Asymmetric Dark Matter and Baryon Asymmetry of the Universe

M.Sc. Thesis

By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Asymmetric Dark Matter and Baryon Asymmetry of the Universe** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF SCIENCE** and submitted in the **DISCIPLINE OF PHYSICS, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from july 2019 to june, 2020 under the supervision of Prof. Subhendu Rakshit.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

19.06.2020

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This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

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Dedicated to my family

ABSTRACT

One of the most popular beyond Standard Model (SM) scenarios to explain the hierarchy in fermion masses and mixings is through the introduction of scalar flavons and an Abelian U_{FN} horizontal symmetry. The flavon field can coherently oscillate around its zero temperature minimum due to the thermal corrections to its potential or if soft symmetry-breaking terms are introduced. Out-of-equilibrium decays of these scalars into SM particles in the early universe can potentially lead to the baryon asymmetry (BA). Moreover, owing to the asymmetric dark matter paradigm, flavons decaying into dark particles may set the correct dark matter (DM) abundance. We investigate whether the decays of flavons can simultaneously generate the observed baryon and dark matter abundance of the universe.

We extend the SM by a scalar flavon and two fermions representing the dark sector. A $\mathcal{Z}_2$ symmetry is introduced in addition to the horizontal U_{FN} symmetry. Since the flavon decay produces entropy, the number density of flavon drops with increasing flavon mass (m_σ). We exclude the possibility of higher flavon mass for the successful generation of BA. Also, the bounds from flavor changing neutral current (FCNC) processes suggest a typical limit $\sqrt{m_\sigma \Lambda} >$ few TeV where Λ is the flavon scale. Even if the flavon scale is too large making the collider experiment irrelevant, a very small m_σ decreases the flavon decay width ($\Gamma_S \sim {m_\sigma}^3$) causing late decays of flavon which can destroy the BBN predictions. Hence $m_\sigma \sim 1$ TeV is a favourable choice for this benchmark model. The relatively long-lived flavon dominates the energy density of the universe while decaying into SM and DM particles. The baryon asymmetry is produced via a mechanism similar to the Dirac leptogenesis from an initial flavon asymmetry which is generated from coherent oscillations of the flavon. The small decay width leads to the decoupling of the LR and DM asymmetry yield equations. We will further study the BEs in order to estimate the asymmetries and get bounds on the decay rates and masses of the DM contents.

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Chapter 1

Introduction

Physicists have been putting all their efforts to learn the language of the universe for centuries but the amount of puzzles to solve is unimaginable. Attempting to understand the mysteries, the great minds have presented beautiful theories to mankind with the help of all the knowledge their predecessors accumulated and the amazing achievements of fellow experimentalists. Among the most successful theories, The Standard Model (SM) of particle physics, developed during the latter half of the twentieth century, can explain the nature of the visible matter of the universe quite astonishingly. Empowered with the SM and the standard cosmology, scientists were able to trace back to the Planck scale (10^{19} GeV) which is approximately 10^{-43} seconds after the Big Bang.

The SM predicted the existence and properties of W and Z bosons, top and charm quarks, Higgs boson and massless neutrinos but the revelations came with more unsolved questions. The hot big bang nucleosynthesis (BBN) model does not incorporate matter-antimatter asymmetry but the universe we see is matter-dominated. The hierarchy in quark and lepton masses and their mixings are merely a coincidence in the context of SM. Also, the neutrinos are left-chiral and massless in the framework of SM. Introducing right-handed neutrinos in order to generate small left-handed neutrino masses costs us to introduce a very high energy scale.

Over the past few decades, astronomical observations have verified the existence of a non-luminous mass density namely the dark matter (DM). The particle physicists interprets the DM as a hidden sector of matter. The

DM contributes dominantly to the masses of the galaxies and it is the key character in the galaxy structure formation of our universe. There is no constituent of DM in the SM but the same order of the energy densities of DM and visible matter suggests the plausibility of the same origin.

In the pursuit of a satisfactory answer, we aim to encounter the fermion mass ratios, their mixings and the matter-antimatter asymmetry of the universe in a framework that contains DM candidates. We expect to explore possible implications of the origin of matter. We begin by summarising the relevant topics on flavons and baryon asymmetry (BA) generation.

