Solar Neutrinos: Spin Flavour Precession and LMA

João Pulido*, Bhag C. Chauhan†
CENTRO DE FÍSICA TEÓRICA DAS PARTICULAS (CFTP)
Departamento de Física, Instituto Superior Técnico
Av. Rovisco Pais, P-1049-001 Lisboa, Portugal

and

R. S. Raghavan‡
Department of Physics
Virginia Polytechnic Institute and State University (Virginia Tech)
Blacksburg VA 24060 USA

Abstract

The time dependence that appears to be hinted by the data from the first 13 years of the solar neutrino Gallium experiments is viewed as resulting from a partial conversion of active neutrinos to light sterile ones through the resonant interaction between the magnetic moment of the neutrino and a varying solar field. A summary of the model and its predictions are presented for the forthcoming experiments Borexino and LENS.

†On leave from Govt. Degree College, Karsog (H P) India 171304. E-mail: chauhan@cftp.ist.utl.pt
‡E-mail: raghavan@vt.edu
1. After LMA has been ascertained as the dominant solution to the solar neutrino problem, the next step in solar neutrino experiments will be the search for time variations of the active flux. Such an effect remains much of an open question because so far most analyses have relied on time averaged solar neutrino data. Moreover, its investigation is of extreme importance because it may reveal the existence of electromagnetic properties of neutrinos and provide a significant addition to our understanding of solar dynamics.

Although the idea of a sizeable neutrino magnetic moment interacting with the solar field [1] lay dormant for some time, it was reintroduced in 1986 [2] to explain the claimed periodicity of the Chlorine event rate, but the effect remains inconclusive. In summary it works as follows: active neutrinos can be converted to sterile ones owing to the interaction of $\mu_\nu$ with $B_\odot$. At times of intense solar activity

$$Strong \ B_\odot \rightarrow large \ \mu_\nu B_\odot \rightarrow large \ conversion$$

(1)

with little or no conversion otherwise. Hence a neutrino flux anticorrelated to solar activity.

| Period          | 1991-97 | 1998-03 |
|-----------------|---------|---------|
| SAGE & Ga-GNO   | 77.8 ± 5.0 | 63.3 ± 3.6 |
| Ga-GNO only     | 77.5 ± 7.7 | 62.9 ± 6.0 |
| no. of sunspots | 52      | 100     |

Table I - Event rates in solar neutrino units for Ga experiments in two different periods of solar activity and number of sunspots in the same periods.

In table I the neutrino event rate in Gallium experiments (SAGE and Gallex-GNO [3]) is shown as a function of time with the number of sunspots in the same period. It is seen from this table that there is a 2.4$\sigma$ discrepancy in the combined results over the two periods. Since the sunspot number is correlated to solar activity, this is suggestive of an anticorrelation of the Ga event rate with the 11-year solar cycle. No other experiments show such a variational effect, therefore since Ga are the only ones with a significant contribution of $pp$, $^7Be$ neutrinos ($\sim 80\%$), the time dependence of these fluxes becomes an open possibility.

2. The bottom of the solar convective zone is a region where, owing to the relatively strong rotation gradient, the solar field is expected to have a maximum which can be as high as 300 kG and may be connected to the magnetic surface activity. The typical density profile of the sun requires the mass square difference associated to resonant conversion from active to nonactive neutrinos to be of the order of $10^{-8} eV^2$ [4],[5]. This excludes the solar and atmospheric mass square differences, $\Delta m_{21}^2$ and $\Delta m_{32}^2$, and therefore conversion to $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$. Since only three neutrino families are known to exist, we must introduce sterile neutrinos.
We consider the simplest possible assumption whereby they mix with active ones through the magnetic moment only, so that in the vacuum

\[
\begin{pmatrix}
\nu_s \\
\nu_e \\
\nu_x
\end{pmatrix} = 
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_\theta & s_\theta \\
0 & -s_\theta & c_\theta
\end{pmatrix}
\begin{pmatrix}
\nu_0 \\
\nu_1 \\
\nu_2
\end{pmatrix}
\]  
(2)

while in matter with a magnetic field

\[
\mathcal{H}_M = 
\begin{pmatrix}
-\frac{\Delta m_{10}^2}{2E} & \mu_\nu B & 0 \\
\mu_\nu B & \frac{\Delta m_{21}^2}{2E} s_\theta^2 + V_e & \Delta m_{21}^2 s_\theta \\
0 & \frac{\Delta m_{21}^2}{4E} c_\theta + V_x & \frac{\Delta m_{21}^2}{4E} c_\theta^2 + V_x
\end{pmatrix}
\]  
(3)

with standard notation §. The 'new' mass square difference $\Delta m_{10}^2 = m_1^2 - m_0^2$ fixes the location of the active $\rightarrow$ sterile transition for each neutrino energy.

