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Neutrinos and Matter-Antimatter Asymmetry

Jiaqi Zhou

Chaoyang KaiWen Academy,
Beijing, China, 100022
Email: 2008290081@
cy.kaiwenacademy.cn

Abstract:

This study is an aggregation of all the information present about neutrinos today, including seesaw mechanisms and their respective theses, as well as discovering how and why those mechanisms answer a much more important and mysterious problem than initially intended – answers to the origin of matter. Tweaking with the theories provided a potential configuration and combination of multiple predominant theories in the physics community in which matter-antimatter asymmetry could exist within the limits of known physical processes. The basic ideas and workings of the Dirac- and Majorana-Neutrino options, Type-I, II and III Seesaws and the Sphaleron process are listed in this study. Experiments have tried to prove these theses, but ultimately only succeeded in bringing about more problems to be solved. But even without experimental proof, the current theories can still make educated predictions on what was really happening at the start of the universe which created the asymmetry.

Keywords: Neutrinos, Matter-Antimatter Asymmetry, Seesaw Mechanisms, Physics

1. Introduction

Neutrinos are a family of arguably the most elusive particles in the Standard Model (SM). The Matter-Antimatter Asymmetry is the most fundamental problem in the universe. Looking at them side by side, correlations between the two become very notable. However, for a possible analysis, two special theories must be inspected. Only then could the analysis start, but also, the relationships become even more obvious.

Looking briefly at neutrino history, it was unsurprising - even uneventful - at first: the particle was first introduced by Pauli in his famous letter in 1930, a “forced” move to solve continuous spectra. The next move, made by Fermi, advanced Pauli’s postulation into a complete theory. Then, after 22 years spent mostly on theorizing and estimating, neutrinos were finally directly observed in 1956. Then comes its rebellious nature. The conservation of Parity, or invariance under space inversion, was long thought to be general. Then, neutrinos decided to defy previous physical understanding of the microscopic world. The discovery of this by Lee and Yang was so surprising that they got the Nobel Prize. However, this theory which seemingly complicated everything boosted understanding of weak processes and granted the theory of the two-component neutrino, with equations naïvely assuming massless neutrinos. This is a natural

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guess, but yet again, it turns out wrong. Finally, with the discovery of neutrino oscillations and the cruel reality of massive neutrinos, physicists were forced to do two things: form a new theory of weak interactions - relatively easy - and guess where the mass came from [1].

Currently, there is a large family of theories - the seesaws - which explain neutrino masses through slight additions to the SM like Right-Handed Neutrinos (RHNs, type of sterile neutrinos), Scalar Triplets, Higgs Triplets, etc. This study will introduce those Seesaws, and pair one with the Sphaleron Process, to conclude with one theoretical probability. This study is an aggregation and summary of all the information present about neutrinos today, it can provide certain reference value for researchers on related topics.

Here, the first term represents kinetic energy for the neutrino, and the second the complex Yukawa couplings of the neutrinos. This hugs the standard Higgs mechanism which, after Electroweak Symmetry Breaking (EWSB) gives the Higgs field a Vacuum Expectation Value (VEV) such that the two neutrinos couple. This model has some attractions: the Electroweak scale would be identified as the fundamental energy scale to explain masses of all other particles; it could explain baryon asymmetry through a neutrinogenesis mechanism based on early decays of Degrees of Freedom (DOFs) in the presence of RHNs; and its

The Majorana-neutrino option adds yet another extension to the Dirac-neutrino option, adding a Majorana mass term to the Lagrangian:

Here, simply one normalized neutrino Majonara mass term is added. In this model, since one would expect the high RHN masses to skyrocket past the EW scale, neutrino masses are not just suppressed by Yukawa couplings, but also by the minute mass ratio, leaving no need for an unrealistic Yukawa coupling. It also links baryogenesis and low-energy neutrino oscillations, due to the asymmetry being created first in the decays of leptons,

Now, returning to the Type-I Seesaw. To simplify everything, only two RHNs were used, since the third is unnecessary due to unsure neutrino masses (with one possibly being zero, therefore only two massive RHN couplings would be enough), and leaves

2. Seesaw Mechanisms

2.1 . Type-I Seesaw

The Type-I Seesaw is the earliest and easiest Seesaw of all [2]. To understand, start by looking at the two building blocks: the Dirac-neutrino option and the Majorana-neutrino option.