1.1 The Standard Model

There are four known fundamental forces in Nature. Except for the gravitational force, the other three have been moulded in gauge theories forming the *Standard Model of Particle Physics*. The gauge theories must have some internal symmetries governing the dynamics of the system within the framework of quantum field theory. If the symmetry is local, there ought to be a gauge boson existing in the theory in order to make the theory gauge invariant. There are conserved quantities named Noether charges corresponding to each symmetry. This section contains a brief review of the symmetries, conserved charges and gauge bosons of the SM. In addition to that short outlines of the Higgs mechanism and global symmetries are discussed.

1.1.1 Symmetries, Charges and Gauge Bosons

The theory of Quantum Electrodynamics (QED) was called “the jewel of physics” by Richard Feynman for its extremely accurate predictions. The theory is renormalisable and the governing gauge symmetry is an Abelian U(1) symmetry. The associated gauge boson, the photon, is massless.

The weak and electromagnetic interactions are invariant under weak isospin $\mathrm{SU}(2)_{\mathbb{L}}$ and hypercharge $\mathrm{U}(1)_Y$ transformations. The strong interactions of the quarks respect the $SU(3)_c$ symmetry.

	$SU(3)_c$	$SU(2)_{\mathbb{L}}$	$U(1)_Y$	Chirality
q	3	2	1/6	left
u	3	1	2/3	right
d	3	1	-1/3	right
ℓ	1	2	-1/2	left
e	1	1	-1	right

Table 1.1: SM fermions and their charges.

The bosons in weak interactions were found to be massive unlike the photon. The $SU(2)_{\mathbb{L}} \times U(1)_Y$ invariant Lagrangian that was developed by Weinberg and Salam during 1967-'68 employing the idea of spontaneously broken gauge theory is now known as the *Standard Electroweak Model.* The mass terms of $Z, W^{\pm}$ bosons are generated from the Lagrangian spontaneously breaking the gauge symmetry by the non-zero vacuum expectation value (VEV) of Higgs boson which has been discussed in the next section. In SM, only the left-handed fermions form $SU(2)_{\mathbb{L}}$ doublets. The Gellmann-Nishijima formula provides a relation between the isospin, hypercharge and electromagnetic charge of a particle,

$$Q = \frac{T^{(3)}}{2} + Y$$

Along with the gauge group $SU(3)_c$ for strong interactions formulated in the theory of Quantum Chromodynamics (QCD), the $SU(3)_c \times SU(2)_{\mathbb{L}} \times U(1)_Y$ transformations keep the SM Lagrangian invariant. Only the quarks carry $SU(3)_c$ colour charges and hence, take part in strong interactions. The gauge boson in strong interactions is called gluon (g). There are four gauge bosons in the theory of electroweak interactions (${W_\mu}^{(1,2,3)}, B_\mu$). The physical (electrically) charged EW bosons, $W^{\pm}$ are linear combinations of $W^{(1,2)}$. The third component of the triplet $W^{(3)}$ and the singlet B combine to give neutral bosons — the photon (γ) and Z.

1.1.2 Spontaneous Symmetry Breaking and Higgs Mechanism

Let us consider a complex scalar doublet $\Phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$ write down the non-derivative terms, usually called the potential of the theory, respecting the EW $SU(2)_{\mathbb{L}} \times U(1)_Y$ symmetry.

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$$

In order to get a lower bound on the energy of the system, the parameter λ

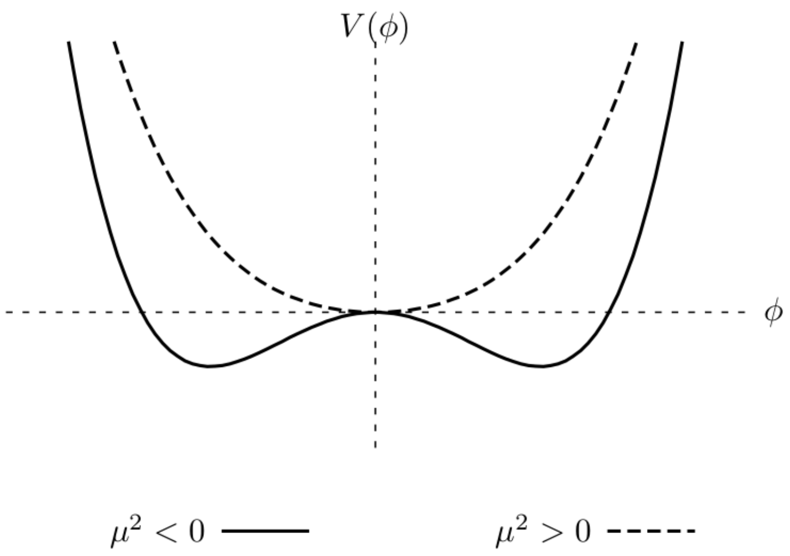

Figure 1.1: Potential $V(\Phi)$ realised in one dimension.

