Electron-neutrino survival probability from solar-neutrino data

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Abstract

With SNO data on electron-neutrino flux from the sun, it is possible to derive the $\nu_e$ survival probability $P_{ee}(E)$ from existing experimental data of Super-Kamiokande, gallium experiments and Homestake. The combined data of SNO and Super-Kamiokande provide boron $\nu_e$ flux and the total flux of all active boron neutrinos, giving thus $P_{ee}(E)$ for boron neutrinos. The Homestake detector, after subtraction of the signal from boron neutrinos, gives the flux of Be+CNO neutrinos, and $P_{ee}$ for the corresponding energy interval, if the produced flux is taken from the Standard Solar Model (SSM). Gallium detectors, GALLEX, SAGE and GNO, detect additionally $pp$-neutrinos. The $pp$ flux can be calculated subtracting from the gallium signal the rate due to boron, beryllium and CNO neutrinos. The ratio of the measured $pp$-neutrino flux to that predicted by the SSM gives the survival probability for $pp$-neutrinos. Comparison with theoretical survival probabilities shows that the best (among known models) fit is given by LMA and LOW solutions.
The recent measurement of boron $\nu_e$ flux by SNO [1], combined with Super-Kamiokande data [2], gives strong evidence for neutrino oscillations [1]. It is based on the fact that the $\nu_e$ flux measured by SNO through the charged current (CC) interaction $\nu_e+d \rightarrow e+p+p$ induces in the Super-Kamiokande detector less electrons than observed. The excess of the electrons can be produced only by active neutrinos of other flavors: $\nu_\mu$ and $\nu_\tau$. This flux of active neutrinos is thus determined and found to be 3.3$\sigma$ above the zero value. Such analysis was suggested earlier in Ref. [3], and recently it was further developed in Ref. [4] (for other recent analysis of SNO data see [5,6]).

In this Letter we shall demonstrate that the new results obtained by SNO allow us to derive the survival probability for boron, beryllium and pp electron neutrinos (for general analysis see [7] and for calculation of survival probability for boron neutrinos [4]).

The probability of electron neutrinos to survive on the way from the production point inside the Sun to the detection site on the Earth is referred to as survival probability, $P_{ee}$. In case of oscillations, $1 - P_{ee}$ is the probability of electron-neutrino conversion into neutrinos of other flavors.

The flux of $^8$B electron neutrinos determined by SNO via CC-events is $\Phi_{\nu_e} = 1.75\pm 0.148 \cdot 10^6$ cm$^{-2}$s$^{-1}$ [1], where we used the upper value for systematic error and summed errors quadratically. SK measurements provide the flux $\Phi_\nu = \Phi_{\nu_e} + 0.154(\Phi_{\nu_\mu} + \Phi_{\nu_\tau})$, where 0.154 is a ratio of cross-sections $\sigma_{\nu_\mu e}/\sigma_{\nu_e e}$. The comparison of these two fluxes allows us to find $\Phi_{\nu_\mu} + \Phi_{\nu_\tau}$ and $\Phi_{\text{tot}} = \Phi_{\nu_e} + \Phi_{\nu_\mu} + \Phi_{\nu_\tau}$, which is equal to $5.44\pm 0.99 \times 10^6$ cm$^{-2}$s$^{-1}$ [1]. Thus the survival probability for $^8$B electron neutrinos can be found as $P_{ee} = \Phi_{\nu_e}/\Phi_{\text{tot}} = 0.32 \pm 0.065$. Note that this derivation of $P_{ee}$ does not depend on the SSM flux. The partial oscillation to sterile neutrinos, $\nu_e \rightarrow \nu_s$, diminishes further $P_{ee}$. This possibility is somewhat disfavored by the observation that $\Phi_{\text{tot}}$ is close to prediction of the SSM [1].

The error in the value of $P_{ee}$ indicated above is calculated by adding all errors in quadrature and it needs further discussion. The uncertainties of $\Phi_{\nu_e}$ and $\Phi_{\text{tot}}$ are correlated.
and therefore the usual interpretation of the indicated error is allowed only in the limit $\Phi_{\nu_e} \ll \Phi_{\text{tot}}$. In fact, the $2\sigma$- and $3\sigma$-equivalent intervals are asymmetric and greater than $1\sigma$ error 0.065 multiplied by factor of 2 and 3, respectively. In particular it can be shown that $1 - P_{ee}$ interval has real $3.3\sigma$ deflection from zero value.