![Figure 1: The evolution of the mass matter eigenvalues along the solar neutrino trajectory.](image-url)

For typical parameter values (peak field $B_0 = 2.2 \times 10^5 G$, $\Delta m_{10}^2 = -6.0 \times 10^{-9} eV^2$, $E = 0.33 MeV$) the eigenvalue evolution within the sun is shown in fig.1. All pp neutrinos resonate around the bottom of the convective zone in this case. It is seen that the strongly

§For details see ref. [4].
adiabatic LMA transition, whose location is determined for each energy by $\Delta m_{21}^2$, takes place in the solar core. The active $\rightarrow$ sterile transition, whose adiabaticity depends on the magnetic field strength and its extension, takes place around the upper radiative/lower convective zone (i.e. the tachocline). The large order of magnitude difference between $\Delta m_{21}^2 (7 - 8 \times 10^{-5} eV^2)$ and $\Delta m_{10}^2 (6 \times 10^{-9} eV^2)$ ensures the two resonances to be located far apart so they do not interfere. In fig.1 the vanishing field case is denoted by the two dotted lines crossing at the place where $\lambda_1$ and $\lambda_0$ nearly meet (critical density).

The two field profiles chosen are peaked at the bottom of the convective zone and can be seen in fig.1 of ref.[5]. If these are time dependent (possibly connected to solar activity), the effect provides a modulation of the pp neutrino flux mainly. For larger $\Delta m_{10}^2 (eV^2)$ ($= -1.0 \times 10^{-8} eV^2$) the spin flavour precession resonance moves in the direction of the solar surface and both pp and $^7Be$ fluxes become modulated ($pp + ^7Be$ modulation).

3. Our knowledge of the solar neutrino spectrum is very limited. $^8B$, the best well known flux, accounts for just $10^{-4}$ of the total, while pp and $^7Be$ accounting for more than 98%, have only been observed in the radiochemical Ga experiments in accumulation with all other fluxes. In view of a hint from Ga experiments that low energy fluxes might be time dependent, we need real time dedicated low energy experiments to ascertain this possibility. We next consider the predictions for two of the forthcoming ones: Borexino and LENS [4].

(I) Borexino

This is a liquid scintillator detector installed in Gran Sasso Laboratory using $\nu e^-$ scattering, aiming at starting physics in late 2006. The kinetic energy threshold of 250 keV and maximum of 664 keV ensures that this experiment is directed mainly at $^7Be$ neutrino flux ($E_{Be} = 0.86 MeV$). The reduced rate for Borexino is, in standard notation

$$R_{Bor} = \frac{\int_{T_{min}}^{T_{max}} dT \int_{E_{min}}^{E_{max}} dE \phi(E) [P_{ee}(E) \frac{d\sigma_{ee}}{dT} + (1 - P_{ee}(E)) \frac{d\sigma_{\nu\mu}}{dT}] [P_{ee}(E) \frac{d\sigma_{ee}}{dT} + (1 - P_{ee}(E)) \frac{d\sigma_{\nu\mu}}{dT}]}{\int_{T_{min}}^{T_{max}} dT \int_{E_{min}}^{E_{max}} dE \phi(E) \frac{d\sigma_{ee}}{dT}}$$

and is shown in fig.2 as a function of the peak field $B_0$. It is seen that in the $pp + ^7Be$ dominated modulation the rate decreases faster for increasing $B_0$, thus exhibiting more sensitivity to solar activity than in the $pp$ case: the more sensitive $^7Be$ flux is to the peak field, the more sensitive will the event rate be. As the Borexino collaboration expects a combined error (statistical+systematic) of 10% and 5% after 1 and 3 years run, both scenarios can be perceptible after 1 year.
(II) LENS (Low Energy Neutrino Spectroscopy)

LENS is a real time detector in late stages of development measuring solar neutrinos through the charged current reaction

\[ \nu_e + ^{115}I \rightarrow ^{115}Sn + e^- \] (5)

with the lowest threshold yet: Q=114 keV. The signal energy is directly and uniquely related to the neutrino energy, hence a resolved spectrum of all low energy components (pp, $^7$Be, pep, CNO) can be obtained that qualitatively shows how the sun shines. The LENS event rate is

\[ R_{\text{LENS}}(E_e) = \int_{Q}^{E_{\text{max}}} P_{ee}(E)f(E'_e, E_e)\phi(E)dE \] (6)

where $E'_e$ is the physical electron energy, $E'_e = E - Q$. For pp + $^7$Be modulation ($\Delta m^2_{10} = -1.0 \times 10^{-8} \text{ eV}^2$) $R_{\text{LENS}}(E_e)$ is shown in fig.3.

4. To conclude: low energy solar neutrino experiments should at present be regarded as a major objective in the solar neutrino program, as time modulation is hinted by the Gallium experiments. Running Borexino and LENS during a significant fraction of a solar cycle will

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Figure 2: Reduced Borexino event rate as a function of the peak field value.
Figure 3: *LENS rate for pp+^7Be modulation and a peak field 250 kG for the lower line.*

certainly test the possible modulation effect in the low energy sector, thus providing evidence for $\mu_\nu$ and new physics.

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