NSI can improve LMA predictions: neutrino decay in solar matter?

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Introduction

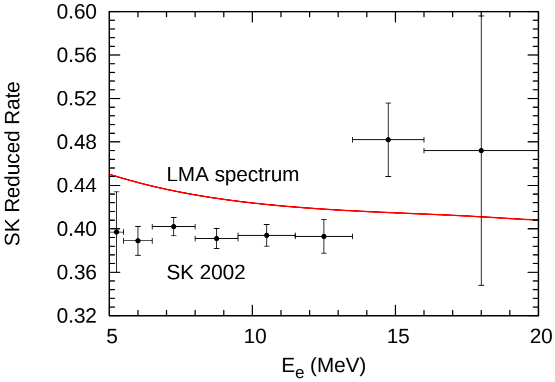
Although apparently dormant in the past two years, solar neutrinos is by no means a closed subject. In fact:

1. The low energy sector is still poorly known.
2. The widely accepted solution for the $\odot\ \nu$ problem, LMA, is likely not to be the ultimate solution because of the discrepancy

R_{Cl}=2.9 - 3.1 SNU (LMA prediction)
R_{Cl}=2.56 $\pm$ 0.21 SNU (experimental)

Introduction

More important, may be the discrepancy



The LMA prediction for SuperKamiokande spectrum shows a negative slope against the energy whereas the data appear to be flat (the same for more recent data).

Introduction

Our purpose: look for the possibility of these discrepancies, in particular the second, to be a messenger from NSI.

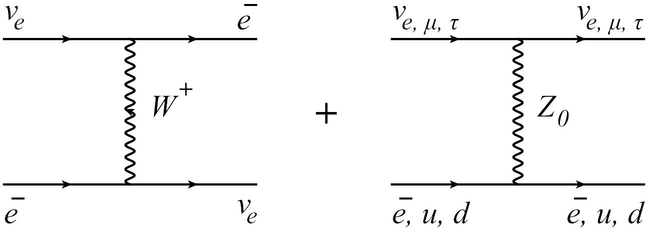
1. We will introduce NSI as extra contributions to the vertices ν_α, ν_β and $\nu_\alpha e$. Recall

$$\mathcal{L} = -2\sqrt{2} G_F \varepsilon^{f\ P}_{\alpha\beta} [\bar{f} \gamma^\mu P f][\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta]$$

2. The NSI parameters $\varepsilon^{f\ P}_{\alpha\beta}$ quantify the deviation from the standard model, $\varepsilon \simeq \Lambda^2_{EW}/\Lambda^2_{NP} \simeq 10^{-2}$ or $\varepsilon \simeq \Lambda^4_{EW}/\Lambda^4_{NP} \simeq 10^{-4}$ (taken as energy independent).
3. NSI vertices are treated like the standard interactions.

The Hamiltonian

In the standard case



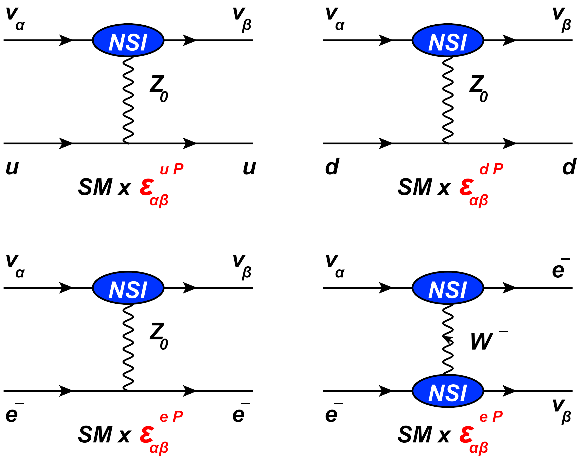
Contribution from all four diagrams $\rightarrow$ interaction potential

$$V(SI) = V_c + V_n = G_F\sqrt{2}N_e\left(1 - \frac{N_n}{2N_e}\right)$$

where $V_c = (V_e)_{CC} = G_F\sqrt{2}N_e$ (CC contribution from electrons),
$V_n = -(G_F/\sqrt{2})N_n$ (contribution from neutrons, NC only).

