

Neutrino Phenomenology

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Neutrino oscillations have demonstrated that neutrinos have mass and, by now, oscillation experiments have been able to determine most of the parameters in the leptonic mixing matrix with a very good accuracy. Nevertheless, there are still many open questions in the neutrino sector. I will briefly discuss some of these questions, pointing out possible experimental avenues to address them.

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1. Open questions in neutrino physics

The discovery of neutrino oscillations has opened many questions which still remain unanswered. The addition of neutrino masses to the Standard Model (SM) lagrangian is not a straightforward task to begin with, as new particles are needed. For this purpose, perhaps the most *naive* way to extend the SM could be through the addition of right-handed neutrinos ν_R to its particle content. This would allow for a Yukawa term with the Higgs ϕ and the left-handed doublets L_L , in the form $Y_V \bar{L}_L \tilde{\phi} \nu_R$. After electroweak symmetry breaking (EWSB) this term would generate Dirac masses for the neutrinos, just as it is done for the rest of the SM fermions.

However, in order to produce neutrino masses below the eV scale through this mechanism, a Yukawa coupling $Y_V \sim 10^{-12}$ would be needed. Even though this is perfectly viable, it poses interesting questions regarding the naturalness of such a small coupling especially since the ones associated to their doublet counterparts, the charged leptons, are at least six orders of magnitude larger. Furthermore, a right-handed neutrino is a singlet under the SM gauge group and, thus, once it is included in the SM nothing forbids the addition of a Majorana mass term in the form of $M \bar{\nu}_R^c \nu_R$ to the lagrangian, except the conservation of lepton number. This brings up the question of whether lepton number is a fundamental symmetry of the SM or just an accidental one. Does the new physics violate lepton number explicitly? Furthermore, what is the scale of new physics associated to this new mass M ? If lepton number is violated explicitly, additional signatures might be observable in future experiments. Neutrinoless double beta decay processes are a well-known example to conduct these searches, but lepton number violation might be observable as well in rare meson decays or even in collider experiments.

Since the discovery of neutrino oscillations, the progress in the field has been outstanding. The three angles involved in the leptonic mixing matrix are now known within a precision which ranges between approximately 8% for the atmospheric mixing angle θ_{23} and a 3% for the reactor angle θ_{13} [1]. Two very different squared mass splittings have also been measured with a very good accuracy: these show that at least two of the light neutrino mass eigenstates are massive, while the third eigenstate could in principle be massless. Such outstanding effort in neutrino oscillation experiments has revealed that the observed pattern in the mixing matrix is very different from the one measured in the quark sector, leading to the so-called “flavor puzzle”: why are these mixing patterns so different? Is there a flavor symmetry behind the observed structure that explains the values of these mixing angles?

Models which advocate for the existence of flavor symmetries try to address these questions, but they will not be able to prosper unless the experimental community provides precise measurements for all the relevant parameters which govern flavor mixing in the SM extended with neutrino masses. The fact that the atmospheric mixing angle lies very close to maximal mixing makes it extremely difficult to determine whether it is exactly maximal or not and, if not maximal, the octant it belongs to. Furthermore, even though we know that the three angles in the leptonic mixing matrix are non-zero, currently there is only a hint for the value of the Dirac CP-violating phase. The ordering of neutrino masses (i.e., whether the lightest mass eigenstate is ν_1 or ν_3) remains also unknown. Current and future long-baseline experiments aim to provide answers to these three questions, which have important consequences in model building for neutrino masses and mixing.

2. Lepton number violating signatures

For concreteness, let us focus on the naive scenario in which we extend the SM with three right-handed neutrinos ν_R . As already explained, as lepton number is not part of the gauge symmetry of the SM, in this case one would have to consider both Yukawa and Majorana mass terms in the neutrino mass lagrangian:

$$\mathcal{L}_\nu \supset Y_\nu \bar{L}_L \tilde{\phi} \nu_R + \frac{1}{2} M \bar{\nu}_R^c \nu_R + h.c. \quad (2.1)$$

After the Higgs acquires a vacuum expectation value v , the full neutrino mass matrix in the basis (ν_L, ν_R^c) reads:

$$\mathcal{M} = \begin{pmatrix} 0 & Y_\nu v \\ Y_\nu^\dagger v & M \end{pmatrix}. \quad (2.2)$$

The limit when $M \gg Y_\nu v$ is particularly appealing. In this limit, after diagonalizing the mass matrix in Eq. 2.2, the eigenvalues take the form

$$m_i \sim v^2 Y_\nu^\dagger M^{-1} Y_\nu, \quad (i = 1, 2, 3), \quad (2.3)$$

$$m_i \sim M + \mathcal{O}(v^2 Y_\nu^\dagger M^{-1} Y_\nu) \quad (i = 4, 5, 6), \quad (2.4)$$

where m_i and M_i refer to the masses of the three eigenstates in the light sector and the heavy sector. As can be seen from Eq. 2.3, the smallness of the light neutrino masses is explained through the suppression with a scale of new physics much higher than the EW scale, without the need for very small Yukawa couplings. This is the well-known See-Saw Type I mechanism [2, 3].