The Dirac-neutrino option adds a massless RHN which couples via a Yukawa Lagrangian to form massive Dirac fermions, which are the current neutrinos:

$$\mathcal{L}_{\mathcal{N}}^{\mathcal{D}} = \frac{i}{2}\overline{N_I^R}\partial N_I^R - y_{I\alpha}\overline{N_I^R}\varphi^{\dagger} L_\alpha + h.c., I = 1,2,3, \alpha = e,\mu,\tau. \tag{1}$$

minimality. Despite these shining factors, its dark side requires some additional work for this option to be complete: tiny SM neutrino masses demand an unrealistically small Yukawa coupling; to form baryon asymmetry high energy scales must be achieved, which has no particular relationship with low energy neutrino oscillations; the EW scale fails to identify as the fundamental energy scale due to failure of direct observation of BSM particles; and imposing lepton symmetry as a global symmetry to prevent an allowed term explicitly breaking it.

$$\mathcal{L}_{\mathcal{N}}^{\mathcal{M}} = \frac{i}{2}\overline{N_I^R}\partial N_I^R - y_{I\alpha}\overline{N_I^R}\varphi^{?} L_\alpha - \frac{1}{2}\overline{N_I^R}M_{IJ}\left(N_J^R\right)^C + h.c. \tag{2}$$

then being transmitted through the Sphaleron process, a further topic. Like usual, though, it comes with its own setbacks: introducing a new particle being way past the EW scale would erase the probability of a common mass origin and the RHN masses are too big for some processes it becomes unnatural via radiative corrections. These problems could be overcome while model building, though, and are therefore far less severe.

room for a dark matter (DM) candidate. It also simplifies workings. By combining the Majorana-neutrino and Dirac-neutrino option and doing some model building and slight corrections, equation 3 arises:

$$\mathcal{L}_{\mathcal{N}}^{\mathcal{M}} \xrightarrow[EWSB]{} \frac{i}{2}\overline{N_I^R}\partial N_I^R - [(m_D)_{I\alpha} + y_{I\alpha}\varphi_0]\overline{N_I^R}\nu_\alpha^L + y_{I\alpha}\varphi_+\overline{N_I^R}l_\alpha^L - \frac{1}{2}\overline{N_I^R}M_{IJ}\left(N_J^R\right)^C + h.c. \tag{3}$$

This equation effectively captures all the essential features of the EWSB in the Type-I Seesaw, an aggregation of the two separate models. Also note that the matrices in this equation could undergo clarifications symbolized in equations 4, 5, 6, and 7:

$$\mathcal{M}_{(\alpha,\mathcal{I})(\beta,\mathcal{J})} = \begin{pmatrix} 0_{\alpha\beta} & \left(m_D^T\right)_{\alpha J} \\ \left(m_D\right)_{I\beta} & M_{IJ} \end{pmatrix} ? \mathcal{D}_{(?,\mathcal{I})(?,\mathcal{J})} = \begin{pmatrix} D_{ij}^{\nu} & 0_{iJ} \\ 0_{Ij} & D_{IJ}^{N} \end{pmatrix} \tag{5}$$

$$\mathcal{M}_{(\alpha,\mathcal{I})(\beta,\mathcal{J})} \rightarrow \mathcal{M}_{(\alpha,\mathcal{I})(\beta,J)}^{?\ell???} \approx \begin{pmatrix} m_{\alpha\beta} & 0_{\alpha J} \\ 0_{I\beta} & M_{IJ} \end{pmatrix} \tag{7}$$

After EWSB, the RHNs and LHNs couple with each other through the Lagrangian in equation 3, and that encapsulates most of the Type-I Seesaw. Combining it with previous discussions on the two neutrino options, the Type-I Seesaw is now completely summarized.

