First we investigate the possibility of detecting solar antineutrinos with the KamLAND experiment. Then we analyze the first Borexino data release to constrain the neutrino magnetic moment. Finally we investigate the resonant spin flavour conversion of solar neutrinos to sterile ones, a mechanism which is added to the well known LMA one. In this last condition, we show that the data from all solar neutrino experiments except Borexino exhibit a clear preference for a sizable magnetic field. We argue that the solar neutrino experiments are capable of tracing the possible modulation of the solar magnetic field. In this way Borexino alone may play an essential role although experimental redundancy from other experiments will be most important.

1 Introduction

Although the effort in solar neutrino investigation has decreased in recent years, several intriguing questions in this area remain open. Their clarification may lead to a better knowledge of the neutrino intrinsic properties, the structure of the inner solar magnetic field, or possibly both. After having determined that the solar neutrino problem is essentially a particle physics one and neutrinos oscillate, the next step is to search for a possible new sub-dominant effects in the active solar neutrino flux and to investigate its low energy sector \((E < 1 - 2 \, MeV)\) which accounts for more than 99% of the total flux. These two issues in association with each other may lead to further surprises in neutrino physics, possibly the hint of a sizable magnetic moment. In fact it is still unclear for example whether the active solar neutrino flux varies in time or why the SuperKamiokande energy spectrum appears to be flat.
2 Non standard neutrino interactions

2.1 KamLAND, solar antineutrinos and their magnetic moment

First we investigate the possibility to detect solar antineutrinos with the KamLAND experiment. These antineutrinos are, i.e., predicted by spin-flavor conversion of solar neutrinos. The recent evidence from SNO shows that a) the neutrino oscillates, only around 34% of the initial solar neutrinos arrive at the Earth as electron neutrinos and b) the conversion is mainly into active neutrinos, however a non $\mu - \tau$ component is allowed. The fraction of oscillation into non-$\mu$-$\tau$ neutrinos is found to be $\cos^2 \alpha = 0.08^{+0.20}_{-0.40}$. This residual flux could include sterile neutrinos and/or the antineutrinos of the active flavors. KamLAND is potentially sensitive to antineutrinos derived from solar $^8$B neutrinos. We report in fig. 1 the expected events at KamLAND compared with a solar antineutrino flux $10^{-2}$ times the solar neutrino flux.

KamLAND put strict limits on the flux of solar antineutrinos, $\Phi(^8B) < 1.0 \times 10^4 \text{ cm}^2 \text{s}^{-1}$, more than one order of magnitude smaller than existing limits, and on their appearance probability $P < 0.15\% \ (95\% \ CL)$ after 3 years of operation. Assuming a concrete model for antineutrino production by spin-flavor precession, this upper bound implies an upper limit on the product of the intrinsic neutrino magnetic moment and the value of the solar magnetic field $\mu_B < 10^{-21} \text{MeV} \ (95\% \ CL)$. For $B \sim 10 - 100 \text{ kG}$, we would have $\mu < 10^{-11} - 10^{-12} \mu_B \ (95\% \ CL)$.

2.2 Three neutrinos: Limit from Borexino $|\mu_\nu| < 0.84 \times 10^{-10} \mu_B$

Then we analyze the first Borexino data release to constrain the neutrino magnetic moment. The analysis is performed analyzing the spectrum of the recoil electron energy. Since the leading contribution to this spectrum comes from the monoenergetic solar $^7$Be neutrinos, the shape of the spectrum is almost independent from the energy dependence of the oscillation probability. The other contribution to the spectral shape is due to the internal background of the detector. The obtained limits are better than the one obtained for SK-I global analysis $|\mu_\nu| < 3.6 \times 10^{-10} \mu_B$, and the combined analysis of the Kamiokande-Clorine experiments $|\mu_\nu| < 5.4 \times 10^{-10} \mu_B$. It is comparable with the combined analysis from other solar neutrino experiments, $|\mu_\nu| < 1.5 \times 10^{-10} \mu_B$ at 90% CL (SSM-GS98), and with the Super Kamiokande total rate analysis, $|\mu_\nu| < 2.1 \times 10^{-10} \mu_B$ at 90% CL (SSM-AGS05). It is competitive with respect to the direct limits from reactors (i.e. $|\mu_\nu| < 1.0 \times 10^{-10} \mu_B$ at 90% CL in MuNu, $|\mu_\nu| < 0.58 \times 10^{-10} \mu_B$ at 90% CL in GEMMA experiment). Moreover our result is independent on the solar standard model. For the single transition magnetic moment we get $|\mu_{\nu_e}| < 1.5 \times 10^{-10} \mu_B$ (to be compared with the PDG value $< 6.8 \times 10^{-10} \mu_B$), and $|\mu_{\nu_x}| < 1.9 \times 10^{-10} \mu_B$ (PDG quote $< 3900 \times 10^{-10} \mu_B$).
3 Light sterile neutrinos and spin flavor precession

