Boron abundance and solar neutrino spectrum distortion

R. Escribano, J.-M. Frère, A. Gevaert and D. Monderen

Service de Physique Théorique, Université Libre de Bruxelles, CP 225, B-1050 Bruxelles, Belgium

Abstract

The presence of neutrinos from Boron decay in the flux observed on Earth is attested by the observation of their energy spectrum. Possible distortions of the spectrum investigated in current detectors are often interpreted in terms of evidence in favour or against various schemes of neutrino oscillations. We stress here that a distortion of the spectrum at high energies could also result from an increase in the ratio of neutrinos originating from $(^3\text{He}+p)$ and $^8\text{B}$ reactions. While a $^8\text{B}$ neutrino depletion would contribute to this effect, an increase in the Hep contribution seems also needed to reproduce the preliminary data.

---

$^1$Chercheur IISN.
$^2$Directeur de recherches du FNRS.
1 Introduction

We want to study the effects of possible changes in the ratio between the fluxes of solar neutrinos produced respectively by the \((^3\text{He}+\text{p})\) reaction and by Boron decay. For simplicity, we will refer to this ratio by the shorthand \(H_{\text{ep}}/B\).

In particular, an increase in \(H_{\text{ep}}/B\) could account for the increase in the number of neutrinos observed in the high-energy part of the spectrum, as suggested by the preliminary data of Super-Kamiokande. This is a crucial point to investigate, as such an increase, thus far interpreted as a distortion of the Boron neutrinos spectrum, is the only direct evidence (by this, we mean largely independent of the solar models) for solar neutrino oscillations.

Boron abundance in the Sun has been considerably discussed since its energetic decay neutrinos play a leading role in most experiments, far out of proportion to their sheer numbers. Furthermore, the \(^8\text{B}\) reduction mechanism depends on the poorly known \(^7\text{Be}(p, \gamma)^8\text{B}\) production cross section\[^3\]. Although the close relation between Boron and Beryllium abundances makes it unlikely to account for all observations by a reduction of the \(^8\text{B}\) abundance alone\[^2\], the impact of a shift in \(^8\text{B}\) abundance on the spectrum distortion, and the importance of the latter in discriminating among oscillation schemes makes it an essential element of a complete analysis.

We began with the question: assuming that the apparent depletion of Boron-produced neutrinos is genuine (i.e. not due to oscillations) would the corresponding change in spectra effectively mimic the Super-Kamiokande signal? This is indeed largely the case, as we see in the first figure below, if the comparison is made directly between the inferred electron recoil curves and the preliminary data. It turns out, however, that a severe smoothing occurs, due to the limited energy resolution of the experiment, and this must be included in the comparison. This is done in the second figure, which shows clearly that a much larger increase in \(H_{\text{ep}}/B\) is needed to reproduce the data. Such a large increase cannot stem from a reduction in the Boron contribution alone, as such a suppression would contradict the data. Instead the possibility of an enhancement of the Hep contribution, either for nuclear or astrophysical reasons, must be called into play.

Even apart from possible astrophysical effects, it turns out indeed that

\[^3\text{For a recent reevaluation of this important quantity see Ref. }[1\text{, and references therein.}\]
the \(^3\text{He}+\text{p}\) reaction is in fact poorly known, and could strongly increase \(Hep/B\).

After discussing the effect of varying \(Hep/B\), we take the opportunity to review in simple terms how it would interfere with the expected spectrum distortions in various oscillation schemes.

\section{Varying \(^8\text{B}\) and Hep neutrino abundances}

The energy range explored by the Super-Kamiokande experiment is dominated by neutrinos from \(^8\text{B}\) decay \(^3\). In the upper part of the spectrum, however, this spectrum crosses the contribution from Hep neutrinos\(^4\). Clearly, despite a higher energy and thus better sensitivity, this upper part is more difficult to measure as the absolute flux drops by orders of magnitude, so that the statistical significance dwindles.