The Hamiltonian

In the non-standard case we will consider instead



The Hamiltonian

with the result

$$\begin{aligned} V(NSI) &= G_F\sqrt{2}N_e \Bigg[(\varepsilon^{eP}_{\alpha\beta})_{CC} + \left(-\frac{1}{2} + 2sin^2\theta_W\right)(\varepsilon^{eP}_{\alpha\beta})_{NC} \\ &+ \left(1 - \frac{8}{3}sin^2\theta_W + \frac{N_n}{2N_e}\right)\varepsilon^{uP}_{\alpha\beta} \\ &+ \left(-\frac{1}{2} + \frac{2}{3}sin^2\theta_W - \frac{N_n}{N_e}\right)\varepsilon^{dP}_{\alpha\beta}\Bigg] \end{aligned}$$

The full interaction potential is

$$V = V(SI) + V(NSI)$$

and the matter Hamiltonian

$$\mathcal{H}_M = G_F\sqrt{2}N_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} v_{ee}(NSI) & v_{e\mu}(NSI) & v_{e\tau}(NSI) \\ v_{\mu e}(NSI) & v_{\mu\mu}(NSI) & v_{\mu\tau}(NSI) \\ v_{\tau e}(NSI) & v_{\tau\mu}(NSI) & v_{\tau\tau}(NSI) \end{pmatrix}$$

$v_{\alpha\beta}$ (e, μ, τ) are the matrix elements of matrix $V(NSI)$

Detection rates (SK and SNO)

Allow of course for the possibility of $\nu_\alpha\, e^- \to \nu_\beta\, e^-$ scattering. The NSI information comes in the probabilities and the cross section

$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[\tilde{g}_L^2 + \tilde{g}_R^2\left(1-\frac{T}{E_\nu}\right)^2 - \tilde{g}_L\tilde{g}_R\frac{m_e T}{E_\nu^2}\right]$$

where $\tilde{g}_{L,R}$ are the modified $g_{L,R}$ couplings

$$\begin{aligned}
(\tilde{g}_{L,R})^2_{\nu_e} &= \left|(g_{L,R})^2_{\nu_e} + \varepsilon^{e\ L,R}_{ee}\right| + \sum_{\alpha\neq e}\left|\varepsilon^{e\ L,R}_{\alpha e}\right| && \text{for} \quad \nu_e\, e^- \to \nu_\alpha\, e^- \\
(\tilde{g}_{L,R})^2_{\nu_\mu} &= \left|(g_{L,R})^2_{\nu_\mu} + \varepsilon^{e\ L,R}_{\mu\mu}\right| + \sum_{\alpha\neq \mu}\left|\varepsilon^{e\ L,R}_{\alpha \mu}\right| && \text{for} \quad \nu_\mu\, e^- \to \nu_\alpha\, e^- \\
(\tilde{g}_{L,R})^2_{\nu_\tau} &= \left|(g_{L,R})^2_{\nu_\tau} + \varepsilon^{e\ L,R}_{\tau\tau}\right| + \sum_{\alpha\neq \tau}\left|\varepsilon^{e\ L,R}_{\alpha \tau}\right| && \text{for} \quad \nu_\tau\, e^- \to \nu_\alpha\, e^-
\end{aligned}$$

with $\alpha = e, \mu, \tau$.

Detection rates (SK and SNO)

Spectral event rate

$$R^{th}_{SK,SNO}(E_e) = \frac{\int_{m_e}^{E'_{e\,max}} dE'_e f(E'_e, E_e) \int_{E_m}^{E_M} dE\,\phi(E) \left[P_{ee}(E) \frac{d\sigma_e}{dT'} + P_{e\mu}(E) \frac{d\sigma_\mu}{dT'} + P_{e\tau}(E) \frac{d\sigma_\tau}{dT'} \right]}{\int_{m_e}^{E'_{e\,max}} dE'_e f(E'_e, E_e) \int_{E_m}^{E_M} dE\,\phi(E) \frac{d\sigma_e}{dT'}}$$

The contribution from NSI in the detection appears to be in practice numerically negligible.

