Chapter 6

Conclusion

The origin of the cosmological baryon asymmetry is one of the burning questions in particle physics as well as in cosmology. There are various proposals to explain the evolution of baryon asymmetry. Among various mechanisms, the baryogenesis via leptogenesis is very attractive because of its simplicity and connection to neutrino physics. In its simplest form, the generation of lepton asymmetry requires the existence of heavy Majorana neutrinos which generate tiny neutrino masses via the seesaw mechanism, and provides significant implications for the light neutrino mass spectrum. The subsequent decay of the Majorana neutrinos, generates a lepton number asymmetry. During the electroweak phase transition the lepton asymmetry is converted into a baryon asymmetry, which survives down to this time. Sakharov's first condition (baryon number violation) is satisfied by the Majorana nature of heavy neutrinos and the sphaleron effect in the standard model at high temperature, while the second condition ($C$ and $CP$—violation) is provided by their $CP$—violating decay. The departure from thermal equilibrium (Sakharov's third condition) is provided by the expansion of the universe.
The extension of standard model with three heavy right-handed Majorana neutrinos have lasting effect in our understanding of neutrino physics and the origin of baryon asymmetry. The celebrated seesaw mechanism entangles the light left-handed neutrino mass matrix $m_{LL}$, Dirac neutrino mass matrix $m_{LR}$ and heavy right-handed Majorana mass matrix $M_{RR}$ in a simple way.

In Chapter-1 we have reviewed the solar and atmospheric neutrino puzzles which when resolved, lead to the concept of non-zero neutrino masses and mixings. The $(L - R)$ symmetric models such as $SO(10)$GUT, where one can have natural explanation of small neutrino masses, are discussed briefly. A discussion on the measurement of neutrino mass in neutrinoless double $\beta$-decay experiments and various models of neutrino masses have also been incorporated.

In Chapter-2 we have discussed the possible explanation of the observed baryon asymmetry of the universe. The $SU(5)$GUT model, which involves $B -$violating $X$ and $Y$ gauge boson interactions and the highly suppressed instanton induced $B -$violation have been discussed. Particularly, we have considered the non-perturbative sphaleron effect, which has significant role to convert the lepton asymmetry to baryon asymmetry in the framework of electroweak baryogenesis.

In Chapter-3 we have consider different neutrino mass models, constructed within the seesaw framework. Considering the oscillation parameters and observed baryon asymmetry as two important criteria, we make a comparative study of degenerate (DegT1A, DegT1B, DegT1C), inverted hierarchical (InvT2A, InvT2B) and normal hierarchical models, with a hope to discriminate some of them. This type of discrimination is very important as the
nature possibly does not possess multiple choices of neutrino mass pattern. We have estimated the contributions of type-I (canonical) and type-II (non-canonical) seesaw mass terms towards baryogenesis. For our choice of the Dirac neutrino mass matrix, our calculation is based on the predictions of \( SO(10) \) GUT, where the Dirac neutrino mass matrix can be of charged lepton (case i) or up-quark type(case ii). In a model where baryon asymmetry is explained via lepton asymmetry through sphaleron process, the out-of-equilibrium decay of the heavy right-handed neutrino plays a significant role. For effective leptogenesis, the lightest of heavy Majorana neutrinos, \( M_1 \) should have out-of-equilibrium decay and this can be realised by considering the decay parameter \( K \). The value of \( K = \frac{m_1}{m_*} \), with effective mass \( \tilde{m}_1 = \frac{(hh')_1 v^2}{M_1} \) and equilibrium neutrino mass \( m_* = \frac{16\pi^2}{3\sqrt{3}} g^{*1/2} \frac{v^2}{2 M_{pl}} \) should be less than one to characterise the out-of-equilibrium decay of \( M_1 \). It is found that only InvT2B and NHT3 models have satisfied \( K < 1 \) condition. Another plus point of NHT3 model is that it is stable under radiative corrections.

So far the oscillation parameters are concerned, the inverted hierarchical (InvT2B) model with \( \Delta m^2_{21} = 9.30 \times 10^{-5} eV^2, \Delta m^2_{23} = 2.50 \times 10^{-3} eV^2, \tan^2 \theta_{12} = 0.98, \sin^2 2\theta_{23} = 1.0, \sin \theta_{13} = 0 \) and normal hierarchical (NHT3) with \( \Delta m^2_{21} = 9.04 \times 10^{-5} eV^2, \Delta m^2_{23} = 3.01 \times 10^{-3} eV^2, \tan^2 \theta_{12} = 0.55, \sin^2 2\theta_{23} = 0.98, \sin \theta_{13} = 0.074 \) are consistent with the experimental values. So just by considering the oscillation parameters, it would not be possible to discriminate different mass models.

