The MOLLER experiment and non-standard neutrino interactions

Rodolfo Ferro Hernández

April 2019

Neutrino oscillations

The PMNS matrix is interpreted as the change of basis matrix between mass and weak eigenstates. In terms of states we have

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \tag{1}$$

The equations of neutrino oscillations are obtained in a simple way. Supose we have an initial weak eigenstate ν_α. Then translate this state over space and time

$$|\nu; T, L\rangle = e^{iHT - iPL} |\nu_\alpha\rangle = \sum_i U_{\alpha i} e^{iHT - iPL} |\nu_i\rangle \tag{2}$$

Neutrino oscillations

If we assume that the neutrinos carry the same momenta then

$$|\nu; T, L\rangle = e^{iHT - iPL} |\nu_\alpha\rangle = \sum_i U_{\alpha i} e^{iE_i L} |\nu_i\rangle \tag{3}$$

the transition amplitude is

$$\langle \nu_\beta | \nu; T, L\rangle = \sum_i U_{\alpha i} e^{iE_i L} U^*_{\beta i} \tag{4}$$

now suppose we have only two flavor neutrinos, in this case

$$U_{\beta i} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \tag{5}$$

The neutrino survival probability is then

$$P(\alpha \to \alpha) = 1 - sin^2 2\theta \sin^2(\frac{\Delta m^2}{4E} L)$$

The same procedure can be done for three neutrino flavours:

$$P(e \to e) = 1 - \frac{1}{2} c_{13}^4 sin^2 2\theta_{12} \sin^2(\frac{\Delta m_{12}^2}{4E} L) - \frac{1}{2} sin^2 2\theta_{13} (1 - \cos(\frac{\Delta m_{13}^2}{2E} L))$$

$$-\frac{1}{2} s_{12}^2 sin^2 2\theta_{13} (\cos(\frac{\Delta m_{13}^2}{2E} L) - \cos(\frac{\Delta m_{13}^2 + \Delta m_{21}^2}{2E} L))$$

But...

But wait....

This workshop was mainly talking about parity violation is in it?

What does this has to do with neutrino oscillations?

R: The BSM operators that can be tested are the same in both type experiments.

Standard Model Effective Field Theory (SMEFT)

Recipe to find new physics:

- Recall that the Standard Model has a symmetry $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$.
- Write all the operators that respect the symmetries.
- Importance of each operator given by power counting of new physics.

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{i,n} \frac{\mathcal{O}_{i,n}}{\Lambda^n} \tag{6}$$

SMEFT classification

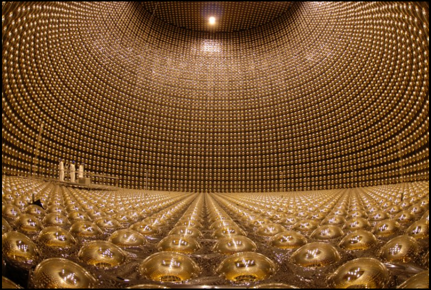
In a recent paper (2010 B Grzadkowski et al.) the complete set of six dimensional operators invariant under the BSM symmetries are obtained. It can be proven that there are only three operators which involve electrons:

$$\bar{\Psi}^e_L \Psi^e_L \bar{\Psi}^e_L \Psi^e_L \quad \bar{\psi}^e_r \psi^e_r \bar{\Psi}^e_L \Psi^e_L \quad \bar{\psi}^e_r \psi^e_r \bar{\psi}^e_r \psi^e_r \tag{7}$$

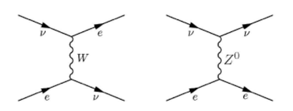
- Can be constrained in a global fit (A Falkowski 2017)
- To relate MOLLER to neutrino physics we need to find experiments that use as detection the scattering of electron neutrinos with electrons!
- This could lead to possible small modification to oscillation parameters.
- Once this operators are constrained we can use this results to find constraints on other operators.

Neutrino oscillation experiments: Solar Neutrinos

One natural source of electron neutrinos is the sun. Solar neutrinos are detected by several experiments such as Borexino, SNO and SuperKamiokande.



SuperKamiokande detects neutrinos through neutrino-electron scattering.



