Type-II seesaw effects on neutrino trident scattering

Ming-Wei Li(1)(2)(*)

(1) *State Key Laboratory of Dark Matter Physics, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai 201210, China*

(2) *Shanghai Key Laboratory for Particle Physics and Cosmology, Key Laboratory for Particle Astrophysics and Cosmology (MOE), School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 201210, China*

Summary. — In this talk, we discussed the constraints from charged lepton flavor violation (CLFV) on the Type-II seesaw model and its impact on neutrino trident scattering. Using data from neutrino oscillation experiments, we derived a lower bound on the triplet vacuum expectation value (vev), v_Δ, as a function of the triplet scalar mass m_Δ: $v_\Delta > 0.625$ eV (1 TeV$/m_\Delta$). Furthermore, we also find that the Type-II seesaw reduces the standard model (SM) neutrino trident scattering cross section, and the deviation ratio remains above 0.98 at the 3σ confidence level.

1. – Introduction

Neutrino oscillations imply nonzero neutrino masses, the first confirmed sign of physics beyond the Standard Model (SM) [1]. Among various mechanisms, the type-II seesaw introduces an electroweak triplet scalar Δ, whose neutral component acquires a small vacuum expectation value (vev) v_Δ to generate tiny neutrino masses [2, 3, 4, 5, 6, 7].

The singly charged component Δ^+ also contributes to neutrino trident scattering $\nu_\mu N \to \nu_\alpha N \mu^+\mu^-$, a rare process measured by CHARM-II, CCFR and NuTeV [8, 9, 10]. Although current data agree with the SM within large uncertainties, upcoming experiments such as neutrino near detectors [11] and forward physics experiments [12] will significantly improve sensitivity.

In this work we combine constraints from the CLFV processes to study the type-II seesaw model contribution to neutrino trident scattering. We find a lower limit on parameter $m_\Delta v_\Delta$, and show that the predicted trident cross section deviates from the SM by less than 2% at 3σ level.

(*) Speaker, email: limw2021@sjtu.edu.cn

2. – Type-II seesaw model

To explain the tiny neutrino mass, a elecroweak triplet higgs scalar is introduced in type-II seesaw, which couples to a pair of lepton doublet via Yukawa interactions, model[2, 3, 4, 5, 6, 7],

$$(1)\quad \begin{aligned} &\mathcal{L}_Y = Y_{\alpha\beta}\overline{L^c_\alpha}P_L L_\beta \Delta + \text{h.c.} \\ =&\overline{\nu^c_\alpha}Y_{\alpha\beta}P_L\nu_\beta\Delta^0 - \frac{1}{2}(\overline{\nu^c_\alpha}Y_{\alpha\beta}P_L\ell_\beta\Delta^+ + \overline{\ell^c_\alpha}Y_{\alpha\beta}P_L\nu_\beta\Delta^+) - \overline{\ell^c_\alpha}Y_{\alpha\beta}P_L\ell_\beta\Delta^{++} + \text{h.c.}\ , \end{aligned}$$

where $\alpha, \beta = e, \mu, \tau$. Due the extended higgs potential

$$(2)\quad V(\Phi,\Delta) = -m^2_\Phi \Phi^\dagger\Phi + m^2_\Delta \,\mathrm{Tr}\,\Delta^\dagger\Delta + \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2 + \mu\Phi^T i\sigma^2\Delta^\dagger\Phi + \ \text{h.c.}\ \ ,$$

the new triplet higgs also acquire a non-zero vev $\langle\Delta^0\rangle = v_\Delta/\sqrt{2}$, $v_\Delta = \mu v^2_\Phi/(\sqrt{2}m^2_\Delta)$, where Φ is usual scalar $SU(2)_L$ doublet with vev v_Φ. Then the extended Yukawa coupling term between neutrinos and Δ^0 can generate the tiny Majorana neutrino mass matrix $(M_\nu)_{\alpha\beta} = m_{\alpha\beta} = \sqrt{2}Y_{\alpha\beta}v_\Delta$,

$$(3)\quad m^\nu_{\alpha\beta} = \sqrt{2}Y^\Delta_{\alpha\beta}\nu_\Delta \equiv \sum_i U_{\alpha i}U_{\beta i}m^\nu_i\ .$$

Due to the Majorana feature of neutrinos in type-II seesaw model, the neutrinoless double beta decay experiment [13] can give the strongest constraint Majorana mass matrix m_{ee} (see in Fig. 1).

