A 17 MeV pseudoscalar and the LSND, MiniBooNE and ATOMKI anomalies

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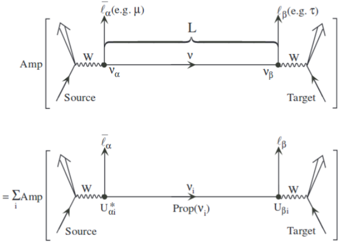
Neutrino Oscillation

- $|\nu_\alpha\rangle = U^*_{\alpha i}|\nu_i\rangle$

$$P(\nu_\alpha \to \nu_\beta) = |\sum_i U^*_{\alpha i} e^{-i\frac{m_i^2 L}{2E}} U_{\beta i}|^2$$



hep-ph/0506165 (B. Kayser)

- Two flavor case:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

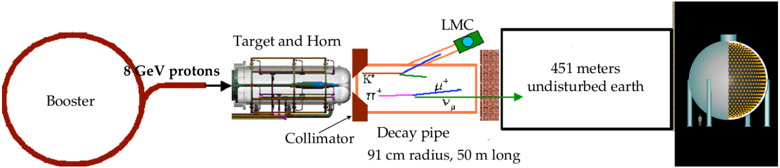
$$P_{\mu e} = \sin^2\theta sin^2 \frac{1.27\Delta m^2 L\,(\mathrm{meter})}{E\,(MeV)}, \text{ where } \Delta \mathrm{m}^2 = \mathrm{m}_2^2 - \mathrm{m}_1^2.$$

$\Delta m^2|_{\mathrm{solar}} \sim 7.5 \times 10^{-5}\, eV^2$ and $\Delta m^2|_{\mathrm{atm}} \sim 2.5 \times 10^{-3}\, eV^2$.

- For short-baseline (or near detector) experiments $L/E \sim 1$ and $P_{\mu e} \sim 0$.

LSND and MB excesses

- LSND and MiniBooNE (MB) were two short-baseline neutrino experiments.
- Schematic representation of MB :



- LSND : proton energy 800 MeV and base-line $\sim$ 30 meters.

- Detectors can not distinguish the signals from e^-, e^+, γ, and under certain conditions e^+e^- pair.

- MB fluxes peak around 800 MeV and the flux drops significantly beyond 1.5 GeV.

- There were two kinds of fluxes for LSND: the DAR flux ($\pi^+ \to \mu^+ + \nu_\mu$, $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$) and DIF flux ($\pi^+ \to \mu^+ + \nu_\mu$).

- MB looked for an electron like signal in the final states.

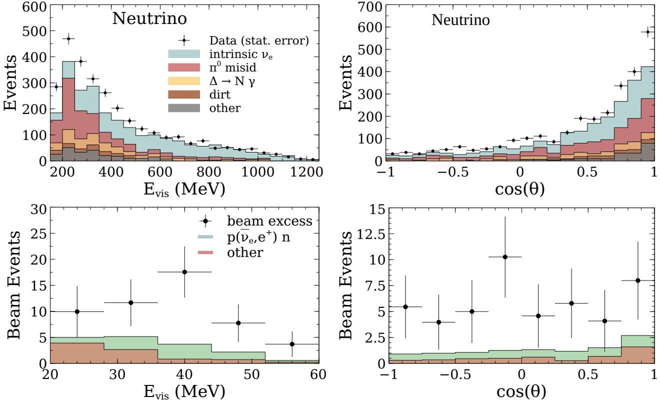
$$\nu_\mu \text{ beam } \text{ and } \nu_\mu + \mathrm{A} \to \mathrm{e}^- + \mathrm{X}$$

- LSND signal looks like an inverse β-decay.

$$\bar{\nu}_\mu \text{ beam } \text{ and } \bar{\nu}_\mathrm{e} + \mathrm{p} \to \mathrm{e}^+ + \mathrm{n}$$

  and n is captured by the free hydrogen in the detector. This produces a unique signature of 2.2 MeV gamma in the detector.

MB and LSND events



- An excess of electron (positron) like events over the expected background was observed.
- Excess events are distributed over all possible directions.
- The combined significance of the excess is $6.1\,\sigma$.
- The MB excess disappears when neutrino flux is suppressed. Hence, the excess is linked to neutrinos.

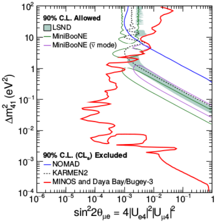
Sterile neutrino

For an eV scale sterile neutrino, $\Delta m^2 \sim 1eV^2$.