The detection cross section is

$$\frac{d\sigma}{dT}(E_\nu, T_e) = \frac{2G_F^2 m_e}{\pi}\left[(g_1^a)^2 + (g_2^a)^2\left(1 - \frac{T_e}{E_\nu}\right)^2 - g_1^a g_2^a \frac{m_e T_e}{E_\nu^2}\right] \tag{8}$$

where

$$g_1^{\mu,\tau} = -\frac{1}{2} + \sin^2\theta_W, \quad g_2^{\mu\tau} = \sin^2\theta_W \tag{9}$$

$$g_1^e = \frac{1}{2} + \sin^2\theta_W, \quad g_2^e = \sin^2\theta_W \tag{10}$$

Neutrino oscillation experiments

When neutrinos are produced in the core of the sun they have to move through the sun itself. This will change the probability formula. Using adiabaticity we get

$$P_e\left(x\right) = \frac{1}{2} + (\frac{1}{2} - P_c)\cos 2\theta\ \cos 2\theta_m \tag{11}$$

the dependence on the potential is in the θ_m term.

$$\sin^2 2\theta_m = \frac{\left(\Delta m_{21}\sin\left(2\theta\right)\right)^2}{\left(\Delta m_{21}\cos\left(2\theta\right) - 2\sqrt{2}G_F n_e E\right)^2 + \left(\Delta m_{21}\sin\left(2\theta\right)\right)^2} \tag{12}$$

Neutrino oscillation experiments

To get a good fit we must combine solar neutrino with the KamLand experiment. This is a long baseline reactor neutrino experiment. Nuclear reactors produce electron antineutrinos through beta decay.

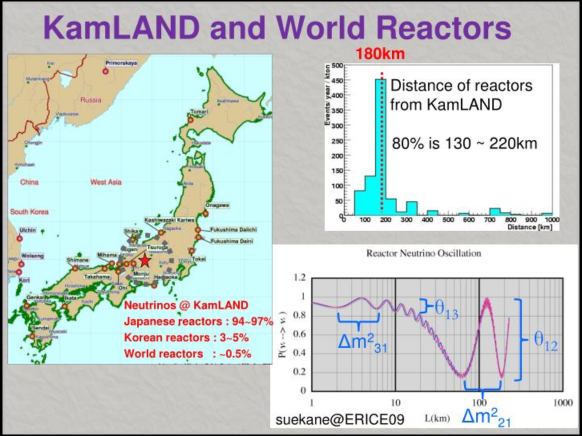
$$n \rightarrow p + e^{-} + \bar{\nu}_e \tag{13}$$

then anitneutrinos are detected using inverse beta decay

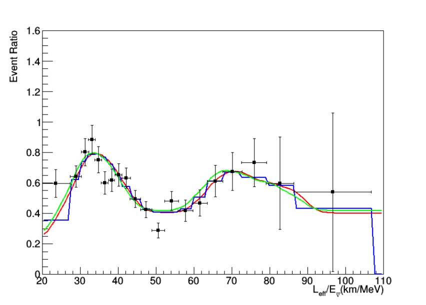
$$p + \bar{\nu}_e \rightarrow n + e^{+} \tag{14}$$

the positron anihilates with an electron and emits light.

KamLand is localized in the Kamioka observatory near Tomaya in Japan. It receives the contribution of 55 nuclear reactors, 20 are dominant.



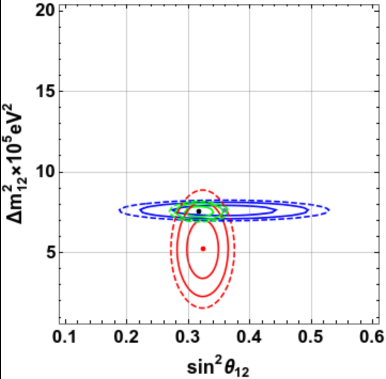
Neutrino oscillation experiments



The results for the original KamLand paper are
$\sin^2 2\theta == 0.92 \pm 0.06$ and $\Delta m^2 = 7.58 \pm 0.21 \times 10^{-5}$

Neutrino oscillation experiments: Solar Neutrinos

Preliminar: The combined fit of SuperKamiokande, SNO and Kamland, bugs and details need to be checked.



Neutrino oscillation experiments

If we include new physics with operators of the form

$$\mathcal{L}_{NC-BSM} = -\frac{2}{v^2}\epsilon_{ee}^{eX}\left(\bar{\nu}_e\gamma^\mu P_L\nu_e\right)\left(\bar{\psi}_X^e\gamma_\mu\psi_X^e\right) \tag{15}$$

then the cross section couplings will change to

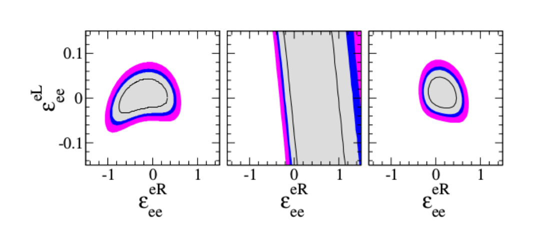
$$g_1^e \to g_1^e + \epsilon_{ee}^{eL}, \quad g_2^e \to g_2^e + \epsilon_{ee}^{eR} \tag{16}$$

Neutrino oscillation experiments: Solar and Reactor Neutrinos

In a paper done by tortola and valle (2008) the BSM coefficients where constrained using the global fit to solar and KamLand data. Their results where

$$-0.27 < \epsilon_{ee}^{eR} < 0.59 \quad -0.036 < \epsilon_{ee}^{eL} < 0.063 \tag{17}$$

so we can see that they can just get a percent precision at best. Here is where MOLLER can play a role.