A non-zero v_Δ also affects the gauge boson mass $m^2_W = g^2(v^2_\Phi + 2v^2_\Delta)/4$, $m^2_Z = (g^2 + g'^2)(v^2_\Phi + 4v^2_\Delta)/4$. Therefore, there is a minimal effects on electroweak parameter ρ

$$(4)\quad \rho = \frac{m^2_W}{m^2_Z\cos^2\theta_W} = 1 + \Delta\rho = 1 - \frac{2v^2_\Delta}{v^2_\Phi + 4v^2_\Delta} = 1 - \frac{2v^2_\Delta}{v^2 + 2v^2_\Delta}\ .$$

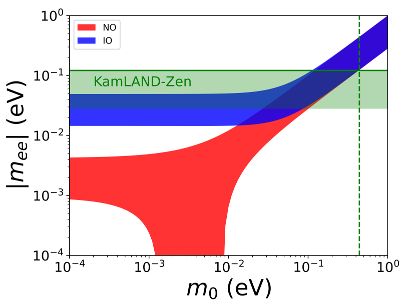

Fig. 1. – Constraints on Majorana neutrino mass matrix, $m_{ee} < 0.45$eV, which implies the lightest neutrino mass $m_0 < 0.44$eV

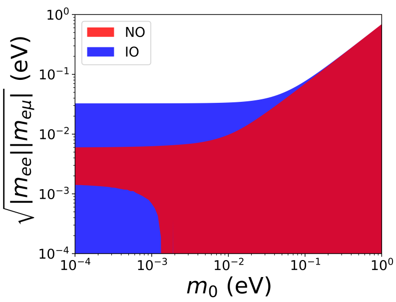

Fig. 2. – The 3σ range of $\left|m^\nu_{\mu e}m^\nu_{ee}\right|^{1/2}$.

where $v^2 \equiv 1/(\sqrt{2}G_F) = 4m_W^2/g^2 = v_d^2 + 2v_\Delta^2 = (246\text{GeV})^2$ [1]. Previous constraint on ρ parameter is given by [1] $\rho = 1.00038 \pm 0.00020$, which implies an upper bound on v_Δ, namely, $v_\Delta < 4.8\text{GeV}$ at 95% CL.

3. – CLFV violation constraints on Type-II seesaw model.

Due to the extend Yukawa interactions, type-II seesaw model would contribute to $l_\alpha \to l_\beta\gamma$ process mediated by Δ^{++} and Δ^+ at the one loop level,

$$\Gamma\left(\mu^- \to e^-\gamma\right) = \frac{m_\mu^5\alpha_{em}}{(192\pi^2)^2}\left(\frac{9\left|Y^\dagger Y\right|_{\mu e}}{m_\Delta^2}\right)^2 = \frac{m_\mu^5\alpha_{em}}{(192\pi^2)^2}\left(\frac{9\left|(m^\nu)^\dagger m^\nu\right|_{\mu e}}{2m_\Delta^2 v_\Delta^2}\right)^2 .$$

where we assume the degenerate triplet higgs spectrum. With the oscillation data [10], we could derive that

$$\begin{aligned}\left|(m^\nu)^\dagger m^\nu\right|_{\mu e} &= \left|\sum_i U_{\mu i}U_{ei}^* m_i^2\right| = \left|U_{\mu 2}U_{e2}^*\Delta m_{21}^2 + U_{\mu 3}U_{e3}^*\Delta m_{31}^2\right| \\ \Rightarrow & 1.36\times 10^{-2}\ \text{eV} < \sqrt{\left|(m^\nu)^\dagger m^\nu\right|_{\mu e}} < 1.81\times 10^{-2}\ \text{eV} .\end{aligned} \tag{5}$$

Currently, experimental searches for these processes have yielded null results, imposing stringent constraints on the model parameters, ie. the lower limit for $m_\Delta v_\Delta$,

$$\text{Br}\left(\mu \to e\gamma\right) < 4.2\times 10^{-13} \ \Rightarrow m_\Delta v_\Delta > \sqrt{9\left|(m^\nu)^\dagger m^\nu\right|_{\mu e}}\times 15.3\text{TeV} \gtrsim 0.625\ \text{eV}\cdot\text{TeV}. \tag{6}$$