As far as the solar magnetic field is concerned, solar physics provides very limited knowledge on its magnitude and shape. Given the above mentioned uncertainties we consider the two following plausible profiles which are approximately complementary to each other (see fig. 2)

Profile 1

\[
B = \frac{B_0}{\cosh[6(x - 0.71)]} \quad 0 < x < 0.71, \quad B = \frac{B_0}{\cosh[15(x - 0.71)]} \quad 0.71 < x < 1
\]

(1)

Profile 2

\[
B = \frac{B_0}{1 + \exp[10(2x - 1)]} \quad 0 < x < 1,
\]

(2)

![Figure 2: The two solar field profiles normalized to their peak field values as a function of the solar radius.](image)

Profile 1 has a peak \(B_0\) at the bottom of the convection zone, for fractional solar radius \(x \simeq 0.71\), its physical motivation being the large gradient of angular velocity over this range. It should not exceed 300 kG at this depth and 20 kG at 4-5% depth, hence its fast decrease along the convection zone. Profile 2 is of the Wood-Saxon type, being maximal at the solar centre. In this case the peak field \(B_0\) could be as large as a few MG.

The number of events in a bin with energy range \([T_{e\text{in}}, T_{e\text{fin}}]\) is

\[
N_{T_{e\text{in}}, T_{e\text{fin}}}^{T_e} = \sum_{\phi = \nu} \int_{E_e = E_{e\text{min}}}^{E_{e\text{max}}} dE_e \Phi_e(E_e) \int_{E_\nu = E_{\nu\text{min}}}^{E_{\nu\text{max}}} dE_\nu \Phi_\nu(E_\nu) \left\{ P(E_\nu \rightarrow E_e, \nu_e, \nu_x, \Phi_\phi) \frac{d\sigma^{e\nu \rightarrow e\nu}}{dE_e} \right\}
\]

(3)

where \(Q_0\) take into account the size of the detector, \(N_{\Phi,\phi}\) is the normalization of the neutrino flux \(\phi\), \(E_\nu\) is the neutrino energy, \(E_e\) is the electron energy, \(\Phi_\phi\) is the neutrino spectrum of the flux \(\phi\), \(R\) is the resolution function of the detector and depend on the observed electron energy range and the detector properties \(\rho\), \(P(E_\nu)\) is the conversion/survival probability, and \(d\sigma\) is the differential neutrino-electron cross section. For the statistical analysis of all solar data (except Borexino) we used the standard \(\chi^2\) definition

\[
\chi^2 = \sum_{ij} (R_j - R_{j\text{exp}})(\frac{1}{\sigma^2})_{ij}(R_i - R_{i\text{exp}})
\]

(4)

where indices \(i,j\) run over solar neutrino experiments and the error matrix includes the cross section, the astrophysical and the experimental uncertainties.
### 3.1 Two gallium data sets, spin flavour precession and KamLAND

Although a lot of effort has been devoted to examining the possible time modulation of the neutrino flux, this question remains largely unsettled. The claim made in the early days of a possible anticorrelation of the Homestake event rate with sunspot activity remained unproven, as no sufficient evidence was found in its support. More recently the Stanford Group has been claiming the existence of two peaks in the Gallium data at 55-70 SNU and 105-115 SNU. Moreover, Gallium experiments, which have been running since 1990-91 and whose event rates are mainly due to $pp$ and $^7$Be neutinos (55% and 25% respectively), also seem to show a flux decrease from their start until 2003. These data are hardly consistent with a constant value and exhibit a discrepancy of 2.4σ between the averages of the 1991-97 and 1998-03 periods (see Table I). No other experiment sees such variations and none is sensitive to low energy neutrinos with the exception of Homestake whose rate contains only 14% of $^7$Be. Hence this fact opens the possibility that low energy neutrinos may undergo a time modulation partially hidden in the Gallium data which may be directly connected in some non obvious way to solar activity. Hence also the prime importance of the low energy sector investigation. To this end, in the near future, two experiments, Borexino and KamLAND, will be monitoring the $^7$Be neutrinos.

