Sterile neutrinos in the $3 + s$ scenario and solar data

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Introduction

3+s neutrino schemes were introduced some time ago to account for anomalies occurring in very short baseline experiments ($L \sim \text{few} \times 10m$): the accelerator (LSND, KARMEN, ICARUS, MiniBooNE), reactor and Gallium anomalies.
A short oscillation length is needed, implying an oscillation to one or two sterile states (s=1 or 2) with

$$\Delta m_{41}^2,\ \Delta m_{51}^2 = O(|1eV^2|).$$

Leading terms (one sterile only):

- Neutrino appearance (accelerator experiments):

$$P_{\nu_\mu \to \nu_e} = 4sin^2 \frac{\Delta m_{41}^2}{4E} L |u_{e4}|^2 |u_{\mu 4}|^2$$

- Neutrino disappearance
(reactor experiments + Gallium calibration):

$$P_{\nu_e \to \nu_e} = 1 - 4sin^2 \frac{\Delta m_{41}^2}{4E} L |u_{e4}|^2 (1 - |u_{e4}|^2)$$

Limits are given in the literature in terms of ‘effective’ angles:

$$sin^2 2\theta_{e\mu} = 4|u_{e4}|^2|u_{\mu 4}|^2, \; sin^2 2\theta_{ee} = 4|u_{e4}|^2(1 - |u_{e4}|^2)$$

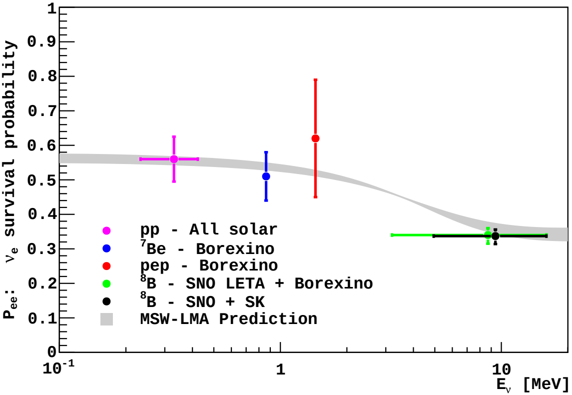
- $sin^2 2\theta_{e\mu} = (4 - 10) \times 10^{-3}$

  $\Delta m^2 = (4 - 7) \times 10^{-1} eV^2$ (accelerator)

- $sin^2 2\theta_{ee} = (70 - 200) \times 10^{-3}$

  $\Delta m^2 = (2 - 3) eV^2$ (reactor, Ga)

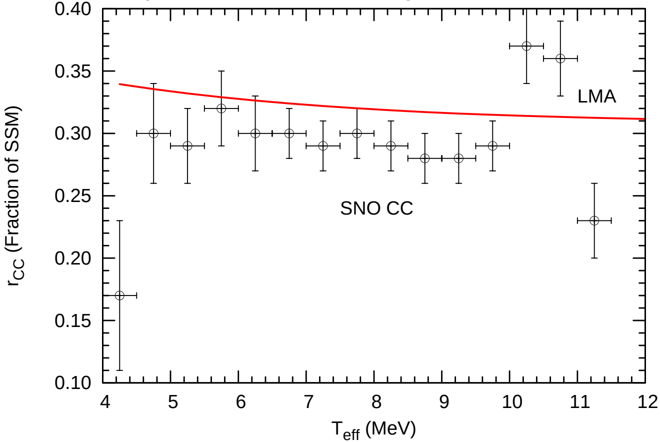
Common prejudice asserts that the solar neutrino problem is by now 'solved' which is not the case. In fact an estimation made by the Borexino Collaboration shows that there is a gap in the knowledge of the neutrino survival probability in the vacuum matter transition region.



Borexino Collaboration, Phys. Rev. Lett. **108**, 051302 (2012).

Introduction

Moreover, besides the long standing problem of the flatness of the SK spectrum which LMA fails to explain, also the LMA CC spectrum prediction seems to proceed in the wrong direction.

