other features like: kinks, knees and peaks which at last are associated to equivalent features displayed in the probabilities reported in [1].

The predicted event rates associated to electronic spectra in Figures from 2.1 to 2.18 are listed in Tab. I. Each electronic spectra is associated with one entry in the table through the numbers in the first column. Event rates expressed in units of $R_{E,0}$ are listed in columns from $4^{th}$ to $7^{th}$. Percentual event rates asymmetries ($A_{R}^s \times 100$) are listed in columns from $8^{th}$ to $10^{th}$. It is evident that even for the event rates the predicted asymmetries are enhanced when the Core sample is extracted by the full set of night neutrinos. This is well displayed by the last column which shows the ratio: $|A_C^R|/|A_N^R|$. The enhancement may be as high as a factor of order six. This enhancement should increase the sensitivity of the Super - Kamiokande detector to the D-N effect, in the case the small mixing angle solution to the solar neutrino problem is correct. From the table it is evident that it is theoretically possible to have a significative asymmetry, at least till $\sin^2 2\theta_V \approx 0.006$ and at least for $5 \times 10^{-6} \text{ eV}^2 \lesssim \Delta m^2 \lesssim 10^{-5} \text{ eV}^2$. As expected from probabilities in [1], a negative Earth effect for $\sin^2 2\theta_V < 0.004$ is also present.
4 Conclusions

In a previous work \[1\] a set of probabilities for the MSW transition $\nu_e \rightarrow \nu_{\mu(\tau)}$ were computed for solar neutrinos traversing the Sun and the Earth. From them, a set of electronic spectra, event rates and related D-N asymmetries is predicted for the Super-Kamiokande detector. The computation was extended over a comprehensive set of neutrino parameters $\Delta m^2$ and $\sin^2 2\theta_V$.

From these predictions it comes that the Super-Kamiokande detector should be sensitive to the D-N effect even for $\sin^2 2\theta_V < 0.01$ and $5 \times 10^{-6} \text{eV}^2 < \Delta m^2 < 10^{-5} \text{eV}^2$. As expected also by previous studies \[3, 6, 7\], this sensitivity may be reached selecting those neutrino events which are induced in the Super-Kamiokande detector by neutrinos whose trajectories cross the Earth core. Our results suggests an enhancement up to a factor six in the D-N asymmetry for the Super-Kamiokande detector.

At last we recall that this is a short communication only, which precedes a more complete and detailed paper presently under writing \[2\].

5 Acknowledgments

M.M. wishes to thank the International School for Advanced Studies, Trieste, Italy, where part of the work for this study has been done, for kind hospitality and financial support. The authors are indebted to the ICARUS group of the University of Pavia and INFN, Sezione di Pavia, and especially to Prof. E. Calligarich, for allowing the use of their computing facilities for the present study. M.M. wishes to thank also Dr. A. Rappoldi for his suggestions concerning the computational aspects of the study, and to Prof. A. Piazzoli for his constant interest in the work and support.

References

[1] Q.Y. Liu, M. Maris, S.T. Petcov, Preprint: Ref. SISSA 16/97/EP, January 1997, E-Print: hep-ph/9702361. Submitted to Phys. Rev. D.
[2] Michele Maris, Sergey T. Petcov, in preparation, to be printed as: Preprint: Ref. SISSA 17/97/EP.
[3] J.N. Bahcall, Neutrino Astrophysics, Cambridge University Press, 1989.
[4] J.N. Bahcall, M. Kamionkowski, A. Sirlin, Phys. Rev. D 51, 6146 (1995).
[5] A.J. Baltz and J. Weneser, Phys. Rev. D 50, 5971 (1994).
[6] P.I. Krastev, E-Print: hep-ph/9610339 (1996).
[7] J.M. Gelb, W. Kwong and S.P. Rosen, E-Print: hep-ph/9612332 (1996).
### Tab. I: Event Rates and D - N Asymmetries for Super - Kamiokande