NSI couplings (ε) and numerical results

Our aims:

- Increase flatness of SK spectrum
- Improve Cl rate prediction
- Keep the quality of other rate predictions

Recall that each NSI Hamiltonian entry $v_{\alpha\beta}$ is a combination of parameters $\varepsilon_{\alpha\beta}^{e,u,d}$ of the form

$$v_{\alpha\beta} = (\varepsilon_{\alpha\beta}^{e})_{CC} + A(\varepsilon_{\alpha\beta}^{e})_{NC} + B\varepsilon_{\alpha\beta}^{u} + C\varepsilon_{\alpha\beta}^{d}$$

with $A,\ B,\ C$ as given before (they are functions of $\theta_W,\ N_e,\ N_n$).

We organize the ε's ($\varepsilon_{\alpha\beta}^{e,u,d} = |\varepsilon_{\alpha\beta}^{e,u,d}|e^{i\phi_{\alpha\beta}^{e,u,d}}$) in three matrices according to whether the charged fermion in the external line is $e,\ u,\ d$:

$$\begin{pmatrix} \varepsilon_{ee}^{e,u,d\ P} & \varepsilon_{e\mu}^{e,u,d\ P} & \varepsilon_{e\tau}^{e,u,d\ P} \\ \varepsilon_{e\mu}^{*e,u,d\ P} & \varepsilon_{\mu\mu}^{e,u,d\ P} & \varepsilon_{\mu\tau}^{e,u,d\ P} \\ \varepsilon_{e\tau}^{*e,u,d\ P} & \varepsilon_{\mu\tau}^{*e,u,d\ P} & \varepsilon_{\tau\tau}^{e,u,d\ P} \end{pmatrix}.$$

and analyse one coupling at a time (taking all others zero).

NSI couplings (ε) and numerical results

For simplicity we consider first the purely real and purely imaginary couplings:

$$\phi^{e,u,d}_{\alpha\beta} = 0, \pi/2, \pi, (3/2)\pi$$

and investigate the range $|\varepsilon_{\alpha\beta}| \,\epsilon\, [5 \times 10^{-5}\,,\ 5 \times 10^{-2}]$.

We find

- Off diagonal entries $\varepsilon^{e,u,d\ P}_{\alpha\beta}$ $(\alpha \neq \beta)$ (3×3×4=36 possibilities) do not induce any change in the LMA probability, nor any visible change in the rates, even if one or more at a time are inserted.
- Diagonal entries $\varepsilon^{e,u,d\ P}_{\alpha\alpha}$
  - (a) Real couplings $\varepsilon^{e,u,d\ P}_{\alpha\alpha} = \pm|\varepsilon^{e,u,d\ P}_{\alpha\alpha}|$ (3×3×2=18 possibilities) do not change the LMA probability, nor the rates.
  - (b) Imaginary couplings $\varepsilon^{e,u,d\ P}_{\alpha\alpha} = \pm i|\varepsilon^{e,u,d\ P}_{\alpha\alpha}|$ do change P_{LMA} for all $|\varepsilon_{\alpha\alpha}| > 5 \times 10^{-5}$.

NSI couplings (ε) and numerical results

Grouping the diagonal couplings in accordance to the modification induced in P_{LMA} (18 possibilities).

This analysis is for one coupling at a time.