The value of $P_{ee}$ is plotted in Figs. 1–3. The calculated value refers to the whole energy interval of boron neutrinos measured in Super-Kamiokande: in Figs.1–3 the horizontal error bars show the width of this interval. The value of $P_{ee}$ is plotted in the middle of this interval and looks asymmetric in logarithmic scale. As already mentioned above, one should not interpret the many standard deviations which separates $P_{ee}$ from unity in the usual way: the probability that $P_{ee} = 1$ corresponds to about $3.3\sigma$ and not to $\approx 10\sigma$ as it might appear from the figure.

The Homestake detector is sensitive to the boron, beryllium and CNO $\nu_e$-neutrinos. Subtracting the contribution of the measured flux of boron $\nu_e$-neutrinos with the standard spectrum to the chlorine detector, we determine the contribution of Be+CNO neutrinos to the signal. For the production fluxes we use that of the SSM [8]: note that the prediction for the Be neutrino flux is reliable and the contribution of CNO neutrinos is small. In this case the extracted survival probability $P_{ee}$ is not affected by possibility of $\nu_e \rightarrow \nu_s$ oscillation. The survival probability is plotted in Figs.1–3 with errors calculated taking into account uncertainties in fluxes together with statistical and systematic errors of detection. The horizontal error bar refers to the energy interval of Be+CNO neutrinos. The error is strongly anticorrelated with the error in the boron flux: a higher (lower) boron flux implies a lower (higher) beryllium flux.

The detected $\nu_e$-neutrino flux of pp-cycle is found from gallium experiments (GALLEX, SAGE and GNO), subtracting the contributions from boron, beryllium and CNO neutrinos found from the Kamiokande, SNO and gallium experiments. The production flux is taken from SSM calculations [8]. The calculated $pp$ flux is robust and agrees with the flux found independently from solar-luminosity sum rule. The survival probability is plotted in Figs. 1-3. The horizontal error bar refers to the pp-neutrino energy interval. The survival probability
FIG. 1. Survival probability of electron neutrinos as a function of energy. Data points are extracted from the gallium, chlorine and boron-neutrino signals. The horizontal error bars give the energy windows of each datum. For the interpretation of vertical error bars see text. The three solid curves show the theoretical survival probabilities for the Gribov-Pontecorvo (GP) solution, the LOW MSW solution (LOW) and for the large mixing angle MSW (LMA) solution. The solid LMA curve corresponds to neutrino production point at the peak of the boron/beryllium production zone; the dashed curve – at the peak of the $pp$ production zone.
is not affected by oscillation to sterile neutrinos. We shall summarize now the assumptions

FIG. 2. Survival probability of electron neutrinos as function of energy. The solid curve shows the theoretical survival probability for the small mixing angle (SMA) MSW solution for neutrino born at the peak of the boron/beryllium production region; the dashed curve – at the peak of the pp production region.

involved in the calculations of survival probabilities at different energies. For boron neutrinos we used only experimental data, neglecting possible oscillation to sterile neutrinos. For the other two energy intervals (pp- and Be-neutrinos) we used for total fluxes the production fluxes calculated in the SSM, but the calculations of these fluxes are reliable. In addition, we assumed that the measured suppression of high energy boron neutrinos (roughly for $E > 6$ MeV) is valid also for the lower part of the boron-neutrino spectrum. Since in both cases only electron neutrinos produce the signal, the extracted survival probability is not affected by oscillation to sterile neutrinos.

