Study of Quasi-Dirac Neutrino @ JUNO

Amina Khatun[a], Fedor Simkovic[a], Adam Smetana[b]

(a) Comenius University, Bratislava
(b) Czech Technical University in Prague

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Quasi-Dirac neutrino is interesting in neutrino oscillation because

- Oscillation between active and light sterile neutrino can be explained in this framework
- Neutrino osc. exps can predict mass parameter measured in $0\nu\beta\beta$ exp.

Dirac–Majorana mass term

The neutrino Dirac–Majorana mass term in Lagrangian is given as

$$\mathcal{L}_m = \frac{1}{2}\begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \mathcal{M} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \mathrm{h.c.}\,,$$

- The mass matrix $\mathcal{M}$ is a 6×6 symmetric matrix

$$\mathcal{M} = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix},$$

The diagonalizing matrix of the mass matrix $\mathcal{M}$ according to

$$\mathcal{U}^{\mathrm{T}} \tilde{\mathcal{M}} \mathcal{U} = \mathcal{M}\,,$$

with $\mathcal{U}$ is 6×6 unitary matrix and $\tilde{\mathcal{M}}$ diagonal mass matrix.

Why mass of neutrino is so tiny?

Understanding with 2×2 matrix (for one generation)

$$\mathcal{M} = \begin{pmatrix} m_L & m_D \\ m_D^T & m_R \end{pmatrix},$$

$$m_{1,2} = \frac{1}{2}[m_L + m_R \pm \sqrt{(m_L - m_R)^2 + 4m_D^2}]$$

1. Dirac Neutrino case: $m_L = m_R = 0$, $m_{1,2} = \pm m_D$
2. Majorana neutrino case:
    - Seesaw regime : $m_L = 0, m_R > m_D$, $m_1 = m_R$, $m_2 = -m_d^2/m_R$
    - Quasi Dirac neutrino: Small deviation from Dirac case, $m_L \sim m_R << m_D$, $m_{1,2} = \pm m_D(1 \pm \epsilon)$ with $\epsilon = (m_L + m_R)/2m_D$

For three generation, the diagonal mass matrix in case of diagonlized mass matrix is

$$\tilde{\mathcal{M}} = \begin{pmatrix} m_i + \epsilon_i & 0 \\ 0 & -m_i + \epsilon_i \end{pmatrix}$$

Paramatrization of mixing matrix $\mathcal{U}$

A general parametrization of the 6×6 unitary diagonalization matrix can be introduced as a product of three unitary matrices [Phys.Rev.D 85 (2012) 013008], $\hat{\mathcal{U}} = \mathcal{A} \cdot \mathcal{X} \cdot \mathcal{S}$.

$$\hat{\mathcal{U}} = \mathcal{X} \cdot \mathcal{A} \cdot \mathcal{S}\,, \tag{1}$$

where $\mathcal{A}$ and $\mathcal{S}$ mix exclusively active or sterile neutrino flavors, ν_L or ν_R, respectively,

$$\mathcal{A} \equiv \begin{pmatrix} U^{\mathrm{T}} & 0 \\ 0 & \mathbb{1} \end{pmatrix}, \mathcal{S} \equiv \begin{pmatrix} \mathbb{1} & 0 \\ 0 & V^{\dagger} \end{pmatrix}, \mathcal{X} = \begin{pmatrix} \mathbb{1} & X^{\dagger} \\ -X & \mathbb{1} \end{pmatrix} + \mathcal{O}(\alpha^2)\,. \tag{2}$$

X has mixing angles and phases beyond Dirac mixing. Dirac case is reprduced with $X = 0$. This can be done by inserting a constant unitary matrix $\mathcal{T}$ into the definition of the QD unitary diagonalization matrix $\mathcal{U}$

$$\mathcal{U} = \mathcal{X} \cdot \mathcal{T} \cdot \mathcal{A} \cdot \mathcal{S}\,, \tag{3}$$

where

$$\mathcal{T} \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} \mathbb{1} & -\mathbb{1} \\ \mathbb{1} & \mathbb{1} \end{pmatrix}. \tag{4}$$

Theoretical Framework

- Present study focuses on the effect of mass splitting between left and right handed neutrino
- Mixing matrix is taken same as Dirac case.
- The problem is simplified with one mass splitting instead of three

$$\tilde{\mathcal{M}} = \begin{pmatrix} m_i + \epsilon & 0 \\ 0 & -m_i + \epsilon \end{pmatrix}, \mathcal{U}_{QD} = \frac{1}{\sqrt{2}} \begin{pmatrix} U_{PMNS} & U_{PMNS} \\ V & V \end{pmatrix}, \alpha \sim |M_{L,R}|/|M_D| \sim 0$$

$$P_{\alpha\beta} = \left| \sum_{i=1}^{6} \mathcal{U}^*_{QD,\alpha i} \mathcal{U}_{QD,\beta i} \mathrm{e}^{-\mathrm{i}\tilde{\mathcal{M}}^2_{ii} L/2E} \right|^2 .$$