<table>
<thead>
<tr>
<th>Period</th>
<th>1991-97 (I)</th>
<th>1998-03 (II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAGE+Ga/GNO</td>
<td>77.8 ± 5.0</td>
<td>63.3 ± 3.6</td>
</tr>
<tr>
<td>Ga/GNO only</td>
<td>77.5 ± 7.7</td>
<td>62.9 ± 6.0</td>
</tr>
<tr>
<td>SAGE only</td>
<td>79.2 ± 8.6</td>
<td>63.9 ± 5.0</td>
</tr>
</tbody>
</table>

Table 2: Best fits to data sets , and LMA best fit. For data set 91-97 only Ga, Cl and Kamiokande data were available and for set 98-03 all SK and SNO data were available but not Cl. In set 98-03 only the Ga rate contributes to $\chi^2_{rates}$. Units are SNU for Ga and Cl and $10^6$ cm$^{-2}$s$^{-1}$ for SK and SNO. Here $\Delta m^2_{01} = 0.65 \times 10^{-7}$eV$^2$.

<table>
<thead>
<tr>
<th></th>
<th>Ga</th>
<th>Cl</th>
<th>K (SK)</th>
<th>SNO NC</th>
<th>SNO CC</th>
<th>SNO CC SNO ES</th>
<th>$\chi^2_{rates}$</th>
<th>$\chi^2_{SNO NC}$</th>
<th>$\chi^2_{SNO CC}$</th>
<th>$\chi^2_{3K}$</th>
<th>$\chi^2_{KL}$</th>
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<tr>
<td>Set (I)</td>
<td>71.7</td>
<td>2.66</td>
<td>2.29</td>
<td>3.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set (II)</td>
<td>69.6</td>
<td>2.18</td>
<td>5.53</td>
<td>1.54</td>
<td>2.16</td>
<td>2.28</td>
<td>44.6</td>
<td>45.8</td>
<td>43.1</td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>LMA</td>
<td>64.8</td>
<td>2.74</td>
<td>3.03</td>
<td>5.10</td>
<td>1.75</td>
<td>2.28</td>
<td>0.95</td>
<td>45.7</td>
<td>43.1</td>
<td>14.5</td>
<td></td>
</tr>
</tbody>
</table>
3.2 SNO+: predictions from SSM and resonant spin flavour precession

One of the key questions that the SNO+ experiment will be able to address is the distinction between the two classes of SSMs which are currently identified as corresponding to a high and a low heavy element abundance. SNO+ will be able to accurately measure the pep and CNO fluxes. The former, largely independent of solar models, will supply the survival probability at low energies, essential to distinguish standard LMA from LMA+RSFP. Consequently SNO+ will be able to severely constrain the RSFP interpretation, thus favoring LMA or vice-versa. We report in fig. 3 the expected rate reduction for the pep flux with respect to the non-oscillation case, as a function of the peak value $B_0$ of the solar magnetic field (profile 1) and $\Delta m^2_{01}$.

![Figure 3: The expected rate reduction for the pep flux with respect to the non-oscillation case.](image)

3.3 SuperKamiokande spectrum with light sterile neutrinos and spin flavour precession

Whereas the Landau Zener approximation works well in the LMA resonance, this is not so for spin flavour precession, thus we resort to the numerical integration of the evolution equations. We take several values of $\theta_{13}$ in the allowed range for both strong and weak solar fields. The model event rates for all solar neutrino experiments are evaluated and confronted with the data. Special emphasis is given to the SK energy spectrum and the recent $^8B$ energy spectrum from the Borexino experiment. We considered the two classes of solar field profiles.

Table 3: Peak field values (profile 1), $\sin \theta_{13}$, total rates (in SNU for Ga and Cl experiments, in $10^6 cm^{-2}s^{-1}$ for SK and SNO), and the corresponding $\chi^2$’s. It is seen that for a sizable field all fits improve with both profiles.