| N. | \(\sin^22\theta_V\) | \(\Delta m^2\) | Event Rates | \(A_R \times 10^4\) | \(|A^C_R|/A_R\) |
|----|-----------------|-------|-------------|------------------|-----------------|
| 1  | 0.0008 | 9.0e-6   | Day | Night | Core | Mantle | Night | Core | Mantle | Day | Night | Core | Mantle |
| 2  | 0.0008 | 7.0e-6   | 0.8441 | 0.8431  | 0.8379 | 0.8440 | -0.12 | -0.75 | -0.01 | 6.25 |
| 3  | 0.0008 | 5.0e-6   | 0.8742 | 0.8722  | 0.8625 | 0.8739 | -0.22 | -1.35 | -0.04 | 6.14 |
| 4  | 0.0010 | 9.0e-5   | 0.9052 | 0.9020  | 0.8949 | 0.9031 | -0.35 | -1.14 | -0.23 | 3.26 |
| 5  | 0.0010 | 7.0e-6   | 0.9413 | 0.9413  | 0.9413 | 0.9413 | 3e-3  | 4e-3  | 3e-3  | 1.33 |
| 6  | 0.0010 | 5.0e-6   | 0.9846 | 0.9809  | 0.9827 | 0.9882 | -0.43 | -1.35 | -0.27 | 3.14 |
| 7  | 0.0020 | 1.0e-5   | 0.6426 | 0.6419  | 0.6386 | 0.6425 | -0.10 | -0.62 | -0.01 | 6.20 |
| 8  | 0.0020 | 7.0e-6   | 0.7270 | 0.7244  | 0.7113 | 0.7266 | -0.36 | -2.18 | -0.07 | 6.06 |
| 9  | 0.0020 | 5.0e-6   | 0.7905 | 0.7852  | 0.7747 | 0.7869 | -0.67 | -2.02 | -0.45 | 3.01 |
| 10 | 0.0040 | 1.0e-5   | 0.4408 | 0.4417  | 0.4465 | 0.4410 | 0.22  | 1.28  | 0.04  | 5.82 |
| 11 | 0.0040 | 7.0e-6   | 0.5469 | 0.5470  | 0.5481 | 0.5468 | 0.01  | 0.21  | -0.02 | 21.0 |
| 12 | 0.0040 | 5.0e-6   | 0.6378 | 0.6343  | 0.6307 | 0.6349 | -0.56 | -1.12 | -0.47 | 2.00 |
| 13 | 0.0060 | 1.0e-5   | 0.3233 | 0.3267  | 0.3430 | 0.3239 | 1.05  | 6.20  | 0.17  | 5.90 |
| 14 | 0.0060 | 7.0e-6   | 0.4243 | 0.4297  | 0.4578 | 0.4251 | 1.26  | 7.60  | 0.17  | 6.03 |
| 15 | 0.0060 | 5.0e-6   | 0.5224 | 0.5248  | 0.5374 | 0.5228 | 0.46  | 2.82  | 0.06  | 6.13 |
| 16 | 0.0080 | 1.0e-5   | 0.2543 | 0.2603  | 0.2913 | 0.2552 | 2.36  | 13.59 | 0.37  | 5.76 |
| 17 | 0.0080 | 7.0e-6   | 0.3405 | 0.3523  | 0.4125 | 0.3423 | 3.39  | 19.10 | 0.53  | 5.63 |
| 18 | 0.0080 | 5.0e-6   | 0.4351 | 0.4458  | 0.4787 | 0.4404 | 2.44  | 9.54  | 1.22  | 3.91 |
| 19 | 0.0100 | 7.0e-6   | 0.2830 | 0.3013  | 0.3942 | 0.2860 | 6.28  | 32.85 | 1.05  | 5.23 |
| 20 | 0.0100 | 5.0e-6   | 0.3688 | 0.3891  | 0.4435 | 0.3802 | 5.36  | 18.38 | 3.03  | 3.43 |
| 21 | 0.0130 | 5.0e-6   | 0.2979 | 0.3333  | 0.4188 | 0.3192 | 11.21 | 33.72 | 6.89  | 3.01 |
| 22 | 0.3000 | 1.5e-5   | 0.2171 | 0.2242  | 0.2530 | 0.2407 | 11.03 | 15.29 | 10.30 | 1.39 |