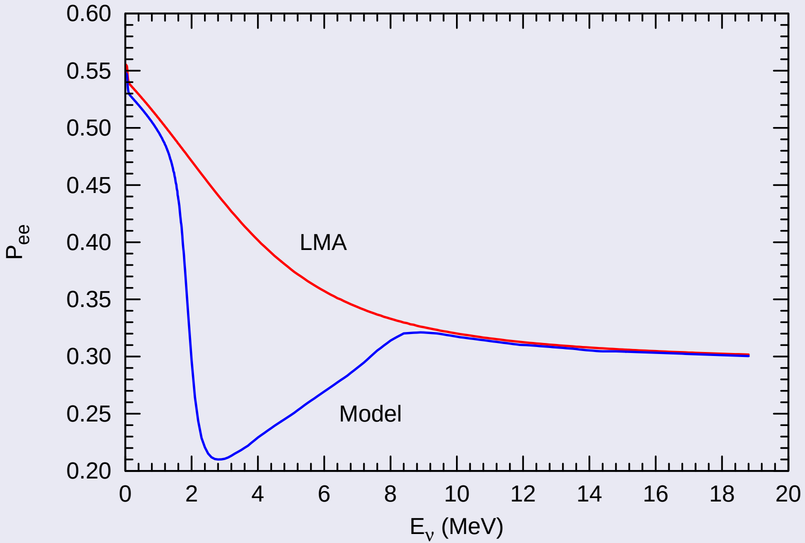


This lead us to investigate different shapes of the neutrino survival probability from the LMA one.

The Model

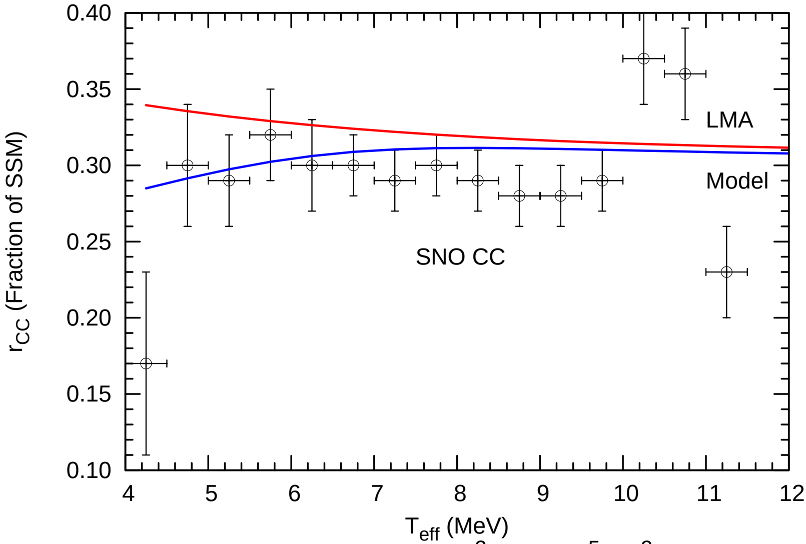
- Hence: introduce light sterile neutrinos and investigate possible ranges of Δm^2_{new}, θ_{new}. Adequate shapes for probability were found with sterile neutrinos which are quasi degenerate with respect to the active ones, ($\Delta m^2_{new} = O(10^{-5}eV^2)$) with small mixing to these.
- So they are different from the ‘conventional’ steriles that are suggested by accelerator, reactor and Ga anomalies.
- The latter do not play any major role in solar neutrino oscillations.

The Model


0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
P_{ee}
0
2
4
6
8
10
12
14
16
18
20
E_ν (MeV)
LMA
Model

The Model

CC spectrum (reduced rate):



Neutrino parameters $sin\theta_{14} = 0.04,\ \Delta m^2_{41} = 10^{-5} eV^2$.

The Model

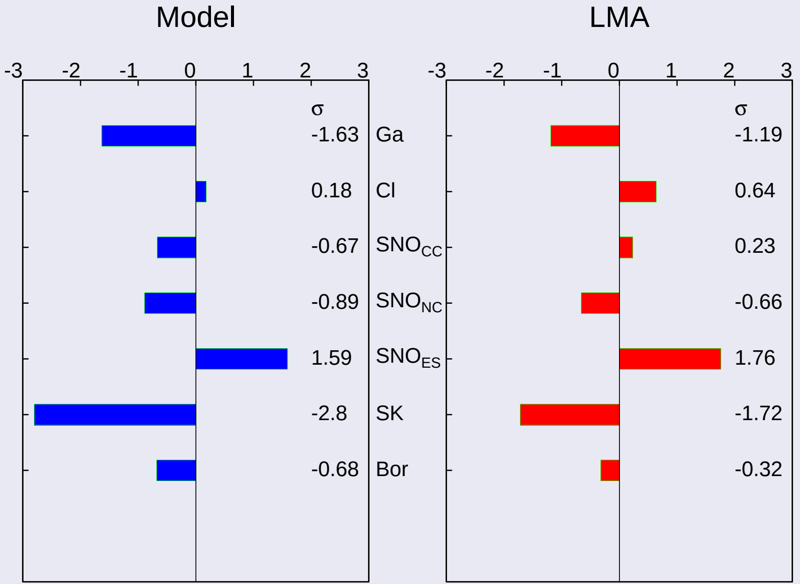
Other model predictions:

Rates

	$Ga(All, \leq Dec.2007)$ (SNU)	Cl (SNU)	$SNO(CC)$ $(\times 10^6\ cm^2 s^{-1})$	$SNO(NC)$ $(\times 10^6\ cm^2 s^{-1})$	$SNO(ES)$ $(\times 10^6\ cm^2 s^{-1})$	SK $(\times 10^6\ cm^2 s^{-1})$	$Borexino$ $(\times 10^6\ cm^2 s^{-1})$
Data	66.1 ± 3.1	2.56 ± 0.16 ± 0.15	1.67 $\pm^{0.05}_{0.04}$ $\pm^{0.07}_{0.08}$	5.54 $\pm^{0.33}_{0.31}$ $\pm^{0.36}_{0.34}$	1.77 $\pm^{0.24}_{0.21}$ $\pm^{0.09}_{0.10}$	2.32 ± 0.04 ± 0.05	2.40 ± 0.4 ± 0.1
LMA	62.4	2.70	1.69	5.22	2.21	2.21	2.27
Model	61.0	2.60	1.61	5.13	2.14	2.14	2.12

We use for SSM AGSS09ph (arXiv: 0910.3690).

The Model


Model
LMA
-3
-2
-1
0
1
2
3
σ
-1.63
Ga
-1.19
0.18
Cl
0.64
-0.67
SNO$_{CC}$
0.23
-0.89
SNO$_{NC}$
-0.66
1.59
SNO$_{ES}$
1.76
-2.8
SK
-1.72
-0.68
Bor
-0.32

Discussion

$$\chi^2_{rates}(LMA) = 8.1/5 \; d.o.f.$$

$$\chi^2_{rates}(model) = 16.0/5 \; d.o.f.$$

Two Caveats:

1. Contribution from Ga rate in χ^2 is extremely large: had we taken Ga/GNO data from the period 1998/03 ($62.9 \pm 5.4 \pm 2.5$ SNU) the result would be:

$$\chi^2_{rates}(LMA) = 3.6/5 \; d.o.f.$$

$$\chi^2_{rates}(model) = 9.4/5 \; d.o.f.$$

So χ^2_{rates} strongly depends on the Ga data period one considers.

Discussion

2. Moreover Ga rate has been decreasing all along the period of data taking:

GallexI	$\leq$ *June* 1992	83 ± 19
GallexII	*Aug*′92 $\rightarrow$ *Jun*′94	76 ± 10
GallexIII	*Oct*′94 $\rightarrow$ *Oct*′95	54 ± 11

	1991 – 97	1998 – 03
Gallex/GNO	$77.5 \pm 6.2 \pm^{4.3}_{4.7}$	$62.9 \pm 5.4 \pm 2.5$
SAGE	$79.2 \pm 8.6 \pm^{4.3}_{4.7}$	63.9 ± 5.0

	2003	2004	2005	2006	2007
SAGE	60 ± 10	72.5 ± 12.5	53 ± 9	68 ± 10	58.5 ± 8.5

This is suggestive that Ga could preferably be removed from χ^2_{rates} calculation.