0.1
0
-0.1
ε_{ee}^{eL}
-1
0
1
ε_{ee}^{eR}
-1
0
1
ε_{ee}^{eR}
-1
0
1
ε_{ee}^{eR}

MOLLER experiment

The Measurement Of Lepton Lepton Electroweak Interaction (MOLLER) JLab is going to measure the parity-violating asymmetry

$$A_{LR} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = m_e \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4\sin^2\theta}{(3+\cos^2\theta)^2} Q_W^e. \tag{18}$$

in the scattering of polarized off unpolarized electrons in an 11 GeV beam.

where θ is the scattering angle in the center of mass frame, and $Q_W^e \equiv 1 - 4\sin^2\theta_W$,

MOLLER experiment

This experiment constraint the following EFT operator

$$\mathcal{L}_{BSM}^{Moller(PV)} = \frac{1}{2v^2}\frac{[c_{ll}]_{eeee} - [c_{ee}]_{eeee}}{2}\left[\bar{\psi}_L^e\gamma^\mu\psi_L^e\bar{\psi}_L^e\gamma^\mu\psi_L^e - \bar{\psi}_R^e\gamma^\mu\psi_R^e\bar{\psi}_R^e\gamma^\mu\psi_R^e\right], \tag{19}$$

in an expansion of the form

$$\mathcal{L}_{BSM}^{Moller} = \frac{[c_{ll}]_{eeee}}{2v^2}\bar{\psi}_L^e\gamma^\mu\psi_L^e\bar{\psi}_L^e\gamma^\mu\psi_L^e + \frac{[c_{le}]_{eeee}}{v^2}\bar{\psi}_L^e\gamma^\mu\psi_L^e\bar{\psi}_R^e\gamma^\mu\psi_R^e + \frac{[c_{ee}]_{eeee}}{2v^2}\bar{\psi}_R^e\gamma^\mu\psi_R^e\bar{\psi}_R^e\gamma^\mu\psi_R^e, \tag{20}$$

using the expected precision for MOLLER we get

$$\left|-[c_{ll}]_{eeee} + [c_{ee}]_{eeee}\right| < 0.024 Q_W, \tag{21}$$

in terms of the neutrino paramaters this translates into

$$\left|4\epsilon_{ee}^{eL} + [c_{ee}]_{eeee}\right| < 0.001 \tag{22}$$

Including LEP2

MOLLER really tests new physics at low energies.If we believe in a power expantion of an UV complete theory then include constraints from collider experiments at high energies. One of them is LEP2. They give

	Λ_-(TeV)	Λ_+	c_-	c_+
LL	8.0	8.7	0.011	0.010
RR	7.9	8.6	0.012	0.010
LR	8.5	11.9	0.011	0.005
RL	8.5	11.9	0.011	0.005

Tabela 1: LEP2 fit to new physics. 95% confidence level.

Future Work

There are still many things that need to be done:

- Include properly the correlations between SNO and SuperKamiokande.
- Include correlations in LEP2 operators.
- Do a global fit Solar+KamLand including BSM in other operators.
- Any other new idea is welcome!

Extra stuff..

RANDOM STUFF STARTS HERE!

Told ya!

Falkowski

Using the correlation matrix given by Falkowski et al (2017) we get

	Neutrino experiment	90% C.L	Our result (B) 95% C.L
ϵ_{ee}^{eL}	solar+KamLAND	$[-0.021, 0.052]$	$[-0.039, -0.001]$
ϵ_{ee}^{eR}	TEXONO	$[-0.07, 0.08]$	$[-0.010, 0.002]$
$\epsilon_{\mu\mu}^{eL}$	reactor+accelerator	$[-0.03, 0.03]$	$[-0.019, 0.018]$
$\epsilon_{\mu\mu}^{eR}$	solar+KamLAND	$[-0.12, 0.06]$	$[-0.023, 0.024]$
$\epsilon_{\tau\tau}^{eL}$	solar+KamLAND	$[-0.021, 0.052]$	$[-0.123, 0.102]$
$\epsilon_{\tau\tau}^{eR}$	solar+KamLAND and Borexino	$[-0.98, 0.23]$	$[-0.072, 0.073]$
$\epsilon_{\tau\tau}^{eR}$	reactor+accelerators	$[-0.25, 0.43]$	$[-0.072, 0.073]$
$\epsilon_{\tau\tau}^{eV}$	atmospheric	$[-0.11, 0.11]$	

Tabela 2: Comparison of BSM coefficients from Neutrino experiments, and using the EFT approach.