In Fig. 1 the observed survival probabilities are compared with the predictions of the LMA MSW, LOW MSW and Gribov-Pontecorvo (GP) solutions. For LMA we use one
of the best fit solutions from Ref. [10]: $\Delta m^2 = 3.7 \times 10^{-5}$ eV$^2$ and $\sin^2 2\theta = 0.79$; for LOW: $\Delta m^2 = 1.0 \times 10^{-7}$ eV$^2$, and $\sin^2 2\theta = 0.97$ [10], and for the Gribov-Pontecorvo solution [9] $\sin^2 2\theta = 1$. The LMA and LOW survival probabilities shown are not averaged over the production points in the sun. The LOW curve is practically independent of the production point. The LMA solid curve is shown for a production point in the boron/beryllium production zone and the dashed curve shows the survival probability for a neutrino produced at the peak of the $pp$ region. Averaging over the production region gives a curve close to the solid one for boron and beryllium neutrinos, and a curve between the solid and dashed one for $pp$ neutrinos (in fact there is little difference between these curves in the energy region of $pp$ neutrinos).

Only for illustration, we present $\chi^2/d.o.f.$ values for the fits of the data by different oscillation solutions: they are $4/3$, $5/3$ and $10/3$ for the LMA, LOW and GP solutions, respectively. In fact, this $\chi^2$ analysis could be misleading because when the survival probability is used as a variable, the probability distribution is not Gaussian.

In Fig. 2 the observed survival probabilities are compared with those calculated in SMA MSW. One of the best fit solutions, with spectral and temporal information included, is given by $\Delta m^2 = 4.6 \times 10^{-6}$ eV$^2$ and $\sin^2 2\theta = 1.36 \times 10^{-3}$. The solid curve corresponds again to the neutrino produced in the boron/beryllium production region, while the dashed curve shows the low-energy part of the survival probability for the neutrino born in the peak of $pp$ production region. The confidence level is characterised illustratively by $\chi^2/d.o.f. \approx 12/3$.

In Fig. 3 the observed survival probabilities are compared with predictions of the Just-So ($\Delta m^2 = 4.6 \times 10^{-10}$ eV$^2$ and $\sin^2 2\theta = 0.83$) and Just-so$^2$ ($\Delta m^2 = 5.5 \times 10^{-12}$ eV$^2$ and $\sin^2 2\theta = 0.96$) solutions. The qualitatively worse agreement can be characterised by $\chi^2/d.o.f. \approx 11/3$ and $\chi^2/d.o.f. \approx 13/3$ for Just-So and Just-So$^2$, respectively.

We repeat again that the quantities $\chi^2$ calculated above have only an illustrative character: the obtained value of $\chi^2$ for each solution is not connected with probability in a usual way. This analysis indicates however the preferred solutions.

The preferred solutions are LMA and LOW which are characterised by the lowest values
FIG. 3. Survival probability of electron neutrinos as function of energy. The solid curve shows the theoretical survival probability for the vacuum oscillation solution; for energy below 0.53 MeV, only the average probability is shown. The dashed curve is for the Just-So\textsuperscript{2} solution.
of $\chi^2$.

In principle the survival probabilities for boron neutrinos can be given for several energy bins. Since the observed spectrum is well described by the SSM spectrum, the energy bin analysis will further decrease the probability of SMA MSW, which produces a significant spectrum distortion in the boron energy window, and will favour the solutions with a flat suppression of boron neutrino spectrum, such as the GP, LMA and LOW solutions. Day-night dependence will not change the analysis in a significant way, since these solutions have little day-night dependence in the boron high-energy window.

In conclusion, using the data of all solar-neutrino experiments we have derived the electron-neutrino survival probabilities. For boron neutrinos only experimental data are used, and the SSM flux is not involved. Survival probability decreases in presence of $\nu_e \rightarrow \nu_s$ oscillation. For Be+CNO and $pp$ neutrinos the SSM calculations are used for production (i.e total) fluxes. This is a plausible assumption, because beryllium and $pp$ neutrino fluxes are reliably calculated and CNO fluxes are small. Oscillation to sterile neutrinos does not affect the extracted survival probabilities for Be+CNO and $pp$ neutrinos.

LMA and LOW solutions give better fits, in comparison with other solutions. It is also possible, in principle, to calculate for boron neutrinos the survival probabilities for several energy bins: the likelihood of solutions with an energy independent suppression for $E > 6$ MeV, i.e. LOW, LMA and GP, will increase as compared with the ones that predict an energy dependent suppression.
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