	1	2	3
A	$+i\left\|\varepsilon_{ee}^{e\ P}\right\|$	$+i\left\|\varepsilon_{\mu\mu}^{e\ P}\right\|$	$-i\left\|\varepsilon_{ee}^{e\ P}\right\|$
B	$+i\left\|\varepsilon_{ee}^{u\ P}\right\|$	$+i\left\|\varepsilon_{\mu\mu}^{u\ P}\right\|$	$-i\left\|\varepsilon_{ee}^{u\ P}\right\|$
C	$-i\left\|\varepsilon_{ee}^{d\ P}\right\|$	$-i\left\|\varepsilon_{\mu\mu}^{d\ P}\right\|$	$+i\left\|\varepsilon_{ee}^{d\ P}\right\|$
D	$-i\left\|\varepsilon_{\mu\mu}^{e\ P}\right\|$	$-i\left\|\varepsilon_{\tau\tau}^{e\ P}\right\|$	$+i\left\|\varepsilon_{\tau\tau}^{e\ P}\right\|$
E	$-i\left\|\varepsilon_{\mu\mu}^{u\ P}\right\|$	$-i\left\|\varepsilon_{\tau\tau}^{u\ P}\right\|$	$+i\left\|\varepsilon_{\tau\tau}^{u\ P}\right\|$
F	$+i\left\|\varepsilon_{\mu\mu}^{d\ P}\right\|$	$+i\left\|\varepsilon_{\tau\tau}^{d\ P}\right\|$	$-i\left\|\varepsilon_{\tau\tau}^{d\ P}\right\|$

Red - Wrong change in $P_{LMA} \rightarrow$ fits worsen
Blue - Change in P_{LMA} in the right direction (improved flatness for high energies but P_{ee} too high at low energies $\rightarrow R_{Ga}$ too high)

NSI couplings (ε) and numerical results

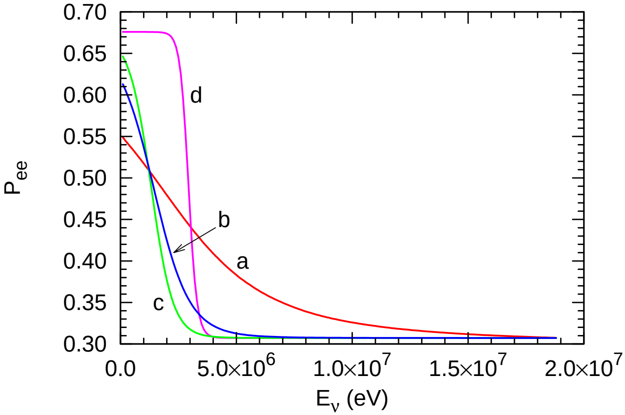
Green - 'Best' change in P_{LMA} with the preferred fit at either of the values

$$\begin{aligned}
\varepsilon_{\mu\mu}^{e\,P} &= -i|\varepsilon_{\mu\mu}^{e\,P}| = -i\;1.5\times10^{-3}\\
\varepsilon_{\mu\mu}^{u\,P} &= -i|\varepsilon_{\mu\mu}^{u\,P}| = -i\;2.5\times10^{-3}\\
\varepsilon_{\mu\mu}^{d\,P} &= +i|\varepsilon_{\mu\mu}^{d\,P}| = +i\;2.0\times10^{-3}
\end{aligned}$$

Comparison of ($-i|\varepsilon_{\mu\mu}^{e\,P}| = -i\;1.5\times10^{-3}$) fit with the LMA one

	Ga	Cl	SK	$\mathrm{SNO_{NC}}$	$\mathrm{SNO_{CC}}$	$\mathrm{SNO_{ES}}$	χ^2_{rates}	$\chi^2_{SK\,sp}$	χ^2_{SNO}	χ^2_{gl}
LMA	64.9	2.84	2.40	5.47	1.79	2.37	0.67	42.0	48.6	91.3
$-i\|\varepsilon_{\mu\mu}^{e\,P}\|$	69.7	2.74	2.23	5.47	1.68	2.26	0.11	40.3	45.0	85.4

NSI couplings (ε) and numerical results



(a) LMA, (b) $\varepsilon_{\mu\mu}^{e\,P} = -i\ 1.5 \times 10^{-3}$,
(c) $\varepsilon_{\mu\mu}^{e\,P} = -i\ 3 \times 10^{-3}$, (d) $\varepsilon_{\mu\mu}^{e\,P} = +i\ 5 \times 10^{-3}$.