Similarly, exchanging Δ^{++} at tree level, one obtains the decay rate of $\mu^- \to e^+e^-e^-$ process,

$$\Gamma\left(\mu^- \to e^+e^-e^-\right) = \frac{1}{4}\frac{m_\mu^5}{192\pi^3}\left|\frac{m_{\mu e}^\nu m_{ee}^\nu}{2m_\Delta^2 v_\Delta^2}\right|^2 \tag{7}$$

The corresponding branching ratio also impose the constraints

$$\text{Br}\left(\mu^- \to e^+e^-e^-\right) < 1.0\times 10^{-12} \Rightarrow m_\Delta v_\Delta > \left|m_{\mu e}^\nu m_{ee}^\nu\right|^{1/2}\times 145\ \text{TeV} \tag{8}$$

While, similar to m_{ee}^ν, as we shown in Fig. 2, there's no low limit for $\left|m_{\mu e}^\nu m_{ee}^\nu\right|^{1/2}$, which means that with the $\mu^- \to e^+e^-e^-$ data, we couldn't give the lower limit for $m_\Delta v_\Delta$ directly.

4. – Type-II seesaw contribution to neutrino trident scattering

Mediated by Δ^+, the operator contributing to neutrino trident scattering $\nu_\mu N \to \nu_\alpha N\mu^+\mu^-$ arises from the Yukawa interaction $\mathcal{L}_Y$,

$$\mathcal{L}_{\Delta^+} = \frac{2Y_{\mu\mu}^\Delta Y_{\alpha\mu}^{\Delta *}}{m_\Delta^2}\bar{\nu_\mu^c}P_L\mu\bar{\mu}P_R\nu_\alpha^c = \frac{m_{\mu\mu}^\nu m_{\alpha\mu}^{\nu\,*}}{4m_\Delta^2 v_\Delta^2}\bar{\nu}_\alpha\gamma^\mu P_L\nu_\mu\mu\gamma_\mu(1-\gamma^5)\mu . \tag{9}$$

where the index α could be e, μ, τ because the flavors of the final neutrinos are not identified experimentally. Due to the γ^5 trace property, we can derive that

$$\frac{\sigma_{\mathrm{SM}+\Delta^+}}{\sigma_{\mathrm{SM}}} = \frac{\left(1+4\sin^2\theta_W - \frac{\sqrt{2}G^{\mu}_{\Delta^+}}{G_F}\right)^2 + \left(1 - \frac{\sqrt{2}G^{\mu}_{\Delta^+}}{G_F}\right)^2 + \frac{4\left(|G^{e}_{\Delta^+}|^2 + |G^{\tau}_{\Delta^+}|^2\right)}{G_F^2}}{\left(1+4\sin^2\theta_W\right)^2 + 1}. \tag{10}$$

where $G^{\mu}_{\Delta^+} = \frac{|m^{\nu}_{\mu\mu}|^2}{4m^2_{\Delta}v^2_{\Delta}}$, $G^{e}_{\Delta^+} = \frac{m^{\nu}_{\mu\mu}m^{\nu\,*}_{e\mu}}{4m^2_{\Delta}v^2_{\Delta}}$, and $G^{\tau}_{\Delta^+} = \frac{m^{\nu}_{\mu\mu}m^{\nu\,*}_{\tau\mu}}{4m^2_{\Delta}v^2_{\Delta}}$. Notice that the parameters $m_{e\mu}, m_{\mu\mu}, m_{\tau\mu}$ depend on the lightest neutrino mass m_0, we can draw the lower bound of the above ratio in Fig.3 with the constrain from $\mu^- \to e^-\gamma$ in eq.(8). The

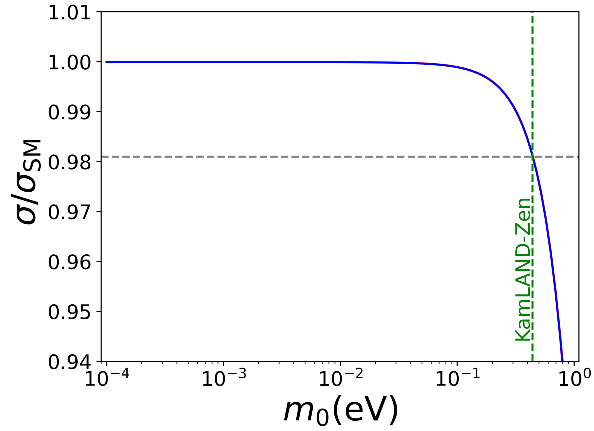

Fig. 3. – The maximum deviation of σ/σ_{SM} with 3σ constraints from $\mu \to e\gamma$.

ratio, σ/σ_{SM}, the cross section σ by experimental measurements to the SM predicted cross section σ_{SM} are 1.58 ± 0.64[8], 0.82 ± 0.28[9] and $0.72^{+1.73}_{-0.72}$[10], respectively. The average value is given by $\sigma_{\mathrm{exp}}/\sigma_{\mathrm{SM}} = 0.93 \pm 0.25$.

