Determination of the Beryllium neutrino flux from helioseismic data

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We show that helioseismology provides information on Beryllium neutrino production in the Sun. In particular, we derive a lower limit on the Beryllium neutrino flux on earth, $\Phi_{Be}^{min} = 1 \cdot 10^9 \mathrm{cm}^{-2}\mathrm{s}^{-1}$, in the absence of oscillations, by using helioseismic data, the B-neutrino flux measured by Superkamiokande and the hydrogen abundance at the solar center predicted by Standard Solar Models. Moreover, we obtain an helioseismic determination of Φ_{Be} by comparing solar model with artificially changed ν_{Be} production with helioseismic data.

1. Introduction

As well known, the production of neutrinos from

$$^7\mathrm{Be} + e^- \rightarrow ^7\mathrm{Li} + \nu_e \tag{1}$$

is an important item in the context of the so called "solar neutrino puzzle", see e.g. [1]. The Standard Solar Model (SSM) prediction for Beryllium neutrino flux [2],

$$\Phi_{Be}^{SSM} = 4.82 \cdot 10^9 \, (1 \pm 9\%) \, \mathrm{cm}^{-2}\mathrm{s}^{-1} \quad (1\sigma) \; , \tag{2}$$

is very robust, much more than that of Boron neutrinos. Nevertheless, it is the outcome of an involved solar model calculation and any additional information which does not rely on SSMs are clearly welcome. We review here some recent determination of the Beryllium neutrino flux based on helioseismology.

2. Helioseismic observables

Helioseismology has added important data on the solar structure which provide severe constraint and tests of SSM calculations. Specifically, by measurements of thousands of solar frequencies (p-modes) with a typical accuracy of $\Delta\nu/\nu \simeq 10^{-4}$, one derives:

i) Properties of the present convective envelope, such as depth and helium abundance:

$$R_b = 0.711(1 \pm 0.4\%) R_\odot \tag{3}$$

$$Y_{ph} = 0.249(1 \pm 4\%) \tag{4}$$

The quoted errors, mostly resulting from systematic uncertainties in the inversion technique, have been estimated conservatively by adding linearly all known individual uncertainties, see [3]. We refer to them as "3σ" errors. If uncertainties are added in quadrature, one obtains the so called "1σ" errors which are about one third of that indicated in eqs. (3,4), see again [3] [1].

ii) Sound speed profile. By inversion of helioseismic data one can determine the isothermal squared sound speed, $u = P/\rho$, in the sun interior. The typical "3σ" errors are of order $\pm 0.4\%$ in the intermediate solar region, $R/R_\odot \simeq 0.4$, and increase up to $\pm 2\%$ near the solar center. Since the p-modes which are observed do not propagate (actually are exponentially damped) deeply in the sun, the question often arises if present helioseismic data can determine the sound speed in region of Beryllium and Boron neutrinos production ($R \simeq 0.05 R_\odot$). From an extensive analysis of the inversion method, it was concluded in [3] that $u(R \simeq 0)$ is determined with a "1σ" accuracy of 1%.

3. A lower limit on the Beryllium neutrino flux

A lower limit on the Beryllium neutrino flux on earth, $\Phi_{Be}^{min} = 1 \cdot 10^9 \, \mathrm{cm}^{-2}\mathrm{s}^{-1}$, in the absence of

[1]We remark that the used terminology is part of a slang, and it does not correspond to well defined confidence levels, as one has to combine several essentially systematic errors.

oscillations, can be obtained by using helioseismic data, the B-neutrino flux measured by Superkamiokande and the hydrogen abundance at the solar center X_c predicted by Standard Solar Model (SSM) calculations (see [4] and references therein).

The basic idea is the following. The B-neutrinos from

$$\begin{aligned} {}^7\mathrm{Be} + \mathrm{p} \rightarrow \quad & {}^8\mathrm{B} + \gamma \\ & {}^8\mathrm{B} \rightarrow 2\alpha + \mathrm{e}^+ + \nu_\mathrm{e} \quad , \end{aligned} \tag{5}$$

have been observed by Kamiokande and Superkamiokande. Since B-neutrinos and Be-neutrinos are both sons of ^{7}Be nuclei, one expects that detection of the former gives information on the latter. As the rates of (1) and (5) depend differently on the solar temperature, one need some information on it. This is (indirectly) provided by helioseismology, which determines the sound speed with an accuracy of one per cent or better, even close to the solar center, see e.g. [3]. Temperature is obtained from the sound speed if the chemical composition of the solar plasma is known. This is the only information which one has to take from SSMs, in the form of the hydrogen abundance at the solar centre X_c. We remark that predictions for X_c are very stable among different (standard and non standard) solar models, see [4]. In fact X_c is essentially an indicator of how much hydrogen has been burnt so far. The stability of X_c corresponds to the fact that any solar model has to account for the same present and time integrated solar luminosity.

By using the limit $\Phi_{Be}^{min} = 1 \cdot 10^9\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, lower bounds for the Gallium signal, $G_{min} = (91 \pm 3)$ SNU, and for the Chlorine signal, $C_{min} = (3.24 \pm 0.14)$ SNU, in the absence of oscillations, can also be derived. They are about 3σ above the corresponding experimental values, $G_{exp} = (75 \pm 5)$ SNU and $C_{exp} = (2.56 \pm 0.22)$ SNU, thus providing a 3σ (essentially) SSM-independent evidence for solar neutrino oscillations.