NSI couplings (ε) and numerical results

Non-equal electron NSI couplings, $(\varepsilon^{eP}_{\alpha\beta})_{CC} \neq (\varepsilon^{eP}_{\alpha\beta})_{NC}$:

$$(\varepsilon^{e\,P}_{\mu\mu})_{CC} = -i(|\varepsilon^{e\,P}_{\mu\mu}|)_{CC} = -i\ 1.4 \times 10^{-3}$$

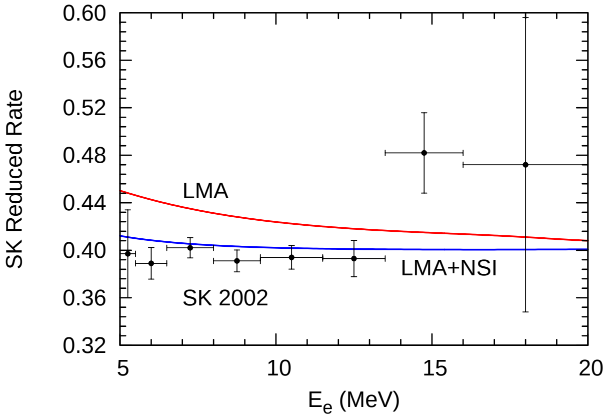
or alternatively

$$(\varepsilon^{e\,P}_{\mu\mu})_{NC} = +i(|\varepsilon^{e\,P}_{\mu\mu}|)_{NC} = +i\ 3.6 \times 10^{-2}.$$

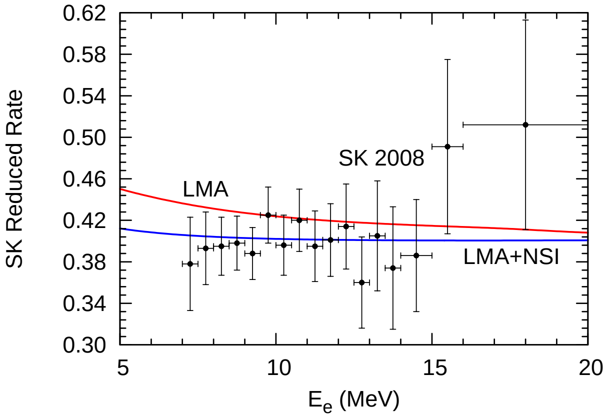
Notice: ratio of couplings $(\varepsilon^{eP}_{\alpha\beta})_{NC}/(\varepsilon^{eP}_{\alpha\beta})_{CC}$ is the inverse of the ratio of their respective coefficients in the Hamiltonian

$$\frac{\varepsilon_{NC}}{\varepsilon_{CC}} = \frac{1}{-1/2 + 2sin^2\theta_W}.$$

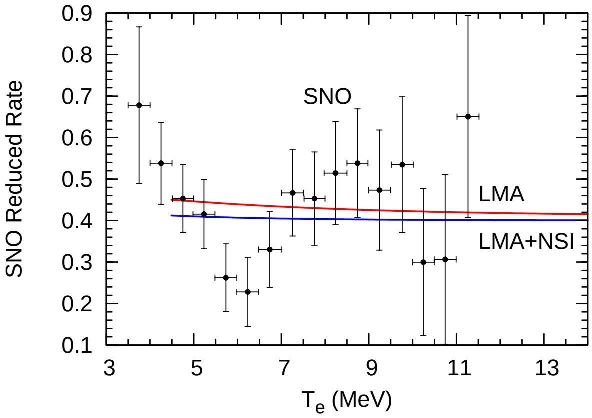
NSI couplings (ε) and numerical results



NSI couplings (ε) and numerical results



NSI couplings (ε) and numerical results



NSI couplings (ε) and numerical results

More than one diagonal coupling at a time different from zero is also possible for example, the following three