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(\epsilon \neq 0) = 1 - P_1 - 4\, c_{13}^4 c_{12}^2 s_{12}^2 F_{21} - 4\, s_{13}^2 c_{13}^2 (c_{12}^2 F_{31} + s_{12}^2 F_{32})$$

with

$$P_1 = c_{13}^4 c_{12}^4 \sin^2 \frac{m_1 \epsilon L}{E} + c_{13}^4 s_{12}^4 \sin^2 \frac{m_2 \epsilon L}{E} + s_{13}^4 \sin^2 \frac{m_3 \epsilon L}{E}$$

$$F_{ij} = \frac{1}{4}\Big(\sin^2 \frac{\Delta m_{ij}^2 + 2\epsilon \Delta m_{ij}}{4E} L + \sin^2 \frac{\Delta m_{ij}^2 - 2\epsilon \Delta m_{ij}}{4E} L + \sin^2 \frac{\Delta m_{ij}^2 + 2\epsilon \sum m_{ij}}{4E} L + \sin^2 \frac{\Delta m_{ij}^2 - 2\epsilon \sum m_{ij}}{4E} L \Big)$$

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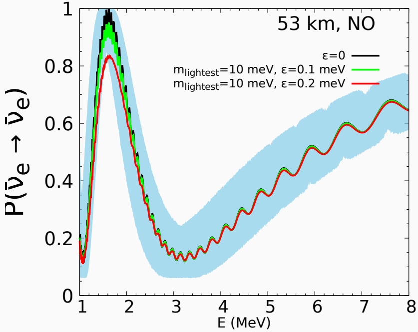
The JUNO detector

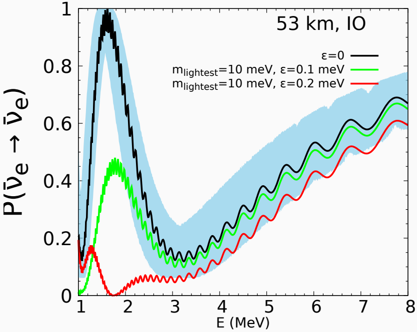
- JUNO is a 20 kiloton liquid scintillator detector, multi-purpose.
- One of the main goals is to measure the neutrino mass ordering, detecting IBD events due to $\bar{\nu}_e$ from reactor power plants
- The energy resolution of the detector should be as good as $3\%\sqrt{E}$ to distinguish the energy spectra for NO and IO
- The baseline is around 53 km,

Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C4
Power (GW_{th})	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	53.21
Cores	TS-C1	TS-C2	TS-C3	TS-V4	DYB	HZ
Power (GW_{th})	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.2	215	265

Table 1: The thermal powers and distances of the nuclear cores that we include in the analysis.

Survival probabilities of reactor $\bar{\nu}_e$





$m_{\text{lightest}} \equiv m_1$ for NO, $m_{\text{lightest}} \equiv m_3$ for IO,

$$\begin{aligned} P_{\bar{\nu}_e \to \bar{\nu}_e}(\epsilon \neq 0) \quad = \quad & P_{\bar{\nu}_e \to \bar{\nu}_e}(\epsilon = 0) - \frac{\epsilon^2 L^2}{E^2}\left[c_{13}^4 c_{12}^4 m_1^2 + c_{13}^4 s_{12}^4 m_2^2 + s_{13}^4 m_3^2\right] \\ & - \frac{\epsilon^2 L^2}{4E^2}\left[4\, c_{13}^4 s_{12}^2 c_{12}^2 \Sigma m_{21}^2 \cos\frac{\Delta m_{21}^2 L}{2E} + 4 s_{13}^2 c_{13}^2 c_{12}^2 \Sigma m_{31}^2 \cos\frac{\Delta m_{31}^2 L}{2E}\right. \\ & \left. + 4\, s_{13}^2 c_{13}^2 s_{12}^2 \Sigma m_{32}^2 \cos\frac{\Delta m_{32}^2 L}{2E}\right] + \mathcal{O}(\epsilon^4)\,, \qquad (5) \end{aligned}$$

where $\Sigma m_{ij}^2 \equiv m_i^2 + m_j^2$.

