Helioseismic determination of Beryllium neutrinos produced in the Sun

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(May 2000)

Abstract

We provide a determination of the Beryllium neutrino luminosity directly by means of helioseismology, without using additional assumptions. We have constructed solar models where Beryllium neutrino, ($\nu_{\text{Be}}$) production is artificially changed by varying in an arbitrary way the zero energy astrophysical S-factor $S_{34}$ for the reaction $^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$. Next we have compared the properties of such models with helioseismic determinations of photospheric helium abundance, depth of the convective zone and sound speed profile. We find that helioseismology directly confirms the production rate of $\nu_{\text{Be}}$ as predicted by SSMs to within $\pm 25\%$ (1$\sigma$ error). This constraint is somehow weaker than that estimated from uncertainties of the SSM ($\pm 10\%$), however it relies on direct observational data.

I. INTRODUCTION

As well known, the production of neutrinos from $^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e$ is an important item in the context of the so called “Solar neutrino puzzle” for several reasons:

i) The result of Gallium experiments would be (partially) consistent with the hypothesis of standard neutrinos only if Beryllium neutrino ($\nu_{\text{Be}}$) production rate, $L(\nu_{\text{Be}})$, is suppressed by an order of magnitude with respect to the prediction of the Standard Solar Model (SSM), see e.g. [1,2].

ii) If one accepts neutrino oscillations as the solution of the solar neutrino puzzle, the determination of the neutrino mass matrix depends however on the predicted value of $L(\nu_{\text{Be}})$. iii) Direct experiments aiming to the determination of the $\nu_{\text{Be}}$ signal are in preparation and of course the interpretation of their result will rely on $L(\nu_{\text{Be}})$ [3,4].

The SSM prediction for Beryllium neutrinos [5],

$$L(\nu_{\text{Be}})^{\text{SSM}} = 1.3 \cdot 10^{37} (1 \pm 9\%) \text{ s}^{-1} (1\sigma \text{ error})$$

(1)

is very robust, much more than that of Boron neutrinos. However any additional information which does not rely on SSM are clearly welcome. In a previous paper [6] we have shown that
helioseismology, supplemented with the Superkamiokande result on $^8$B neutrinos, already yields a lower limit for $^7$Be production:

$$L(\nu_{Be}) \geq 2.8 \cdot 10^{36} \ (1 \pm 24\%) \ \text{s}^{-1}.$$  

(2)

In this paper we make a step forward and we provide a determination of $L(\nu_{Be})$ directly by means of helioseismology without using additional assumptions.

The basic idea is the following. In the SSM the pp-II termination (which is the Beryllium production branch) accounts for an appreciable fraction of the $^4$He produced near the solar center. As a consequence, if Beryllium production were suppressed – now and in the past – less $^4$He would have been produced near the center. As a consequence, the molecular weight there decreases and one expects that the sound speed increases in this region. In other words, we know that SSM calculations are in good agreement with helioseismology and we can expect that this agreement is spoiled if $\nu_{Be}$ production is substantially altered.

In refs. [7] it was shown that models where the production of $\nu_{Be}$ is (artificially) forbidden are in conflict with helioseismology. In this paper we attempt to a quantitative determination of the $^7$Be-neutrino luminosity. In order to fulfill this program, we have constructed solar models where $\nu_{Be}$ production is artificially changed by varying in an arbitrary way the zero energy astrophysical S-factor ($S_{34}$) for the reaction $^3$He + $^4$He → $^7$Be + $\gamma$. As well known (see e.g. [8,2,9]), the production rate $L(\nu_{Be})$ is directly proportional to $S_{34}$, so that this is an efficient way for arbitrary variations of $L(\nu_{Be})$. We remind that $S_{34}$ is measured with an accuracy of about ten per cent, ($S_{34}^{SSM} = 0.54 \pm 0.09 \ \text{KeVb}$ [10]). Its variation well beyond the experimental uncertainty is just a way of simulating several effects which have been claimed to suppress $\nu_{Be}$ production, e.g. hypothetical plasma effects which could alter nuclear reaction rates. These effects, which correspond to an anomalous screening effect, can be described by introducing an effective zero energy astrophysical factor $S_{34} \neq S_{34}^{SSM}$.