4. Helioseimic determination of the Beryllium neutrino flux

A determination of Φ_{Be} can be directly obtained by means of helioseismology without using additional assumptions (see [5] and reference therein). The basic idea is the following. In the SSM the pp-II termination (which is the Beryllium productng branch) accounts for an appreciable fraction of the ^{4}He produced near the solar center. If Beryllium production is suppressed – now and in the past – less ^{4}He would have been produced near the center. As a consequence, the molecular weight should decrease and the sound speed should increase 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 ν_{Be} production is substantially altered.

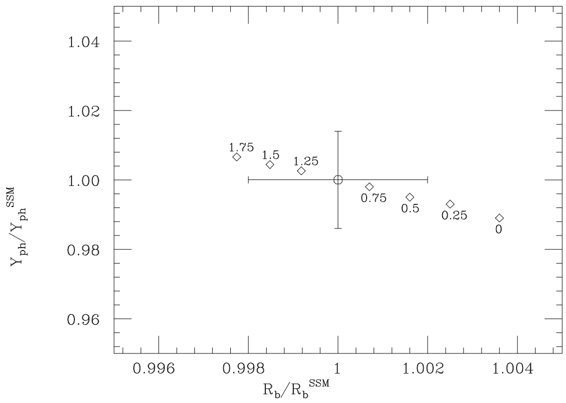

Figure 1. The photospheric helium abundance Y_{ph} and the depth of the convective envelope R_b in solar models with the indicated values of $s = S_{34}/S_{34}^{SSM}$. The error bars correspond to the "1σ" helioseismic uncertainties, from ref.[3].

In order to test this idea, solar models with artifically changed ν_{Be} production were constructed. An efficient way to do this is to vary the zero energy astrophysical S-factor (S_{34}) for the reaction ${}^3\mathrm{He} +{}^4\mathrm{He} \rightarrow{}^7\mathrm{Be} + \gamma$, since, as well known (see e.g. [1]), the production rate of Beryllium neutrinos is directly proportional to S_{34}:

$$\Phi_{Be}/\Phi_{Be}^{SSM} \simeq S_{34}/S_{34}^{SSM} \ . \tag{6}$$

We remind that S_{34} is measured with an accuracy of about ten per cent, ($S_{34}^{SSM} = 0.54 \pm 0.05$ KeVb) It has been varied, however, well beyond its experimental uncertainty in order to simulate several effects which have been claimed to suppress ν_{Be} production, e.g. hypothetical plasma effects which could alter nuclear reaction rates. The resulting values for the quantities which can

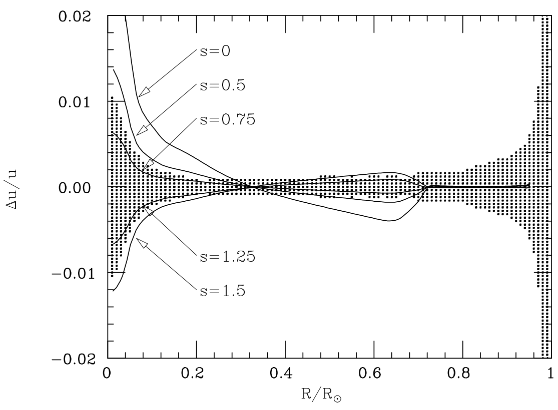

Figure 2. Fractional difference with respect to the SSM prediction, (model-SSM)/SSM, of the isothermal squared sound speed, $u = P/\rho$, in solar models with the indicated values of $s = S_{34}/S_{34}^{SSM}$. The dotted area corresponds to the "1σ" helioseismic uncertainty on u, from ref.[3].

be tested by means of helioseismology are shown in Fig. 1 and Fig. 2, for several assumed values of the parameter $s = S_{34}/S_{34}^{SSM}$.

The photospheric helium abundance Y_{ph} is weekly sensitive to the value of S_{34} whereas the depth of the convective envelope R_b is altered by more than 1σ if S_{34} is reduced below one half of the SSM value. This shows that, in the absence of oscillations, the Beryllium neutrino flux on the earth should not differ by more than 50% from SSM estimate, i.e.:

$$\Phi_{Be} = 4.82 \cdot 10^9 \,(1 \pm 50\%)\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \;\; (1\sigma)\;. \qquad (7)$$

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 $R \simeq 0.2 R_\odot$. The requirement that the sound speed is not changed by more than 1σ yields:

$$\Phi_{Be} = 4.82 \cdot 10^9 \,(1 \pm 25\%)\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \;\; (1\sigma)\;. \qquad (8)$$

In conclusion, helioseismology directly confirms the production rate of Beryllium neutrinos as predicted by SSMs to within ±25% (1σ error). This constraint is somehow weaker than that estimated from uncertainties of the SSM, see Eq.2, however it relies on direct observational data.

5. Conclusions

We summarize here the main points of our discussion:

i) By using helioseismic data, the B-neutrino flux measured by Superkamiokande and the hydrogen abundance at the solar center X_c predicted by SSMs, one obtains the lower limit $\Phi_{Be}^{min} = 1 \cdot 10^9\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for Beryllium neutrino flux on earth in the absence of oscillations;

ii) By comparing solar models in which ν_{Be} production is artificially changed with helioseismic data, one confirms the Be-neutrino flux predicted by SSMs to within ±25% (1σ error).

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