However, *a priori* there is no strong reason which forces the Majorana masses to lie above the EW scale. In particular, the limit when $M \rightarrow 0$ is also interesting, as in this limit the number of symmetries in the lagrangian increases (lepton number is recovered). Furthermore, if the scale of new physics M is below the EW scale, additional phenomenological consequences could take place at low energies. For example, for $M \sim \mathcal{O}(\text{eV})$, new states would be present at the eV-scale: this could offer an explanation for the observed anomalies in short-baseline experiments. On the other hand, a right-handed neutrino at the keV scale would be a good candidate for warm dark matter. Higher scales could have interesting phenomenological consequences as well: for example, the existence of additional neutrinos in the MeV-GeV regime could lead to lepton number violating signatures in rare meson decays or in beta decays.

The addition of relatively light right-handed neutrinos could have an impact in lepton flavor violating processes as well. Currently, the strongest experimental constraints impose the impressive upper bound on the branching ratio for $\mu \rightarrow e\gamma$, $B(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ [4]. In presence of right handed neutrinos, an extra contribution to the branching ratio for this process would be generated. This imposes tight constraints on the mixing between light and heavy states, as the extra contribution goes like [5, 6, 7]

$$B(\mu \rightarrow e\gamma) = \frac{3\alpha}{8\pi} \left| \sum_I V_{eI} V_{\mu I}^* f\left(\frac{m_I^2}{m_W^2}\right) \right|^2. \quad (2.5)$$

Here, the sum on I runs only over heavy mass eigenstates, α is the electroweak fine constant, m_W is the mass of the W boson, and $f(x)$ is a loop function which takes values between 0 and 1 as x

goes from 0 to infinity. It should be noted that the elements of the mixing matrix V which mix the light and heavy sectors are roughly proportional to the ratio between the light and heavy masses.

Finally, the existence of additional light neutrinos could also lead to observable deviations from the expected observable rate for neutrinoless-double beta decay. In this case, the situation is a bit more complicated, as the unitarity of the whole mixing matrix leads to exact cancellations when all the new mass eigenstates lie either below or above the energy scale associated to the nuclear transition ($\mathcal{O}(100)$ MeV), see e.g. Ref. [8, 9] for a detailed discussion. However, in scenarios where there is a large hierarchy between the Majorana masses associated to the right-handed neutrinos, such cancellations could in principle be avoided [9, 10]. This may lead to a considerably different rate with respect to the expected result in the standard scenario, where only the light neutrinos participate in the process. For instance, in Ref. [11] a phenomenological study was performed including a sterile neutrino at the eV scale. This example highlights the importance of cross checks of different measurements in order to pin down possible effects coming from new physics. For example, if long-baseline experiments determine that the neutrino mass ordering is normal, and the neutrinoless double beta decay rate is measured to be compatible with the inverted ordering scenario, this could be pointing out to the existence of new physics which violates lepton number at low energies, see, e.g. Ref. [12].

3. Oscillations, CP violation and the flavor puzzle

The current and future generation of neutrino oscillation experiments that will aim at determining the mass ordering can be divided into three main categories: long-baseline neutrino oscillation, atmospheric neutrino and medium-baseline reactor experiments. A quantitative comparison between the expected performance of these facilities and their projected sensitivities to the mass ordering can be found, e.g., in Ref. [13]. Both long-baseline (T2K [14], NOvA [15], DUNE [16]) and atmospheric neutrino oscillation experiments (ICAL at INO [17], PINGU [18], ORCA [19], Hyper-Kamiokande [20]) are sensitive to the mass ordering through the observation of the MSW effect [21, 22]. It leads to a resonant enhancement of the oscillation probabilities for normal ordering for neutrino oscillations, while in the inverted ordering scenario the resonance takes place for antineutrinos. On the other hand, reactor experiments at medium baselines (JUNO [23] and RENO-50 [24]) are sensitive to this observable through the appearance of an interference pattern in the oscillation probabilities in vacuum between the solar and the atmospheric contributions to the oscillation amplitude. The exact location of the interference and its evolution with the neutrino energy would be different depending on whether Δm_{31}^2 is larger or smaller than Δm_{32}^2 , and thus probes the neutrino mass ordering directly.