$$\mathcal{L}_{\mathcal{N}}^{\mathcal{M}} \supset -\frac{1}{2}\left(\overline{\left(\nu_\alpha^L\right)^C}\,\overline{N_I^R}\right)\begin{pmatrix} 0_{\alpha\beta} & \left(m_D^T\right)_{\alpha J} \\ \left(m_D\right)_{I\beta} & M_{IJ} \end{pmatrix}\begin{pmatrix} \nu_\beta^L \\ \left(N_J^R\right)^C \end{pmatrix} + h.c. \tag{4}$$

$$D_{ij}^{\nu} = m_i\delta_{ij}, D_{IJ}^{N} = M_I ? \delta_{IJ} \tag{6}$$

2.2 . Other Seesaws

There are, of course, other Seesaw Mechanisms. The Type-II Seesaw adds a scalar triplet with a doubly-charged component to the SM which directly couples to lepton doublets and generates masses for neutrinos [3]. The Type-III Seesaw adds heavy fermionic triplets which are similar to the Type-II Seesaw [4]. Mixed Seesaw is a combination of Type-I and Type-II in which neutrinos get masses contributed from both the scalar triplet and the RHNs. Type 2/3 Seesaw combines Type-II and Type-III with neutrino masses contributed from both the triplets. The Inverse Seesaw is a more realistic version of the Type-I Seesaw, adding additional sterile neutrinos and of course, lepton-number violating parameters to lower the scale of RHNs. The Linear Seesaw improves the Inverse Seesaw so that neutrino masses linearly depend on a lepton-number violating term. The Double Seesaw combines everything aforesaid and builds a model on it. Other Seesaws, collectively called Extended Seesaws, are either innovative but with their own setbacks and lack in popularity or are just copies of other Seesaws. Even non-seesaw theories exist.

The reason the Type-I Seesaw is used will be clear once it is noted that except for a few, most of the Seesaws mentioned were based on the idea of the Type-I Seesaw. It was a basis and a starting point, and because of that, it shines on a few points: it is simple, useful, and adds nothing useless. Also due to its minimalism, equations and calculations will scarcely be overcomplicated. It also functions as a candidate to solve Matter-Antimatter Asymmetry, the main topic. Of course, the other seesaws were also figured to solve Matter-Antimatter Asymmetry, but as a starting point, the Type-I Seesaw suffices.

3. Matter-Antimatter Asymmetry

3.1 . Leptogenesis

Before proceeding onto the Sphaleron Process and creating the asymmetry, there is still one more important process (arising from all the seesaws but Type-I makes it the simplest) to inspect called leptogenesis [5]. Inferable from its name, it generates lepton asymmetry. By using the Type-I Seesaw, RHNs and scaler singlets will be added into consideration. the general Lagrangian can then be written down regarding interactions between RHNs and the scalar singlet:

$$\mathcal{L} \to -M_\delta^2 \delta^{+?} \delta^+ + \left[-\frac{1}{2} M_{N_i} N_{iR}^T C N_{iR} - H^? \bar{N}_{iR} (Y_N)_{ij} \psi_{jL} - (Y_R)_{ij} N_{iR}^T C \delta^+ l_{jR} - (Y_L)_{ij} \psi_{iL}^T C i \tau_2 \delta^+ \psi_{jL} + h.c. \right] \quad (8)$$

Here, the main concept is contained in the brackets: a Majonara mass term, two separate terms for left-handed leptons and RHNs, and a coupling term. Everything else is for normalization. It is very possible for the scalar singlet to be lighter than the RHNs, though, which means that RHNs will predominantly decay into those scalar singlets and the effects of other decay processes involving Yukawa-couplings can be neglected for this use. Of course, the actual asymmetry being created also needs to be mentioned, represented by equations 9 and 10:

$$?_{N_1} = \sum_i \frac{\Gamma\left(N_1 \to l_{iR} + \delta^+\right) - \Gamma\left(N_1 \to \bar{l}_{iR} + \delta^-\right)}{\Gamma_{N_1}} \cdot C_L \quad (9)$$

$$\Gamma_{N_1} = \frac{1}{16\pi} M_{N_1} \sum_i \left|(Y_R)_{1i}\right|^2 \quad (10)$$

Equation 9 is a standard CP-Violation calculation and equation 10 is the tree-level decay width. However, the scalar singlet does not have a vanishing lepton number, and it will decay into two left-handed antileptons. This will have to be accounted for in equation 11:

$$\epsilon_{N_1} = \frac{1}{8\pi} C_L \sum_j \frac{Im\left[\left(Y_R Y_R^?\right)_{1j}^2\right]}{\sum_i \left|(Y_R)_{1i}\right|^2} \sqrt{x_j} \left[1 - \left(1 + x_j\right) log\left(1 + \frac{1}{x_j}\right) + \frac{1}{2} \frac{1}{1 - x_j}\right] \quad (11)$$