Discussion

If we do so:

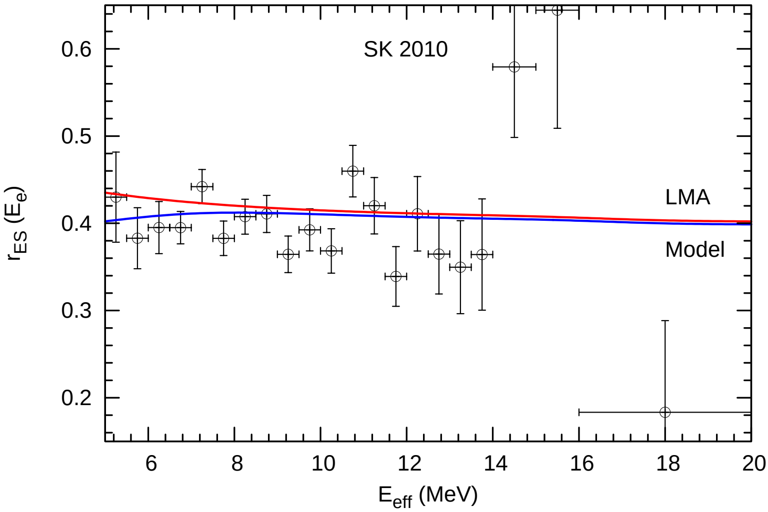
$$\Rightarrow \ \chi^2_{rates}(LMA) = 4.1/4 \ d.o.f. \ \ \text{(no Ga)}$$

$$\chi^2_{rates}(model) = 3.7/4 \ d.o.f. \ \ \text{(no Ga)}$$

which shows an improvement in the rates fitting (LMA$\rightarrow$ sterile ν model):

$$\chi^2_{rates}(model) < \chi^2_{rates}(LMA)$$

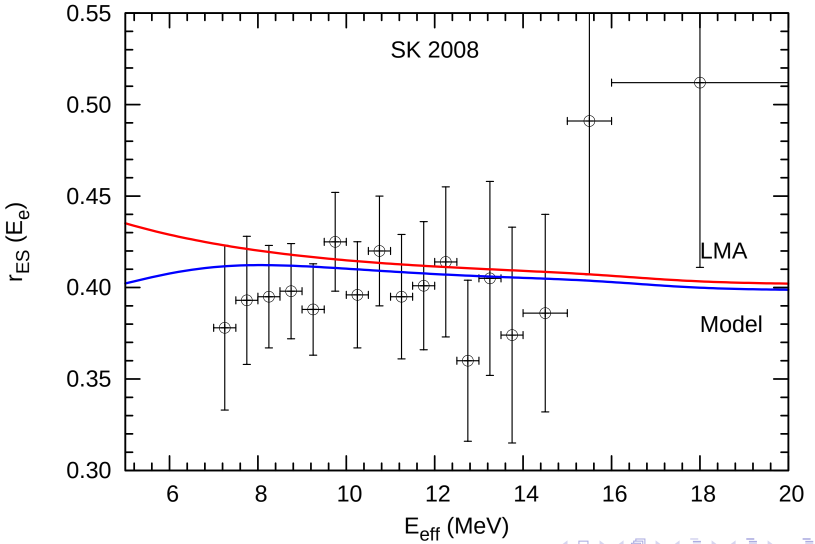
ES spectrum (reduced rate):



$\chi^2_{ES\ spectrum}(LMA) = 19.2/16 d.o.f.,\ \chi^2_{ES\ spectrum}(model) = 19.5/16 d.o.f.$

Discussion

If we resort to SK 2008 data the result seems more favourable:



Discussion

Recalling charged current (CC) reduced rate:

$$\chi^2_{CC\ spectrum}(LMA) = 24.3/13\ d.o.f.$$

$$\chi^2_{CC\ spectrum}(model) = 21.6/13\ d.o.f.$$

Conclusions

- We still need to fill the gap in our knowledge of the solar neutrino survival probability in the intermediate energy region (i.e. the vacuum matter transition).
- LMA prediction for CC spectrum seems to point in the wrong direction as T_{eff} decreases.
- LMA provides no clue as to why SK spectrum is flat.
- Oscillations to sterile $\nu's$ which are almost degenerate with the active ones ($\Delta m^2 = 10^{-5} eV^2, sin\theta_{14} = 0.04$) lead to a CC spectrum pointing in the right direction and explain the flatness of the SK spectrum.
- We would be in presence of a 5th or 6th sterile neutrino. This would add to the already confusing situation concerning the sterile neutrinos.
- However as an example, the story of neutrino oscillations reminds us that a confusing picture at the start may eventually emerge, after an accumulation of experimental tests for several years, as a clear and positive one.