| 23 | 0.3000 | 2.0e-5   | 0.2181 | 0.2357  | 0.2426 | 0.2346 | 7.79  | 10.66 | 7.31  | 1.37 |
| 24 | 0.3000 | 3.0e-5   | 0.2214 | 0.2323  | 0.2348 | 0.2319 | 4.78  | 5.85  | 4.61  | 1.22 |
| 25 | 0.3000 | 4.0e-5   | 0.2275 | 0.2352  | 0.2370 | 0.2349 | 3.31  | 4.07  | 3.19  | 1.23 |
| 26 | 0.4800 | 3.0e-5   | 0.2717 | 0.2885  | 0.2916 | 0.2879 | 5.99  | 7.08  | 5.81  | 1.18 |
| 27 | 0.4800 | 5.0e-5   | 0.2887 | 0.2975  | 0.2992 | 0.2972 | 2.99  | 3.57  | 2.89  | 1.19 |
| 28 | 0.5000 | 2.0e-5   | 0.2735 | 0.3011  | 0.3078 | 0.3000 | 9.60  | 11.79 | 9.23  | 1.23 |
| 29 | 0.5600 | 1.0e-5   | 0.2800 | 0.3693  | 0.4234 | 0.3604 | 27.50 | 40.77 | 25.11 | 1.48 |
| 30 | 0.6000 | 8.0e-5   | 0.3685 | 0.3738  | 0.3746 | 0.3736 | 1.42  | 1.65  | 1.38  | 1.16 |
| 31 | 0.7000 | 3.0e-5   | 0.3449 | 0.3683  | 0.3715 | 0.3677 | 6.56  | 7.43  | 6.41  | 1.13 |
| 32 | 0.7000 | 5.0e-5   | 0.3588 | 0.3712  | 0.3733 | 0.3708 | 3.38  | 3.95  | 3.29  | 1.17 |
| 33 | 0.7700 | 2.0e-5   | 0.3697 | 0.4083  | 0.4110 | 0.4079 | 9.94  | 10.59 | 9.83  | 1.07 |
| 34 | 0.8000 | 1.3e-4   | 0.4744 | 0.4771  | 0.4777 | 0.4770 | 0.57  | 0.69  | 0.55  | 1.21 |
Figure Captions

**Figure 1**: Electronic spectra for Super-Kamiokande. Spectra are computed for $\sin^2 2\theta = 0.01$ and $\Delta m^2 = 5 \times 10^{-5} \text{eV}^2$, in the plot spectra are normalized in units of the SSM event rate for Super-Kamiokande per MeV$^{-1}$. The *Upper Full* line is the *Standard* spectrum $S_{e,0}(T_e)$ while the other lines are for spectra with matter effect. The *Long Dashed* line denotes the *Day* spectrum, the *Short Dashed* line the *Night* spectrum, the *Full* line is for the *Core*, while *Dots* are for *Mantle* sample.

**Figure 2**: Electronic spectral distortion and asymmetries for Super-Kamiokande. In the upper frame of each figure it is drafted the spectra deformation in the lower the related asymmetry as a function of $T_e$. The number on the top left of each figure associates it with a row of table I. *Long Dashed* lines mark the *Day* spectrum distortion (D-N asymmetry) *Short Dashed* lines the *Night* spectrum distortion (D-N asymmetry), *Full* lines are for *Core* while *Dots* are for *Mantle*.
Figure 1