Where the high-order corrections after $\frac{M_\delta}{M_{N_1}}$ could be neglected by assuming a small δ^+:

$$?_{N_1} = -C_L \frac{1}{8\pi} \sum_j \frac{Im\left[\left(Y_R Y_R^?\right)_{1j}^2\right]}{\sum_i \left|(Y_R)_{1i}\right|^2} \frac{M_{N_1}}{M_{N_j}} \quad (12)$$

Equations 11 and 12 may be thought of a summary for CP-Violation Asymmetry of RHNs. This will be all the theoretical leptogenesis covered in the scope of this study. However, after integrating the Sphaleron Process, theory can be brought into reality.

3.2 . Sphaleron Process

The final buildup before a conclusion is reached: the Sphaleron Process [6]. There are no direct papers about it - in fact, it is just a convenient label without any specific process being named like it. The inner workings, actually, include less about sphalerons than gauge transformations and the Cherns-Simon number. The reason it is called the Sphaleron Process is to emphasize the central piece. Anyways, the Sphaleron Process is of help due to one single prospect of the Cherns-Simon number: it violates B + L, but conserves B - L. First, note that Baryon and Lepton Asymmetry are anomalous, as seen through equation 13:

$$\partial_\mu j_B^\mu = \partial_\mu j_L^\mu = n_f \left(\frac{g^2}{32\pi^2} W_{\mu\nu}^a W^{a\mu\nu} - \frac{g^{¡®2}}{32\pi^2} F_{\mu\nu} F^{\mu\nu} \right) \quad (13)$$

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The final change in Baryon number, assuming transitions to different vacuum spaces from t to t_f with average field strength being 0 at start and finish, is:

$$\Delta B = \Delta N_{CS} \equiv n_f \left[N_{CS}\left(t_f\right) - N_{CS}\left(0\right) \right] \quad (14)$$

Here, the N_{cs} is the Cherns-Simon number, defined as:

$$N_{CS}\left(t\right) \equiv \frac{g^2}{32\pi^2} \int d^3x ?^{ijk} \operatorname{Tr}\left(A_i \partial_j A_k + \frac{2}{3} ig A_i A_j A_k \right) \quad (15)$$

Note that different vacuum spaces are characterized by different Cherns-Simon numbers. Therefore, quantum tunneling through an energy border into a different, stable vacuum space will bring about a non-zero. Plugging into equation 14, baryon asymmetry would have been created.

However, this process has its Achille's Heel. To trigger this quantum tunneling, one would need to have both matter-antimatter asymmetry in whichever section and sphalerons. Sphalerons, however, are only active in the early universe, and must be before and during EWSB, leaving little space for any theory. But the Type-I Seesaw predicts a form of leptogenesis which fits this requirement.

4. Conclusion

To summarize and bond everything aforesaid together, the entire matter-antimatter asymmetry happens roughly like this: RHNs in the early universe decay predominantly into scalar singlets due to them being possibly lighter than them, and due to them not having a vanishing lepton number, will create asymmetry in the lepton sector. This happens before EWSB. Also, since Sphalerons are active at this point in time and that they conserve B - L, there is a non-zero difference and due to the frequent interactions in the early thermal bath, some of it will be converted into the baryon sector. As the universe cooled down to ~100 GeV, EWSB happens, and both leptogenesis and the Sphaleron process stop, locking in the baryon asymmetry and finally completing the process.

There are still problems in this process, like scalar singlets being potentially heavier than RHNs resulting in them not predominantly decaying into those and breaking the rest of the chain. But that awaits further experimental proof. Currently, experimentalists have been trying to use particle accelerators to form RHNs through smashing, trying to observe neutrinoless double beta decay (0νββ) from nuclear decays, analyzing the Cosmic Microwave Background Radiation (CMBR) for any hints of the Sphaleron process and trying to directly measure CP violation from neutrino decays. The best bet should be lepton-number violating processes like 0νββ. As long as one of the two processes is scientifically proven, there is a great nudge that this is the correct explanation. However, that can only be proven by the passage of time.

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