We have plotted in Fig. 1 the expected electron recoil spectrum versus the energy for various \(Hep/B\) ratios. The plot is based on SSM data and standard differential cross sections \(^4\).

The curves are normalized to give an equal number of events above the Super-Kamiokande threshold, and the plotted points have then been reduced to the SSM expectation. For completeness, we have also plotted a curve omitting completely the Hep contribution. In these conditions, decreasing the \(^8\text{B}\) abundance amounts to increasing the relative role of the Hep contribution, and thus in an enhancement of the expectation for large recoil energies. While such graphs are now standard, it may at first sight seem surprising that, when all the sets of data have been normalized to the same total number of events, increasing \(Hep/B\) leads to an increase at high energy values, apparently not compensated for by a decrease at low energies. The reason for this somewhat misleading effect is simply understood when referring to the raw values (not normalized to SSM expectations). Indeed the fall in energy distribution is so steep that the high-energy events (and in particular the Hep contribution) have only a minute impact on the normalization. When the data are normalized to the SSM model, the depletion of the low-energy part reaches the graphical resolution limit.

The top four curves shown in Fig. 1 correspond respectively to reductions of the \(^8\text{B}\) abundance by 0.1, 0.2, 0.4, and 0.8 of its standard value with respect

\(^4\) Hep neutrinos are those produced in the nuclear reaction \(^3\text{He}+\text{p} \rightarrow \text{He}+e^++\nu_e\).
Figure 1: Electron recoil spectra as a function of $^8$B abundance in the Sun. The solid line refers to the SSM, to which all curves are normalised.

to the Hep contribution, or alternatively to $Hep/B = 10, 5, 2.5$ and 1.25.

The curves shown in Fig. 1, while close in aspect to the preliminary data for the larger values of $Hep/B$, are however not the ones effectively observed. Even discounting the habit of grouping all points above 14 MeV in a single bin, care has to be taken to include the effective energy resolution, which is usually not deconvoluted from experimental presentations. This is usually done using a convolution with a gaussian-like resolution function [7]. We illustrate the effect in Fig. 2. Obviously, the effect of Hep neutrinos is dwarfed in with respect to Fig. 1 for a given $Hep/B$, since a number of lower energy $^8$B neutrinos now inevitably “bleed” into the higher energy region.

We will refrain here from reproducing the experimental points (which can only be gathered from figures presented at conferences, see Ref. [3]) since they have not been actually published. Suffice it for now to say that the higher curves in Fig. 2 match closely the experimental results, as we know them today. We also performed tentative $\chi^2$ fits based on these preliminary data (unfortunately the error bars could only be taken from the figures). This
indeed favours high $Hep/B$ ratios, giving notably a numerically better fit than the small angle MSW solution when fitting the spectrum in search for neutrino oscillations. Our central value falls between the top two curves in Fig. 2. At this moment, however, the data accuracy is not sufficient to conclude.

It is thus clearly important to allow for a (large) variation of the ratio of Hep to $^8$B contributions in the study of oscillations.

While the observed neutrino flux does seem to indicate a suppression of the $^8$B with respect to SSM expectations (assuming for the moment the absence of oscillations) by a factor 2 to 3, this is totally insufficient to account for the large enhancement of $Hep/B$ needed according to Fig. 2. However, even not taking into account possible astrophysical effects, the ratio of the Hep to $^8$B neutrinos is further affected by the severe uncertainty on the $^3$He($p, e^+\nu_e$)$^4$He cross section. The central values quoted in the recent literature for the nuclear factor $S_{13}(0)$ of this cross section vary from
(1.3 to 57) $\times 10^{-20}$ keV [3], with the lowest value used by [4], which we have adopted for normalization. Increase in $Hep/B$ of up to 150 with respect to [4], and resulting from both $^8$B depletion and Hep enhancement could thus be considered (even outside possible astrophysical effects).

3 Oscillation schemes

Oscillation effects are known to affect the shape of the electron recoil spectrum. We list briefly the expected effects in order to see how they conspire or interfere with a possible increase in the $Hep/B$ ratio.