In Fig. 3, the green line shows the $0\nu\beta\beta$ constraint on the lightest neutrino mass, which has been discussed in Fig. 1. Besides, the recent tritium β decay experiment [14] also report their result of the effective electron antineutrino mass $m_\nu < 0.45$eV at 2σ level, which also implies that the nlightest neutrino mass $m_0 << 0.44$eV. Considering these constraints, $\sigma/\sigma_{\mathrm{SM}}$ deviates from the SM by at most 2% at 3σ, close to the current experimental central value. If we also take into account the cosmological constraints from the Planck collaboration [15], which impose stronger limits on neutrino masses, $m_0^{\mathrm{NO}} < 0.030$ eV and $m_0^{\mathrm{IO}} < 0.015$ eV, the effect of Δ on $\sigma/\sigma_{\mathrm{SM}}$ is restricted to less than 0.1%, making it very challenging to test experimentally.

5. – Acknowledgments

I am grateful to Yu Cheng, Xiao-Gang He, and Zhong-Lv Huang for their collaboration and insightful discussions. I would also like to thank the organizers of the MAYORANA International Workshop II edition for kindly inviting me to present this talk. This work was supported by the NSFC (Grant No. 123B2079).

REFERENCES

[1] P. A. Zyla *et al.* [Particle Data Group], PTEP **2020**, no.8, 083C01 (2020) doi:10.1093/ptep/ptaa104
[2] G. Lazarides, Q. Shafi and C. Wetterich, Nucl. Phys. B **181**, 287-300 (1981) doi:10.1016/0550-3213(81)90354-0
[3] R. N. Mohapatra and G. Senjanovic, Phys. Rev. D **23**, 165 (1981) doi:10.1103/PhysRevD.23.165
[4] W. Konetschny and W. Kummer, Phys. Lett. B **70**, 433-435 (1977) doi:10.1016/0370-2693(77)90407-5
[5] T. P. Cheng and L. F. Li, Phys. Rev. D **22**, 2860 (1980) doi:10.1103/PhysRevD.22.2860
[6] M. Magg and C. Wetterich, Phys. Lett. B **94**, 61-64 (1980) doi:10.1016/0370-2693(80)90825-4
[7] J. Schechter and J. W. F. Valle, Phys. Rev. D **22**, 2227 (1980) doi:10.1103/PhysRevD.22.2227
[8] D. Geiregat *et al.* [CHARM-II], Phys. Lett. B **245**, 271-275 (1990) doi:10.1016/0370-2693(90)90146-W
[9] S. R. Mishra *et al.* [CCFR], Phys. Rev. Lett. **66**, 3117-3120 (1991) doi:10.1103/PhysRevLett.66.3117
[10] T. Adams *et al.* [NuTeV], Phys. Rev. D **61**, 092001 (2000) doi:10.1103/PhysRevD.61.092001 [arXiv:hep-ex/9909041 [hep-ex]].
[11] P. Ballett, M. Hostert, S. Pascoli, Y. F. Perez-Gonzalez, Z. Tabrizi and R. Zukanovich Funchal, JHEP **01**, 119 (2019) doi:10.1007/JHEP01(2019)119 [arXiv:1807.10973 [hep-ph]].
[12] W. Altmannshofer, T. Mäkelä, S. Sarkar, S. Trojanowski, K. Xie and B. Zhou, Phys. Rev. D **110**, no.7, 072018 (2024) doi:10.1103/PhysRevD.110.072018 [arXiv:2406.16803 [hep-ph]].
[13] S. Abe *et al.* [KamLAND-Zen], [arXiv:2406.11438 [hep-ex]].
[14] M. Aker *et al.* [KATRIN], Science **388**, no.6743, adq9592 (2025) doi:10.1126/science.adq9592 [arXiv:2406.13516 [nucl-ex]].
[15] N. Aghanim *et al.* [Planck], Astron. Astrophys. **641**, A6 (2020) [erratum: Astron. Astrophys. **652**, C4 (2021)] doi:10.1051/0004-6361/201833910 [arXiv:1807.06209 [astro-ph.CO]].