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Predictions for the Spectrum Deformations and Energy Dependence of the Day-Night Asymmetry for the SNO Detector

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Abstract. Predictions for the e^-−spectrum deformations and the energy dependence of the day-night (D-A) asymmetry for the SNO Detector are obtained in the case of the LMA solution of the solar neutrino problem, which is favored by the current solar neutrino and KamLAND data. Results have been obtained for a large set of values of the solar neutrino oscillation parameters - neutrino mass squared difference and mixing angle, Δm^2 and θ. The measurement of the final state e^-−spectrum in the charged current (CC) reaction and of energy dependence of the D-A asymmetry with the SNO Detector would allow to better constrain the solar neutrino oscillation parameters.

Key words. Neutrinos – Elementary Particles – Sun: Particle Emission

1. Introduction

The recent results of SNO (Ahmad et al. 2002a,b) and KamLAND (Eguchi et al. 2003) experiments establish, under the plausible assumption of CPT-invariance, which we will suppose to hold, the large mixing angle (LMA) MSW solution essentially as a unique solution of the solar neutrino problem. These results bring us, after more than 30 years of research, initiated by the pioneer works of B. Pontecorvo (Pontecorvo 1946, 1967) and the experiment of R. Davis et al. (Davis 1968), very close to a complete understanding of the true cause of the solar neutrino problem. Within the LMA solution, the solar neutrino deficit (Bahcall, Pinsonneault, Basu 2001) is explained by the transitions of ν_e (the only kind of neutrinos produced in the Sun) on their way to the Earth into $\nu_{\mu,\tau}$ neutrinos which either are not, or are less efficiently, detected by the experiments.
The SNO collaboration measures the rate of *Neutral Current* (NC) reactions $\nu_x + D \rightarrow n + p + \nu_x$, x = e, μ, τ and of *Charged Current* reactions (CC) $\nu_e + D \rightarrow p + p + e$, induced by ^8B neutrinos in its target mass of 1 KTon of heavy water (D_2O). The rate of NC reactions, equally sensitive to ν_e,

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ν_μ and ν_τ, is comparable within the errors with that expected from the Standard Solar Model (Bahcall, Pinsonneault, Basu 2001). By comparing it with the reduced rate of the CC reaction, sensitive to ν_e only, SNO demonstrates that "missing ν_e" has to be converted into ν_μ or ν_τ, or a mix of the two, excluding at the same time significant transitions of of ν_e into a sterile neutrino (Ahmad et al. 2002a). The SNO data were shown to favor the LMA solution of the solar neutrino problem. The results of the SNO experiment on the *Day - Night (D-N) asymmetry* in the rate of CC reactions SNO (Ahmad et al. 2002b) have been so far inconclusive. The asymmetry must be non-zero in the case of the LMA MSW solution of the solar neutrino problem due to the fact that solar neutrinos to reach the detector at night have to cross the Earth, suffering further conversion. In this way the CC reaction has a different rate at night than during the day. It should be added that the D-N asymmetry under discussion can be rather small.

The KamLAND experiment (Eguchi et al. 2003) searched for a disappearance of $\bar{\nu}_e$, produced by a number of nuclear reactors in Japan, as well as for a distortion of the spectrum of the e^+ from the reaction $\bar{\nu}_e + p \to n + e^+$. It confirmed the SNO results and the LMA solution, strongly disfavoring all other possible solutions of the solar neutrino problem. The combination of all the results leads to the two parameters which drive the solar neutrino oscillations - the neutrino mass squared difference and mixing angle, Δm^2 and θ, (Fogli et al. 2003):

$$\begin{aligned} \Delta m^2 &= (7.3 \pm 0.05) \times 10^{-5}\ \mathrm{eV}^2 \\ \sin^2 2\theta &= 0.85 \pm 0.05 \end{aligned} \tag{1}$$

The progresses of this field will require a more accurate determination of ($\sin^2 2\theta$, Δm^2) in order, in particular, to i) constrain models of generation of neutrino masses and mixing, ii) "remove" the effect of neutrino oscillations in order to study better the physics of the Sun. A way to improve the present knowledge on ($\sin^2 2\theta$,Δm^2) is to look for subtle energy dependencies in the solar neutrino data. This is the aim of the work presented in this communication.