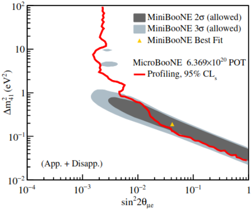
$$P_{\mu e} = \sin^2\theta sin^2 \frac{1.27\Delta m^2 L\,(\mathrm{meter})}{E\,(MeV)}$$

Leptonic mixing matrix in the presence of an eV scale sterile neutrino:

$$U^{3+1} = O(\theta_{34}, \delta_{34})O(\theta_{24}, \delta_{24})O(\theta_{14})O(\theta_{23})O(\theta_{13}, \delta_{13})O(\theta_{12})$$



Daya Bay + MINOS Collaboration 1607.01177



MicroBooNE collaboration 2210.10216

Solution to LSND and MB anomalies via light sterile neutrino does not fit well in the global picture.

The proposed model:

We consider two Higgs doublet model (2HDM) with a singlet pseudoscalar $\phi_{h'}$. In addition, three right-handed neutrinos help to generate neutrino masses via the seesaw mechanism and participate in the interaction which gives the signal both in MB and LSND.

$$\begin{aligned} V_{2\mathrm{HDM}} &= \mu_1|\phi_h|^2 + \mu_2|\phi_H|^2 + \frac{\lambda_1}{2}|\phi_h|^4 + \frac{\lambda_2}{2}|\phi_H|^4 + \lambda_3|\phi_H|^2|\phi_h|^2 + \lambda_4(\phi_h^\dagger\phi_H)(\phi_H^\dagger\phi_h) \\ &+ \frac{\lambda_5}{2}\{(\phi_h^\dagger\phi_H)^2 + h.c\} + (\lambda_6|\phi_h|^2 + \lambda_7|\phi_H|^2)(\phi_h^\dagger\phi_H + \phi_H^\dagger\phi_h), \\ V_{h'} &= \mu'|\phi_{h'}|^2 + \lambda'_2|\phi_{h'}|^4 + \lambda'_3|\phi_h|^2|\phi_{h'}|^2 + \lambda'_4|\phi_H|^2|\phi_{h'}|^2 + \{(\lambda'_5|\phi_{h'}|^2 - \mu_3)(\phi_h^\dagger\phi_H) \\ &+ (m_1|\phi_h|^2 + m_2|\phi_H|^2 + m_3\phi_h^\dagger\phi_H - m_s\phi_{h'})\phi_{h'} + h.c.\}. \end{aligned}$$

Here,

$$\phi_h = \begin{pmatrix} G^+ \\ \frac{v+H_1^0+iG^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_H = \begin{pmatrix} H_2^+ \\ \frac{H_2^0+iA_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_{h'} = i\,A_3^0/\sqrt{2}\,.$$

In the Higgs basis the relevant Lagrangian $\mathcal{L}$ can be written as follows

$$\begin{aligned} \mathcal{L} = \sqrt{2}\Big[&(X_{ij}^u\tilde{\phi}_h + \bar{X}_{ij}^u\tilde{\phi}_H)\bar{Q}_L^i u_R^j + (X_{ij}^d\phi_h + \bar{X}_{ij}^d\phi_H)\bar{Q}_L^i d_R^j + (X_{ij}^e\phi_h + \bar{X}_{ij}^e\phi_H)\bar{L}_L^i e_R^j \\ &+ (X_{ij}^\nu\tilde{\phi}_h + \bar{X}_{ij}^\nu\tilde{\phi}_H)\bar{L}_L^i\nu_{R_j} + \frac{1}{\sqrt{8}}m_{ij}\bar{\nu}_{R_i}^c\nu_{R_j} + \lambda_{ij}^N\bar{\nu}_{R_i}^c\phi_{h'}\nu_{R_j} + h.c.\Big], \end{aligned}$$

The Interaction in MB and LSND and the benchmark parameters :

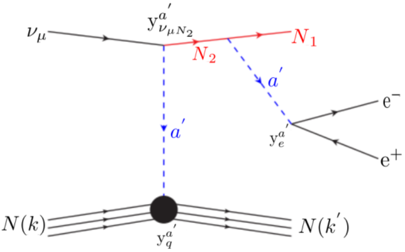


Figure 1. Feynman diagram of the scattering process involving a' which leads to the excess in MB and LSND.