must be positive. But there is no such constraint on the other parameter. A positive μ^2 can simply be realised as the mass of the particle corresponding to the field ϕ. In the case $\mu^2 < 0$, there are an infinite number of degenerate minima lying at $\langle \Phi^\dagger \Phi \rangle = \frac{v^2}{2}$. Quantum fields are expandable in creation and annihilation operators and have vanishing vacuum expectation value (VEV). The annihilation operator acting on the ground state from the left and the creation operator from the right produces zero. The doublet field Φ can not be a quantum field due to its non-zero VEV. If the system chooses the ϕ_3 direction, $\langle \phi_3 \rangle^2 = \frac{v^2}{2}$, considering h as the fluctuation around the minima in the direction of ϕ_3, the doublet can be expressed as

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}.$$

The only remnant h, namely the Higgs field, will be a quantum field with vanishing VEV.

The covariant derivative term of the field Φ, $(D_\mu \Phi^\dagger)(D^\mu \Phi)$, when expanded around the minima, gives rise to the gauge boson masses. The alignment is such that it prevents the photon to get mass. Electromagnetic $U(1)_{em}$ is the remaining gauge symmetry of the Lagrangian after the spontaneous breaking of $SU(2)_{\mathbb{L}} \times U(1)_Y$ has taken place. The fermion masses are proportional to their couplings to the Higgs doublet. A theoretical argument to study beyond SM is the ratios of these couplings, which has been discussed in section 1.4.

In 2012, the finding of a new particle with mass 125 GeV was reported and lated it was confirmed to be the Higgs boson.

1.1.3 Accidental Symmetries of SM and Sphalerons

The SM Lagrangian was developed respecting the Poincare symmetry and the internal gauge symmetries. In order to make the theory renormalisable, only interaction terms with a mass dimension four or less were considered in the process. Also, there were a limited number of particle fields to begin with. Baryon and each generation lepton number conservation, arise from these constraints. The fact that these symmetries were not introduced when the Lagrangian was developed, indicates these symmetries are accidental.

If we sacrifice our constraint of renormalisability and consider a dimension 6 term $q_{\mathbb{L}} q_{\mathbb{L}} q_{\mathbb{L}} \ell_{\mathbb{L}}$ in the Lagrangian with the following transformation under the gauge group $SU(3)_c \times SU(2)_{\mathbb{L}} \times U(1)_Y$,

$$q_{\mathbb{L}} : (3, 2, \frac{1}{6}) \quad \text{and} \quad \ell_{\mathbb{L}} : (1, 2, -\frac{1}{2}).$$

The three quark field can make a colour singlet and the four $SU(2)_{\mathbb{L}}$ doublets can combine to a $SU(2)_{\mathbb{L}}$ singlet. The weak hypercharge of this term is clearly zero. The baryon and lepton number violation is obvious in this interaction.

The global symmetries are respected in the tree level but are anomalous in the quantum theory of non-perturbative interactions (instantons), though the associated rates of these processes are highly suppressed. The

$B + L$ number is violated but the three $\frac{B}{3} - L_\alpha$ numbers are conserved. The instantons are realised as the tunneling between minima of the periodic vacuum fluctuations. The sphaleron is a configuration where, in the presence of Higgs VEV, thermal fluctuation of the field enables it to climb over the potential barrier. The $B + L$ violation rate for the sphaleron is Boltzmann suppressed.

1.2 Objective

One of the most successful theories of physics, the SM, faced empirical and aesthetic displeasure in the last few decades. The evidence of DM and baryon asymmetry are suggestive empirical demonstrations about the incompleteness of SM. Among the primary philosophical arguments, the hierarchy problem is approached for the present case.