Neutrino Masses

The sponateuous symmetry breaking of the $SU(2) \times U(1)$ gauge symmetry is a consequence of the higgs boson adquiring a vev. This vev will give masses to the fermions. Thus

$$\mathcal{L}_{SM}^{\text{mass}} = \frac{v}{\sqrt{2}} \left[\sum_{i,j=e,\mu,\tau} y_{ij}^{l} \bar{\psi}_R^i \psi_L^j + \sum_{i,j=e,\mu,\tau} y_{ij}^{\nu} \bar{\nu}_R^i \bar{\nu}_L^j \right]$$

we can diagonalize this matrices by rotating the fields in the flavour space

$$D_L^{i\beta} \psi_L^\beta = \psi_L^i \quad D_R^{i\beta} \psi_R^\beta = \psi_R^i \quad U_R^{i\beta} \nu_R^\beta = \nu_R^i \quad U_L^{i\beta} \nu_L^\beta = \nu_L^i$$

This rotations give diagonal mass matrices, and they cancel almost everywhere, except in one place: The charged current interactions. This is

$$\mathcal{L}_{SM}^{\text{charged}} = \sum_{j=e,\mu,\tau} i\frac{g}{\sqrt{2}}\bar{\Psi}_L^j\gamma^\mu\left(W_\mu^+T^+ + W_\mu^-T^-\right)\Psi_L^j$$

$$= \sum_{j=e,\mu,\tau} i\frac{g}{\sqrt{2}}\bar{\psi}_L^j\gamma^\mu W_\mu^+\nu_L^j + \text{H.C}$$

$$= \sum_{\alpha=1,2,3}\sum_{\beta,j=e,\mu,\tau} i\frac{g}{\sqrt{2}}\bar{\psi}_L^\beta\gamma^\mu W_\mu^+ D_L^{\dagger j\beta}U_L^{j\alpha}\nu_L^\alpha + \text{H.C}$$

Neutrino oscillations

$$\langle \nu_\beta \,| \nu;\, T, L\rangle = -\cos\theta \sin\theta e^{iE_1 L} + \cos\theta \sin\theta e^{iE_2 L} \tag{23}$$

from this expression it is trivial to obtain the transition probability

$$|\langle \nu_\beta \,| \nu;\, T, L\rangle\,|^2 = \sin^2 2\theta \sin^2(\frac{E_2 - E_1}{2} L) \tag{24}$$

the difference in energies is directly related to the difference in masses

$$E_2 - E_1 = \sqrt{m_2^2 + p^2} - \sqrt{m_1^2 + p^2} = p\left(\sqrt{1 + \frac{m_2^2}{p^2}} - \sqrt{1 + \frac{m_1^2}{p^2}}\right)$$

$$\simeq p\left(1 + \frac{1}{2}\frac{m_2^2}{p^2} - 1 - \frac{1}{2}\frac{m_1^2}{p^2}\right) \simeq \frac{1}{2}\frac{\Delta m^2}{E}$$

Neutrino oscillation experiments

- 4 different isotopes $^{235}U,\ ^{238}U,\ ^{239}Pu,\ ^{241}Pu$
- Approximate same proportion $f_{i=isotopes}$ for all reactors.
- Spectrum of antineutrinos produced by each isotope is approximated by an exponential

$$\frac{dN_\nu^j}{dE_\nu} = \exp\left\{\sum_{l=0}^{5} a_l^j E_\nu^l\right\}, \tag{25}$$

To get the number of expected events we need to compute

$$N_{KL} = \eta N_p \int dE_{\text{vis}} \int dE_{e^+} R\left(E_{\text{vis}}, E_{e^+}\right) \sigma\left(E_\nu\right) \sum_i S_i \frac{P_i\left(\bar{\nu}_e \leftrightarrow \bar{\nu}_e\right)}{4\pi d_i^2} \tag{26}$$

usually experimentalists show in their plots the ratio of oscillation over non oscillation results $R = \frac{N_{KL}^{os}}{N_{KL}^{non}}$.