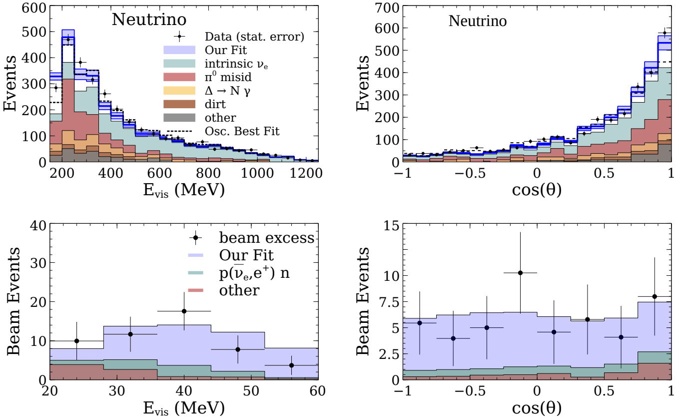
m_{N_1}	m_{N_2}	m_{N_3}	$y^{a'}_u \times 10^6$	$y^{a'}_e \times 10^5$	$y^{a'}_\mu \times 10^5$	$M_{H^\pm}$	$y^{a'}_c$	$y^{a'}_t$
70 MeV	120 MeV	10 GeV	4.34	2.3	1	305 GeV	0	0
$M_{a'}$	M_H	$\sin\xi$	$y^{a'}_d \times 10^6$	$y^{a'}_{\nu_\mu N_2} \times 10^2$	$\lambda^{a'}_{N_{12}}$	M_A	$y^{a'}_s$	$y^{a'}_b$
17 MeV	300 GeV	0.01	4.0	3.15	0.1	400 GeV	0	0

Table 1. Benchmark parameter values used to generate the event spectrum in LSND and MB.

Results:

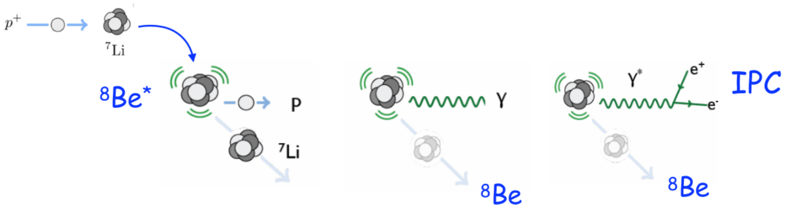
The total differential cross section for the interaction with CH_2 is

$$\left[\frac{d\sigma}{dE_{N_2}}\right]_{\mathrm{CH_2}} = \underbrace{(8F_p^2 + 6F_n^2)\left[\frac{d\sigma}{dE_{N_2}}\right]}_{\text{incoherent}}$$



W. Abdallah, R. Gandhi, T. Ghosh, N. Khan, S. Roy, S. Roy; JHEP10(2024)086

Atomki anomaly



- The experiment observes unexpected bumps in the invariant mass and angular separation of the e^+e^- pair, as opposed to SM expectation that the invariant mass and angular distribution would fall monotonically.
- Data is consistent with the production of an new particle X with

$$M_X = 16.7 \pm 0.35\,(\mathrm{stat} \pm 0.5\,(\mathrm{sys}))\quad \mathrm{MeV}$$

- The excess events were also observed in the other nuclei such as ^4He ^{12}C.

- The observation correspond to an excess of 6.8 sigma. The BR fraction is

$$\frac{\mathrm{BR}(^8\mathrm{Be}^* \to \, ^8\mathrm{Be}\, X) \times \mathrm{BR}(X \to e^+ e^-)}{\mathrm{BR}(^8\mathrm{Be}^* \to \, ^8\mathrm{Be}\, \gamma)} = 5.8 \times 10^{-6}$$

- From parity and angular momentum conservation, X can be a vector, axial vector or pseudoscalar.
- The effective average coupling of a' to nucleus from which one gets the above BR fraction, $\bar{h}_N^2 = \frac{(F_p+F_n)^2}{4} \sim 9.38 \times 10^{-7}$.

m_{N_1}	m_{N_2}	m_{N_3}	$y_u^{a'} \times 10^6$	$y_e^{a'} \times 10^5$	$y_\mu^{a'} \times 10^5$	$M_{H^\pm}$	$y_c^{a'} \times 10^3$	$y_t^{a'} \times 10^5$
70 MeV	120 MeV	10 GeV	4.613	2.3	1	305 GeV	−6.827	1.0
$M_{a'}$	M_H	$\sin\xi$	$y_d^{a'} \times 10^5$	$y_{\nu_{\mu N_2}}^{a'} \times 10^3$	$\lambda_{N_{12}}^{a'}$	M_A	$y_s^{a'} \times 10^5$	$y_b^{a'}$
17 MeV	300 GeV	0.01	1.0	2.2	0.1	400 GeV	1.356	0

Table 2: Benchmark parameters used to generate the event spectrum in LSND, MB and for calculating the ATOMKI.

Conclusions

- Evidence for anomalous signals at short-baseline neutrino experiments is increased over time.
- Our proposed model could provide a common, non-oscillatory new physics explanation for both the LSND and MicroBooNE excess events, as well as the ATOMKI anomaly.
- The ongoing experiment, MicroBooNE will investigate e^+e^- pair scenario in the near future. This also provides a test of our model.
- Confirmation of the ATOMKI anomaly by other independent experiments (MEG II, PADME) is important.

Thank you for your attention!