II. RESULTS AND DISCUSSION

As well known, helioseismology determines quite accurately several properties of the sun, see e.g. [11,13]:

a) The depth of the convective envelope $R_b$ and the photospheric helium abundance $Y_{ph}$ are determined as:

$$R_b/R_\odot = 0.711 \pm 0.001$$

(3)

$$Y_{ph} = 0.249 \pm 0.003 \ ,$$

(4)

where here and in the following the so called “statistical” or 1$\sigma$ uncertainties are considered [11].

b) The sound speed profile is determined with an accuracy of about 0.2% in the intermediate solar region, say between 0.1-0.7$R_\odot$. Recent SSM calculations, see e.g. [5], are in good agreement with these observational data within the quoted errors (with the possible exception of the sound speed just below the convective envelope, which is slightly underestimated in the calculated models [11,5]).
By keeping as a free parameter \( s = S_{34}/S_{34}^{SSM} \) we have built a series of solar models. This means that, for a fixed value for \( s \), the stellar evolution code FRANEC \([14]\) was run by varying the three free parameters of the model (initial helium abundance \( Y_{\text{in}} \), initial metal abundance \( Z_{\text{in}} \) and mixing length \( \alpha \)) until it provides a solar structure, i.e. it reproduces the observed solar luminosity, radius and photospheric metal abundance at the solar age. As well known by varying \( S_{34} \) the \( \nu_{\text{Be}} \) luminosity scales linearly, see e.g. \([8,2,9]\) and Fig. 1.

In fact, the production rate of Be nuclei is obviously proportional to \( S_{34} \) and practically each beryllium nucleus produces one \( \nu_{\text{Be}} \) (neglecting the small probability of proton capture compared with that of electron capture).

The resulting values for the quantities which can be tested by means of helioseismology are shown in Fig. 2 and Fig. 3.

The photospheric helium abundance \( Y_{\text{ph}} \) is weekly sensitive to the value of \( S_{34} \) whereas the depth of the convective envelope \( R_b \) is altered by more than 1\( \sigma \) if \( S_{34} \) is reduced below one half of the SSM value, i.e.:

\[
L(\nu_{\text{Be}}) = 1.3 \times 10^{37} (1 \pm 50\%) \text{ at } 1\sigma .
\] (5)

As previously mentioned, one expects that the sound speed is altered, particularly near the solar center. In fact, stringent constraints arise from the sound speed profile, particularly near \( R \approx 0.2R_{\odot} \). The requirement that the sound speed is not changed by more than 1\( \sigma \) yields:

\[
L(\nu_{\text{Be}}) = 1.3 \times 10^{37} (1 \pm 0.25) \text{ at } 1\sigma .
\] (6)

In conclusion, helioseismology directly confirms the production rate of Beryllium neutrinos as predicted by SSMs to within \( \pm 25\% \) (1\( \sigma \) error). This constraint is somehow weaker than that estimated from uncertainties of the SSM, see Eq. [1], however it relies on direct observational data.

Finally we remark that the helioseismic determination of \( ^7\text{Be} \)-neutrino production rate also shows that the sun is producing \( ^7\text{Be} \) nuclei and that the \( ^7\text{Be} \) abundance is correctly calculated by SSMs.

ACKNOWLEDGMENTS

We are extremely grateful to V. Castellani, S. Degl’innocenti and G. Fiorentini for useful suggestions and comments.
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FIGURES

FIG. 1. Flux of $^7$Be-neutrinos, normalized to the SSM value, as a function of $s = S_{34}/S_{34}^{SSM}$.

FIG. 2. The photospheric helium abundance $Y_{ph}$ and the depth of the convective envelope $R_b$ in solar models with the indicated values of $s = S_{34}/S_{34}^{SSM}$. The error bars corresponds to the 1σ helioseismic uncertainties, from ref.[11].

FIG. 3. Fractional difference with respect to the SSM prediction, $(\text{model-SSM})/\text{SSM}$, of the isothermal squared sound speed, $u = P/\rho$, in solar models with the indicated values of $s = S_{34}/S_{34}^{SSM}$. The dotted area corresponds to the 1σ helioseismic uncertainty on $u$, from ref. [11].
Figure 1

\[ \Phi_{\text{Be/Be}}^{SSM} \]

Plot showing the relation between \( S_{34}/S_{34}^{\text{SSM}} \) and \( \Phi_{\text{Be/Be}}^{SSM} \). The graph includes several data points represented by diamonds.