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Expected Constraints on Majorana contribution ϵ

Number of IBD events from all the reactors (listed in JUNO yellow book)

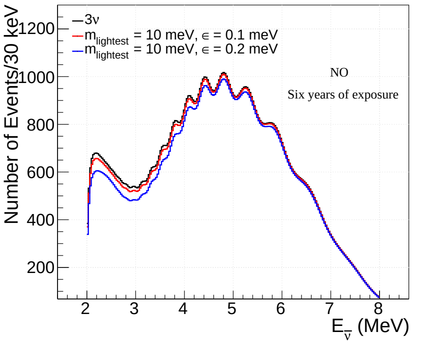
$$\frac{dN_d}{dE_{true}} = \sum_r \epsilon \frac{N_p}{4\pi L_{rd}^2} \frac{P_{th}^r}{\sum_k f_k < E_k >} \sum f_k \frac{d\Phi_k(E)}{dE_\nu} \frac{dE_\nu}{dE_{true}} \sigma_{IBD}(E)\, P_{ee}(E, L_{rd})\,, \quad (6)$$

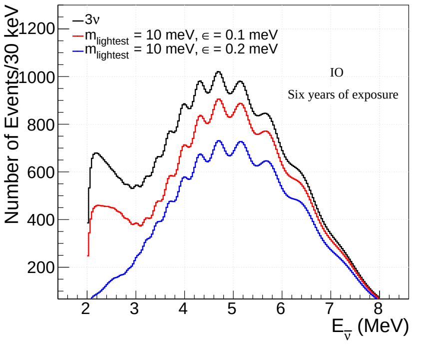
The total number of IBD events to appear in the i-th bin with reconstructed prompt energy E_{min} to E_{max} is given by

$$N_i^{rec} = \int_{E_{min}^i}^{E_{max}^i} dE_{rec} \int_0^\infty dE_{true} \frac{dN_d}{dE_{true}}\ P(E_{rec}; E_{true})\ . \quad (7)$$

- $P(E_{rec}; E_{true})$ is calculated using Gaussian distribution of E_{rec} with $\sigma = 3\%\sqrt{E_{rec}}$.
- Efficiency of the detector is taken as 73% (Neutrino physics at JUNO, arXiv:1507.05613)
- Energy spectra of reactor antineutrino from isotopes ^{235}U, ^{239}U and ^{241}Pu are taken from Phys.Rev.C 84, by P. Huber. That from ^{238}U is taken from Phys. Rev. C83, Mueller et.al.
- Cross-section is taken from A. Strumia and F. Vissani, Phys. Lett. B 564 (2003) 42–54, [astro-ph/0302055]

IBD Spectra at JUNO



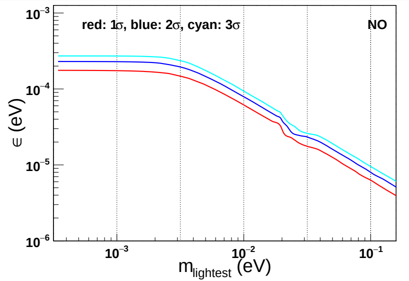


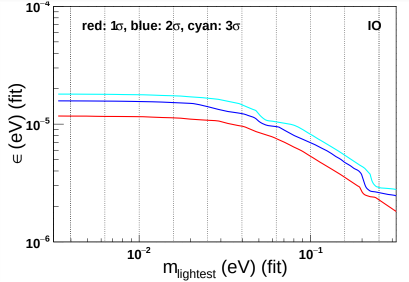
- The change for IO is larger than that for NO
- Change is in normalization of the spectra, both for IO and NO
- The normalization error of flux is important in analyzing data for the QD signal

Constraint in the plane of lightest neutrino mass and ϵ

$$\chi^2 = min(syst.) \sum_{i=1}^{N_{\text{bins}}} \frac{\left[M_i - T_i(1 + a_{\text{norm}} + \sum_r w_r \alpha_r + \epsilon_d)\right]^2}{M_i} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \frac{\epsilon_d^2}{\sigma_d^2} + \frac{a_{\text{norm}}^2}{\sigma_{\text{norm}}^2}$$

- Uncorrelated error in reactor flux $\sigma_r = 0.8\%$
- Uncertainty in detection $\sigma_d = 1\%$
- Uncertainty in normalization of reactor antineutrino flux is kept 100%. If this error changed to ~ 0, then χ^2 values get increased by 10%





Concluding remarks

- Quasi-Dirac neutrino is interesting since the mixing between active and light sterile neutrino can be accommodated into the framework
- The neutrino oscillation can give a prediction of neutrino mass parameter measured in the $0\nu\beta\beta$ decay. For our constrained case $\epsilon_i = \epsilon$ and $X = 0$, it reduces to the expression

$$m_{\beta\beta} \quad = \quad \left|\sum_{i=1}^{3} U_{ei}^2 \epsilon\right| = \epsilon \left| c_{12}^2 c_{13}^2 + e^{2\mathrm{i}\alpha_{21}} c_{13}^2 s_{12}^2 + e^{2\mathrm{i}\alpha_{31}} s_{13}^2 \right| .$$

- The 2σ C.L. limit is $\epsilon < 0.2$ meV with $m_{\text{lightest}} < 3$ meV and NO. For IO, this limit is one order stringent.
- At $m_{\text{lightest}} > 3$ (20) meV with NO (IO), limits on ϵ and m_{lightest} are anticorrelated
- Analysis with adding new mixing angles would be interesting
- Certainly, the high baseline would be helpful with matter effects taken into account

Thank you!