2. Time / Energy Dependencies

The probability P_s for a ν_e produced in the Sun to be detected as a ν_e after crossing the Sun and eventually at night the Earth, given as an example in Krastev, Petcov (1998) and references therein, is a function of the neutrino energy E_ν, of the electronic density profile n_e along the propagation path and ($\sin^2 2\theta$, Δm^2). So that energy dependencies are a distinctive signature of such scenario. However NC reactions do not keep any information about the distribution in energy of the interacting neutrinos. While SNO only reports the spectrum of electrons generated in CC reactions as a function of their kinetic energy T_e. Since the kinetic energy of the protons produced by the reaction can not be determined, E_ν remains undetermined. However part of the E_ν dependence in P_s is translated in the T_e dependence of the electronic spectrum. Usually the effect of neutrino oscillations is evidenced as an *electronic spectra distortion* for CC reactions

$$\delta_{\bar{\mathrm{t}}}(T_e) = \frac{r_{\mathrm{cc},\bar{\mathrm{t}}}(T_\mathrm{e}, \Delta m^2, \sin^2 2\theta)}{r_{\mathrm{cc},0,\bar{\mathrm{t}}}(T_\mathrm{e})} - 1, \tag{2}$$

With $r_{\mathrm{cc},0,\bar{\mathrm{t}}}(T_\mathrm{e})$ the theoretical expected number of electrons within a given time / energy bin, i.e. the reaction rate, without neutrino oscillations. While $r_{\mathrm{cc},\bar{\mathrm{t}}}(T_\mathrm{e}, \Delta m^2, \sin^2 2\theta)$ the observed the reaction rate including neutrino oscillations. Reaction rates are defined as *differential* or *cumulative* in a manner consistent with the SNO data. In differential rates electrons are collected in bins defined as [T_e, T_e + 0.5 eV]. In cumulative rates all the electrons with T_e greater than a given threshold $T_{\mathrm{e,Th}}$ are binned together. Time-bins are denoted by the $\bar{\mathrm{t}}$ index and are defined consistently with SNO and Maris, Petcov (2002). Then $\bar{\mathrm{t}}$ = D$\bar{\text{a}}$y and Nig$\bar{\text{h}}$t are used to denote

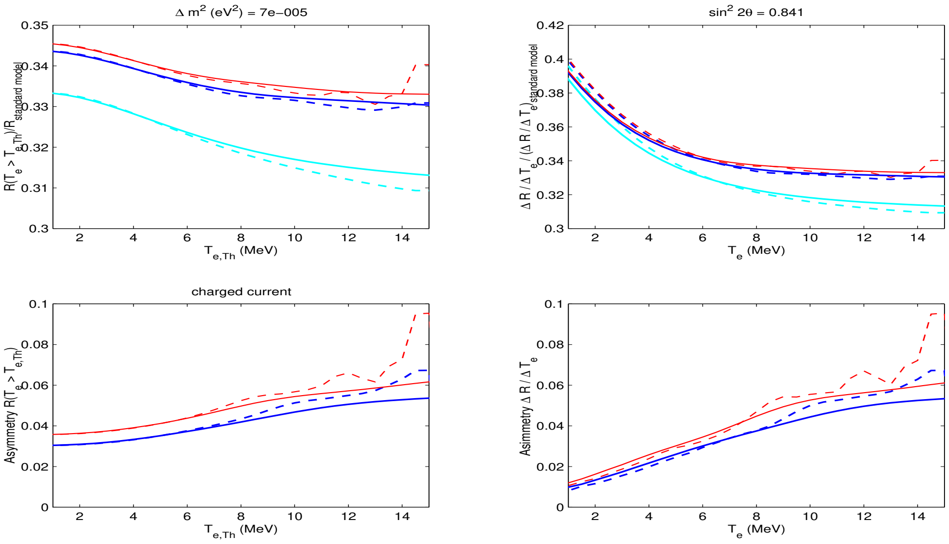

Fig. 1. Energy dependencies of spectral distortions and Day/Night asymmetries for $\sin^2 2\theta = 0.841$ and $\Delta m^2 = 7 \times 10^{-5}$ eV^2. Top - left spectral distortion for cumulative rates as a function of $T_{\mathrm{e,Th}}$, top - right spectral distortions for differential rates as a function of T_{e}. Bottom-left Day/Night asymmetry for cumulative rates, bottom-right Day/Night asymmetry for differential rates. Spectral distortions and Day/night asymmetries are calculated for Day (light blue), Night (blue) and Core (red) including (full lines) or not including (dashed lines) ΔT_{e}.