<table>
<thead>
<tr>
<th>$B_0$</th>
<th>$\sin \theta_{13}$</th>
<th>Ga</th>
<th>Cl</th>
<th>SK</th>
<th>SNO NC</th>
<th>SNO CC</th>
<th>SNO ES</th>
<th>$\chi^2_{\text{rates}}$</th>
<th>$\chi^2_{\text{SK},p}$</th>
<th>$\chi^2_{\text{SNO}}$</th>
<th>$\chi^2_{\text{gl}}$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>67.2</td>
<td>2.99</td>
<td>2.51</td>
<td>5.62</td>
<td>1.90</td>
<td>2.49</td>
<td>0.07</td>
<td>42.7</td>
<td>57.2</td>
<td>99.9</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>66.0</td>
<td>2.94</td>
<td>2.49</td>
<td>5.62</td>
<td>1.87</td>
<td>2.46</td>
<td>0.30</td>
<td>42.1</td>
<td>55.2</td>
<td>97.6</td>
</tr>
<tr>
<td></td>
<td>0.13</td>
<td>65.0</td>
<td>2.90</td>
<td>2.46</td>
<td>5.62</td>
<td>1.84</td>
<td>2.44</td>
<td>0.62</td>
<td>41.7</td>
<td>53.7</td>
<td>96.0</td>
</tr>
<tr>
<td>Profile 1</td>
<td>0</td>
<td>66.4</td>
<td>2.82</td>
<td>2.32</td>
<td>5.37</td>
<td>1.76</td>
<td>2.31</td>
<td>0.20</td>
<td>37.6</td>
<td>46.0</td>
<td>83.8</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>65.3</td>
<td>2.77</td>
<td>2.29</td>
<td>5.37</td>
<td>1.73</td>
<td>2.28</td>
<td>0.53</td>
<td>37.9</td>
<td>44.9</td>
<td>83.3</td>
</tr>
<tr>
<td></td>
<td>0.13</td>
<td>64.3</td>
<td>2.72</td>
<td>2.27</td>
<td>5.37</td>
<td>1.70</td>
<td>2.25</td>
<td>0.95</td>
<td>38.4</td>
<td>44.1</td>
<td>83.4</td>
</tr>
<tr>
<td>Profile 2</td>
<td>0</td>
<td>64.7</td>
<td>2.75</td>
<td>2.32</td>
<td>5.38</td>
<td>1.76</td>
<td>2.32</td>
<td>0.76</td>
<td>38.0</td>
<td>46.1</td>
<td>84.8</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>63.6</td>
<td>2.70</td>
<td>2.30</td>
<td>5.38</td>
<td>1.73</td>
<td>2.29</td>
<td>1.32</td>
<td>38.4</td>
<td>45.0</td>
<td>84.7</td>
</tr>
<tr>
<td></td>
<td>0.13</td>
<td>62.6</td>
<td>2.66</td>
<td>2.28</td>
<td>5.38</td>
<td>1.70</td>
<td>2.26</td>
<td>1.92</td>
<td>38.8</td>
<td>44.2</td>
<td>84.9</td>
</tr>
</tbody>
</table>

Our numerical calculations are based on the updated central values for the best fit in the LMA scenario for $\Delta m^2_{21}$, $\theta_{12}$, $\theta_{23}$, $\Delta m^2_{32}$ and we use a neutrino transition moment between flavour states not larger than $\mu_{\nu} = 1.4 \times 10^{-12} \mu_B$. As for $\theta_{13}$ we chose to investigate three cases:
\( \theta_{13} = 0, 0.1 \) and the central value, 0.13. The fits to all data, including rates and spectra (except for Borexino) improve once the magnetic field is introduced. As regards Borexino, the fit worsens in this case. In contrast, solar data alone show no clear preference for a vanishing or sizable \( \theta_{13} \).

4 Conclusions

We studied several scenarios where non standard interactions, and in particular the neutrino magnetic moment, as a mechanism which is added to the well known LMA one, can play a relevant role in the solar neutrino physics. The most promising one is when, in a 4 \( \nu \) scenario, the transition magnetic moments from the \( \nu_\mu \) and \( \nu_\tau \) to \( \nu_s \) play the dominant role in fixing the amount of active flavor suppression via the Resonant Spin Flavor Precession of Solar neutrinos to light sterile neutrino. The data from all solar neutrino experiments except Borexino exhibit a clear preference for a sizable magnetic field either in the convection zone or in the core and radiation zone. We argue that the solar neutrino experiments are capable of tracing the possible modulation of the solar magnetic field. Those monitoring the high energy neutrinos, namely the \( ^8B \) flux, appear to be sensitive to a field modulation in the convection zone. Those monitoring the low energy fluxes will be sensitive to the second type of solar field profiles only. In this way Borexino alone may play an essential role, since it examines both energy sectors, although experimental redundancy from other experiments will be most important.

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References