$$\begin{aligned} \varepsilon^{e\ P}_{\mu\mu} &= -i|\varepsilon^{e\ P}_{\mu\mu}| &= -i\ 0.7 \times 10^{-3} \\ \varepsilon^{u\ P}_{\mu\mu} &= -i|\varepsilon^{u\ P}_{\mu\mu}| &= -i\ 0.7 \times 10^{-3} \\ \varepsilon^{d\ P}_{\mu\mu} &= +i|\varepsilon^{d\ P}_{\mu\mu}| &= +i\ 0.7 \times 10^{-3} \end{aligned}$$

taken together with all others zero.

Alternatively or all nine diagonal ones

$$|\varepsilon^{e,u,d}_{ee}| \simeq |\varepsilon^{e,u,d}_{\mu\mu}| \simeq |\varepsilon^{e,u,d}_{\tau\tau}| = (2-4) \times 10^{-4}$$

with the choice of signs

$$\varepsilon^{e}_{ee} = +i|\varepsilon^{e}_{ee}|,\ \varepsilon^{u}_{ee} = +i|\varepsilon^{u}_{ee}|,\ \varepsilon^{d}_{ee} = -i|\varepsilon^{d}_{ee}|$$

$$\varepsilon^{e}_{\mu\mu} = -i|\varepsilon^{e}_{\mu\mu}|,\ \varepsilon^{u}_{\mu\mu} = -i|\varepsilon^{u}_{\mu\mu}|,\ \varepsilon^{d}_{\mu\mu} = +i|\varepsilon^{d}_{\mu\mu}|$$

and

$$\varepsilon^{e}_{\tau\tau} = +i|\varepsilon^{e}_{\tau\tau}|,\ \varepsilon^{u}_{\tau\tau} = +i|\varepsilon^{u}_{\tau\tau}|,\ \varepsilon^{d}_{\tau\tau} = -i|\varepsilon^{d}_{\tau\tau}|$$

NSI couplings (ε) and numerical results

Our proposed NSI Hamiltonian is therefore

$$\mathcal{H}_{\mathcal{NSI}} = G_F\sqrt{2}N_e \left[x_1 \begin{pmatrix} \frac{i}{2}\varepsilon & & \\ & -i\varepsilon & \\ & & \frac{i}{2}\varepsilon \end{pmatrix} + x_2 \begin{pmatrix} \frac{i}{2}\varepsilon & & \\ & -i\varepsilon & \\ & & \frac{i}{2}\varepsilon \end{pmatrix} + x_3 \begin{pmatrix} -\frac{i}{2}\varepsilon & & \\ & i\varepsilon & \\ & & -\frac{i}{2}\varepsilon \end{pmatrix} \right]$$

with $\varepsilon = 3.5 \times 10^{-4}$

Neutrino decay in solar matter?

We have found the following result:

Any possibility for solving the flatness problem of the LMA predicted spectrum for SK on the basis of NSI requires imaginary diagonal couplings of the Hamiltonian. At the same time the Cl fit is improved and all other fits are preserved.

This implies that neutrino decay is involved in its matter propagation through the sun.

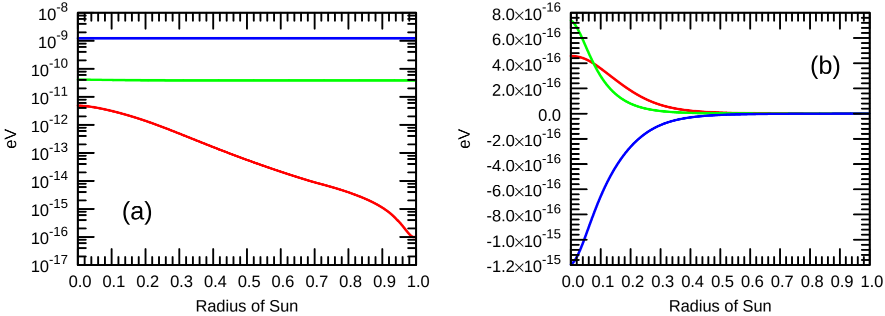
The number of neutrinos and antineutrinos should remain constant as a consequence of unitarity.