respectively the rate of CC reactions occurred during days and nights in the period in which data have been acquired, while $\bar{\mathrm{t}}$ = Core the rate of CC reactions occurred at night when the Sun is behind the Earth Core so that neutrinos have to cross it to reach the detector. The other indicator of a time / energy dependence discussed in this paper is the Day/Night asymmetry due to the Day/Night effect

$$A_{\mathrm{DN},\bar{\mathrm{t}}}(T_{\mathrm{e}}) = 2\frac{r_{\mathrm{cc},\bar{\mathrm{t}}}(T_{\mathrm{e}}) - r_{\mathrm{cc},\bar{\mathrm{day}}}(T_{\mathrm{e}})}{r_{\mathrm{cc},\bar{\mathrm{t}}}(T_{\mathrm{e}}) + r_{\mathrm{cc},\bar{\mathrm{day}}}(T_{\mathrm{e}})} \quad (3)$$

Note that (2) compares a model dependent prediction with data, while (3) refers completely to measured data.

Those quantities have been evaluated for SNO according to Maris, Petcov (2002) and references therein but with the new cross-sections for CC and NC reactions of Nakamura et al. (2002). The improved cross sections however does not improve $A_{\mathrm{DN},\bar{\mathrm{t}}}(T_{\mathrm{e}})$ of more than some fraction of percent respect to the old result. Calculations considers all T_{e} above 2 MeV, i.e. below the current SNO cutoff T_{e} = 5 MeV. A large range of possible combinations of $(\sin^2 2\theta, \Delta m^2)$ including those allowed by (1) have been considered. In addition, when forming energy bins the accuracy ΔT_{e} by which SNO measures T_{e} has to be taken in account. Two series of simulations have been generated and compared both neglecting or including the error distribution function given by Ahmad et al. (2002a).

3. Results

Figure 1 is a typical result for electronic spectral distortions (top frames) and Day/Night asymmetries (bottom frames) calculated for one of the most probable values for $\sin^2 2\theta$ and Δm^2. It is evident that a linear dependence can not be used to describe the spectral distortion, which is flat above $T_\mathrm{e} = 5$ MeV and has an $\approx 10\%$ increase for T_e between 2 - 4 MeV both for differential and cumulative rates. The plot suggests that an improvement of SNO which allow a reduction of its cutoff below 4 MeV would allow to observe the "neck" denoting the change in slope around $T_\mathrm{e} \approx 5$ MeV. The value of T_e at which the neck occurs ($T_{\mathrm{neck},\delta}$) is quite sensitive to Δm^2 and θ so that the determination of this spectral feature would improve the determination of these parameters.

The effect of Earth crossing for neutrinos detected at night is well evidenced both as an 4% - 6% energy dependent Day/Night asymmetry and as an up to 6% differences in spectral distortions (less strong at night) for different time bins. Even for the Day/Night asymmetry the energy dependence can not be described by a linear dependence but a two-slope function with a "neck" at $T_\mathrm{e} = T_{\mathrm{neck,DN}} > 5$ MeV shall be appropriate. This neck would be detectable even for the current cutoff for SNO being $T_{\mathrm{neck,DN}} \approx 9$ MeV.

As expected, given the highest density in the Earth core, the Day/Night asymmetry for $\bar{\mathrm{C}}$ore, is slightly more pronounced than the effect for Ni$\bar{\mathrm{g}}$ht in agreement with previous studies. The inclusion of ΔT_e, does not affect significantly spectral distortions or Day/Night asymmetries up to $T_\mathrm{e} = 8$ MeV in agreement with Maris, Petcov (2000(@, 2002). The "new" thing in these plots is the presence of "ripples" or "peaks" at high T_e ($T_{\mathrm{e,Th}}$) observable when ΔT_e is not included. Tho$\bar{\mathrm{s}}$e features are more pronounced for the $\bar{\mathrm{C}}$ore time bin and are due to "peaks" in P_s for ν_e crossing the Earth Core. The detection of these ripples will require a significant progress in the detection technology. However it would allow to improve the present measures on Δm^2 and θ, since they are an unmistakable signature of the MSW effect and their location is sensitive to Δm^2 and θ but not to other details such as: the electron density distribution in the Sun, the shape of the ^8B neutrino spectrum and its normalization.

4. Conclusions

Motivated by the recent experimental results from SNO and KamLAND, supporting the idea of neutrino oscillations as a solution for the Solar Neutrino Problem, we updated the analysis in Maris, Petcov (2002) and presented predictions for the e^-−spectrum deformations and the energy dependence of the D-A asymmetry for the SNO Detector in the case of the LMA solution of the solar neutrino problem. The measurement of the indicated energy dependencies by the SNO experiment can lead to further important constrains on the solar neutrino oscillation parameters Δm^2 and $\sin^2 2\theta$.

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