If we look into the predicted values of baryon asymmetry we observe that both degenerate model (DegT1A) and normal hierarchical (NHT3) model are in equal footing with the observed value \( Y_B = (6.1^{+0.3}_{-0.2}) \times 10^{-10} \). The
DegT1A model predicts \( Y_B = 2.49 \times 10^{-9} \) and \( 2.03 \times 10^{-11} \) for case(i) and case(ii) respectively. Again the normal hierarchical model (NHT3) predicts \( Y_B = 1.08 \times 10^{-9} \) and \( 8.80 \times 10^{-12} \) respectively for case(i) and case(ii). The DegT1A model is neither stable under radiative corrections nor it has competent predictions of oscillation parameters. For NHT3 the mass of \( M_1 \) is also within the Ibarra-Davidson bound i.e., \( M_1 > 4 \times 10^8 \) GeV. Considering all the above points, it appears that normal hierarchical (NHT3) model represents most favourable choice of nature.

In Chapter-4 we have attempted to understand the possible structure of Dirac neutrino mass matrix in the light of observed baryon asymmetry. The structure of Dirac neutrino mass matrix \( m_{LR} \) solely depends on the choice of different Higgs multiplets required for the generation of fermion masses in grand unified theory such as \( SO(10) \) GUT. Different models of \( SO(10) \) GUT predict that \( m_{LR} \) can be of (i) charged lepton type: \( m_{LR} = \text{Diag}(\lambda^6, \lambda^2, 1)v \), (ii) up-quark type: \( m_{LR} = \text{Diag}(\lambda^5, \lambda^4, 1)v \), (iii) down-quark type: \( m_{LR} = \text{Diag}(\lambda^4, \lambda^2, 1)v \) in terms of Wolfenstein parameter \( \lambda \) and \( v \) as overall weak scale factor. The Dirac mass matrix enters in the estimation of \( CP \)-asymmetry through the construction of Yukawa coupling \( h = \frac{m_{LR}}{v} \), in the basis where the right-handed mass matrix \( M_{RR} \) is diagonal with real and positive eigenvalues. Again the predicted values of baryon asymmetry of NHT3 indicates that the actual Dirac neutrino mass matrix might have different structure other than predicted by \( SO(10) \) GUT. Constraining the observed baryon asymmetry to normal hierarchy mass model within the seesaw framework, we look for the possible structure of Dirac neutrino masses. Assuming normal hierarchical mass model as favourable choice
of nature we have found the Dirac neutrino mass matrices to be \((\lambda^7, \lambda^2, 1)\nu\) with \(\lambda = 0.3\) and \(\nu\) as the overall scale factor.

In Chapter-5 we have considered the inverted hierarchy model for two specific mixing patterns. The inverted hierarchical patterns of light left-handed neutrinos \((m_1 \simeq m_2 > m_3)\) are best understood in terms of two mass models: Inverted hierarchical type-2A (InvT2A) and Inverted hierarchical type-2B (InvT2B) based on the relative \(CP\)-parity between \(m_1\) and \(m_2\). For InvT2A the mass pattern is denoted by \((m_1, m_2, m_3)\) whereas for InvT2B the mass pattern is \((-m_1, m_2, m_3)\). The inverted hierarchical model of neutrinos with odd \(CP\)-parity generally predicts nearly bimaximal mixings in the diagonal basis of the charged lepton mass matrix. The InvT2B model has been considered for two different mixings patterns of light neutrinos. Starting with the bimaximal and tribimaximal mixing patterns of inverted hierarchical light neutrino mass matrix \(m_{LL}\), the heavy right-handed Majorana neutrino mass matrices \(M_{RR}\) have been constructed via inverse seesaw relation. In case of bimaximal mixing pattern of light neutrinos we observe that the corresponding heavy right-handed neutrino masses manifest quasi-degenerate structure i.e., \(M_1 \simeq M_2 < M_3\). This peculiar structure of heavy masses enhance the produced asymmetry by a factor \((|M_1| + |M_2|)^{-1}\) known as ‘resonance enhancement’ by modifying the propagator. This scenario is completely changed when we come to tribimaximal mixing (TBM) pattern, with hierarchical pattern of heavy neutrinos i.e., \(M_1 < M_2 < M_3\). This type of hierarchical structure will bypass the resonance enhancement effect and this is clearly seen in the produced asymmetry. For bimaximal case and for three choices of Dirac neutrino mass matrices, the range of lep-
ton asymmetry is found to be $10^{-4} < \epsilon_1 < 10^{-2}$ whereas in tribimaximal scenario the range is $10^{-11} < \epsilon_1 < 10^{-6}$. For tribimaximal mixing pattern of InvT2B with down quark mass matrix taken as Dirac neutrino mass matrix, we have found $\epsilon_1 = 2.08 \times 10^{-6}$, effective mass $\tilde{m}_1 = 2.03 \times 10^{-2}$eV, dilution factor $\kappa_1 = 8.4 \times 10^{-3}$ which leads to $Y_B = 3.78 \times 10^{-10}$, consistent with the experimental value. The lightest of the heavy Majorana neutrino mass $M_1 = 9.76 \times 10^{10}$GeV, is in tune with the famous Davidson-Ibarra bound. In the present calculation we are able to establish the validity of tribimaximal mixing in inverted hierarchical mass model.