Two possibilities

1. Matter enhanced radiative decay or ‘neutrino spin-light’ $\longrightarrow$ far too small in the sun
2. Decay into Majoron with neutrino or antineutrino emission (open possibility)

Neutrino decay in solar matter?

Real and imaginary parts of the eigenvalues for the Hamiltonian solution above plotted against solar fractional radius for neutrino energy $E = 1\ MeV$



(a) Adiabatic LMA resonance is seen near the solar centre.

(b) The lower curve ($-i\Gamma$) is associated with the decaying state (the heaviest of the mass eigenvalues). $\langle\Gamma\rangle \simeq 10^{-16} eV$ (trajectory averaged).

Neutrino decay in solar matter?

Other choices for imaginary diagonal ε's are possible which lead to the same suitable survival probability. Different values of Γ may be involved for each choice. Also the shape of the Γ curve against solar radius may or may not change according to energy.

Sun produces neutrinos, not antineutrinos. In this decay antineutrinos may be produced. Their flux is constrained by the Borexino (2% for $E \geq 1.8 MeV$) and KamLAND (2.8×10^{-2}% for $8.3 < E < 14.8 MeV$) bounds.

Assuming neutrinos spend $1s <> 2.4 \times 10^{14} eV^{-1}$ inside the sun, a fraction

$$exp(-\Gamma t) = exp[-\Gamma(eV) \times 2.4 \times 10^{14} eV^{-1}]$$

will decay into other neutrinos (or antineutrinos) and a Majoron.

Neutrino decay in solar matter?

For $E = 1MeV$, $\langle\Gamma\rangle \simeq 10^{-16}eV$ which gives a 2% component consistent with the Borexino limit.

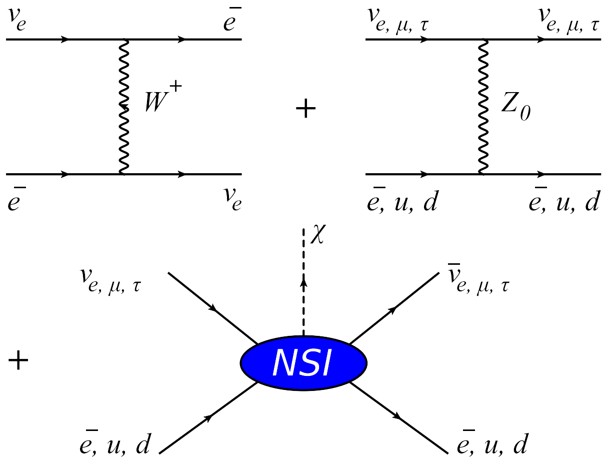
Other suitable choices of ε parameters allow for $\langle\Gamma\rangle \simeq 10^{-18}eV$ in the energy range of the KamLAND bound. Then an antineutrino fraction of

$$exp(-\Gamma t) = exp[-10^{-18}(eV) \times 2.4 \times 10^{14}eV^{-1}] = 2.4 \times 10^{-4}$$

in agreement with the KamLAND bound.

Neutrino decay in solar matter?

The full physical process in our model for neutrino propagation and decay through NSI in the sun is



Neutrino decay in solar matter?

The form used for the Hamiltonian in our numerical calculation does not take into account the extra physics of the Majoron models and corresponds therefore to a partial Hamiltonian, whose hermiticity is restored once the detailed Majoron emission process is taken into account.

To summarize:

Resolving the tension between LMA and the data can be done with NSI and implies neutrino decay in solar matter. This is consistent with the decay into a Majoron and a lighter neutrino or antineutrino. Our results are independent of the detailed physics of Majoron models.