In the case of MSW oscillations, the situation differs according to the adiabatic or otherwise evolution of the system. In the adiabatic case, for a large enough value of $\frac{E}{\delta m^2}$ the electronic neutrinos are the “heavy” solution inside the Sun and move continuously into the “heavy” solution (a $\nu_\mu$, $\nu_\tau$ or a sterile neutrino $\nu_s$) outside the Sun. Since the resonance condition is met at lesser densities for higher energies, the cross-over occurs at a larger solar radius, and thus a larger proportion of the energetic neutrinos are effectively (totally or partially) transformed/sterilized. The distortion is then expected to be negative, but could be partially hidden by the above abundance considerations.

In the non-adiabatic case, however, the slope of the solar density close to the resonance point changes fast enough to allow the neutrinos to jump from the “heavy” solution to the “light” solution of the level-crossing diagram. This occurs increasingly with energy, so for small mixing at least, a positive slope is expected.

Such a situation is usually invoked because it allows for the suppression of a “slice” of the neutrino spectrum (typically the $^7$Be lines) while restoring a sufficient proportion of $^8$B neutrinos for the Super-Kamiokande observations. In this case, clearly, the two effects, i.e. non-adiabatic oscillations and $Hep/B$ enhancement, would go in the same direction, but the detailed pattern is quite different. $^8$B depletion typically affects the end part of the spectrum, while the effect of non-adiabaticity is rather gradual. Higher statistics will be needed to disentangle the two effects.

Finally, a possible solution in the shape of long-range (mostly vacuum) oscillations has been discussed recently [8]. Here, the distortion of the spectrum depends on the position of the oscillation curve $\sin^2 \left( \frac{\Delta m^2 L}{4E} \right)$, that is, on
the number of oscillations between the Sun and the Earth. Both positive and negative slopes are then possible. As pointed out in [8], the two effects will be distinguishable through different correlations with the Sun-Earth distance, which only affects the oscillation part.

4 Conclusions

Future experiments and extra statistics from Super-Kamiokande will improve understanding of the solar neutrino problem. In comparing with models, we insist, however, that both the ratio \( \text{Hep}/B \) of Hep to \(^8\text{B} \) neutrinos (as well as its implications for other experiments) and various oscillation schemes must be considered simultaneously. Preliminary values favour a large ratio of Hep to \(^8\text{B} \) neutrinos. Alternatively, a cut in the energy spectrum might allow a nearly independent study of both effects, since \(^8\text{B} \) depletion and/or Hep enhancement show up significantly only in the higher parts of the energy spectrum.

5 Acknowledgements

This work was supported by I. I. S. N. Belgium. D. Monderen benefits from a FRIA grant. We thank P. Vilain and G. Wilquet for numerous discussions.

References

[1] F. Hammache et al., Phys. Rev. Lett. 80, 928 (1998).
[2] N. Hata and P. Langacker, Phys. Rev. D 56, 6107 (1997).
[3] Talks given by the Super-Kamiokande collaboration, available at the following URL: www-sk.icrr.u-tokyo.ac.jp/doc/sk/pub/pub_sk.html.
[4] J. N. Bahcall and R. K. Ulrich, Rev. Mod. Phys. 67, 781 (1995); J. N. Bahcall, Neutrino Astrophysics (Cambridge University Press, Cambridge, England, 1989).
[5] Y. Fukuda et al., the Super-Kamiokande collaboration, hep-ex/9805021.
[6] E. G. Adelberger et al., astro-ph/9805121, to appear in Rev. Mod. Phys. 10/98, and references therein.

[7] J. N. Bahcall, P. I. Krastev and E. Lisi, Phys. Rev. C 55, 494 (1997).

[8] S. P. Mikheyev and A. Yu. Smirnov, hep-ph/9708403; A. Yu. Smirnov, in Neutrino 96, talk given at the 17th International Conference on Neutrino Physics and Astrophysics, Helsinki, Finland, 1996, hep-ph/9611433.