However, the major goal for the current and future generation of long-baseline neutrino experiments is to determine whether there is CP violation in the lepton sector. In the SM there are two possible sources of CP violation: the CP phase involved in the CKM matrix, which has been measured to be very close to $\sim 70^\circ$, and the θ -vacuum of QCD, which is experimentally bounded to be below $\theta < \mathcal{O}(10^{-10})$ [25]. There is little understanding as to why these parameters take these values. Thus, determining whether there are additional CP-violating sources in the lepton sector could help to shed light onto this long-standing problem of particle physics.

Recent data from the T2K [26] and NOvA [27] experiments (in combination with a very precise determination of θ_{13} from reactor experiments) currently seem to point to a negative value of δ , possibly maximally CP-violating. In the upcoming years, they will keep accumulating additional statistics which may strengthen this hint further. If δ is indeed close to -90° , the sensitivity obtained from the combination of T2K and NOvA data could reach a significance of $\sim 2\sigma$ for this observable (see, e.g., Ref. [28]). Their final combined sensitivity will eventually depend on other factors as well, such as the true values of θ_{23} and the neutrino mass ordering. Future experiments such as DUNE or T2HK will be much more sensitive to this observable, with an expected signal significance above 5σ if δ is around $\pm 90^\circ$ and θ_{23} lies in the lower octant [29, 20].

The discovery of CP violation in the lepton sector would be a major step forward in particle physics. Nevertheless, a precise measurement of the value of δ would have important consequences for model building in the flavor sector as well. The flavor puzzle in the SM has been object of extensive investigations, especially since the discovery of the large mixing angles which dominate neutrino mixing: while the CKM mixing matrix is very close to being diagonal, the leptonic mixing matrix obeys a completely different pattern. Flavor models attempt to explain the large differences observed in the mixing between quarks and between leptons, sometimes even linking the two sectors. In this context, models based on discrete symmetries have become very popular. In some of these, tight relations between the observable mixing angles in the PMNS matrix and the CP-violating phase (*aka*, sum rules) take place. Therefore, a precise determination of all parameters in the PMNS matrix could allow to discriminate between them. In fact, current measurements of the three mixing angles already allow to reject some of these flavor models, as their corresponding sum rules provide predictions for $\cos \delta$ which lie in unphysical regions of the parameter space (see Fig. 3 in Ref. [30]). Additional recent works along these lines include Refs. [31, 32, 33, 34, 35, 36, 37], among others.

In order to further discriminate among different flavor models, it is therefore crucial to improve the determination of the mixing angles (in particular the atmospheric mixing angle, which currently holds the largest uncertainty) and, especially, to get a precise measurement of δ . Current experiments will provide a hint on whether δ is CP-violating or not; however, if its value turns out to be close to $\delta \sim \pm 90^\circ$ (as favored by current data), T2K and NOvA will only determine its value with a rather large error bar, $\sim 70^\circ$ [38]. In other words, having a hint for CP-violation does not guarantee a precise measurement of the CP-violating phase itself *a priori*. Again in this case, future experiments with larger statistics and better precision will be needed for this purpose. The final precision achievable for δ will depend on its value: DUNE is expected to reach an accuracy around $\sim 15^\circ$ at 1σ [29]; a similar precision is expected for T2HK [20].

4. Summary

The discovery of neutrino masses has evidenced the existence of new particles beyond the SM. Even in the simplest scenario when only right-handed neutrinos are added to the SM particle content, new questions remain to be answered. If lepton number is just an accidental symmetry of the SM model, the inclusion of Majorana masses for the right-handed neutrinos seems mandatory: this implies the existence of a new physics scale. In this talk I have given a few examples of new observable phenomena which could take place in rare meson decays, colliders, lepton flavor

violating observables and neutrinoless double beta decay, among others. The final answer will depend on the physics scale responsible for the generation of neutrino masses.

I have also stressed out the complementarity between different experimental searches and its importance in order to pin down possible effects coming from new physics in the neutrino sector. As an example, I discussed the importance of the determination of the neutrino mass ordering in order to interpret the results from neutrinoless double beta decay searches. Finally, I have also discussed the relevance of CP-violation searches in the lepton sector and, most importantly, the precise determination of the value of the CP-violating phase. This could provide valuable data to attack the flavor puzzle in the SM extended with neutrino masses.

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