1.2.1 Existence of the Dark Matter

The idea of the existence of a non-luminous mass density, namely the dark matter was first reported in 1933 by investigating the motion of the Coma cluster of galaxies using the virial theorem. Since then, various observations have established the case of DM [20]. The power spectrum of the CMB anisotropy determines the cosmological parameters by fitting the spectrum to the flat ΛCDM model [21].

$$\Omega_M h^2 = 0.127^{+0.007}_{-0.013} \text{ and } \Omega_B h^2 = 0.0223^{+0.0007}_{-0.0009},$$

where Ω_M and Ω_B are the matter and the baryonic fraction of the critical energy density, $\Omega_{M,B} = \frac{\rho_{M,B}}{\rho_{crit}}$ and h is the present hubble parameter. So the most of the matter of our universe is non-baryonic, $(\Omega_M - \Omega_B)h^2 = 0.107^{+0.007}_{-0.013}$.

Another method to determine the BA is to measure the abundances of the light elements based on BBN. The study of primordial (at high redshift) hydrogen gas leads us to measure the deuterium abundance [22] and eventually, we obtain the baryon density, $\Omega_B h^2 = 0.0216^{+0.0020}_{-0.0021}$ which is consistent with the measurement from CMB anisotropy. The results referring to two very different epochs of the evolving universe, $T \sim 1$ MeV (BBN) and $T \sim 0.1$ eV (CMB), are in agreement giving us confidence on the determined BA.

The power spectrum of the correlation function between the galaxies is another novel technique to measure the matter density that uses large scale structures. The power spectrum shows "baryon oscillation" due to the acoustic oscillation of baryon-photon fluid [23]. The result, $\Omega_M h^2 = 0.130 \pm 0.010$, again confirms the need for non-baryonic DM.

There are other methods for measuring the density of "missing mass". From the rotation curve of the spiral galaxies, there is conclusive evidence for invisible matter far beyond the most distant stars from the galaxy center. This is determined from the doppler shift of the 21 cm line emission from cold hydrogen atoms residing in that outskirts. The rotation speed is found to be constant well beyond the outermost star of the galaxy.

The observation of the galaxy cluster 1E 0657-56, also known as the "Bullet Cluster", gives direct evidence that the dominant mass of the cluster is dark. The cluster was formed due to the collision of two large cluster of galaxies. The optical image shows that the hot gas was slowed during the collision but the image formed using the effect of gravitational lensing clearly indicates that most of the mass do not make an impact.

1.2.2 The Baryon Asymmetry of the Universe

As discussed in section 1.2.1, the value of baryon asymmetry in our universe is inferred in two different ways — via BBN [22] (abundances of the light elements D, ^{3}He, ^{4}He and ^{7}Li) and from the measurements of Cosmic Microwave Background anisotropies [21] (decomposing the signal into spherical harmonics). It is convenient to define the asymmetry relative to the entropy density, $s = \frac{2\pi^2}{45} g_* T^3$ because in the expanding universe the entropy of a comoving volume is conserved. The observed baryon asymmetry of our universe,

$$Y_{\Delta B} = \left.\frac{n_B - n_{\bar{B}}}{s}\right|_{present} = (8.75 \pm 0.23) \times 10^{-11}.$$

The mere existence of sphalerons can not generate the correct order of BA from a symmetric universe in the SM framework. This requires us to look beyond the SM.

1.2.3 Hierarchy in Fermion Masses and Mixings

The hierarchy in the masses of different generations of quarks and leptons and their mixing angles can not be explained in the SM of particle physics. It is plausible that there exists a more fundamental theory behind the quarks to Higgs couplings. The mass ratios in the quark sector are listed below,

$$\frac{m_d}{m_s} = 0.051 \pm 0.004, \quad \frac{m_s}{m_b} = 0.032 \pm 0.012,$$
$$\frac{m_u}{m_c} = 0.0038 \pm 0.0012, \quad \frac{m_c}{m_t} \sim 0.006^{+0.003}_{-0.002}$$
$$\text{and} \quad \frac{m_b}{m_t} \sim 0.025^{+0.015}_{-0.008}.$$

The masses of the quarks and leptons approximately satisfy,

$$m_t : m_c : m_u \simeq 1 : \epsilon^2 : \epsilon^4 \text{ and } m_b : m_s : m_d \simeq m_\tau : m_\mu : m_e \simeq 1 : \epsilon : \epsilon^3.$$

And the mixing angles [12],

$$|V_{us}| = 0.2205 \pm 0.0018, \quad |V_{cb}| = 0.040 \pm 0.007 \; and \; \frac{|V_{ub}|}{|V_{cb}|} = 0.10 \pm 0.03.$$

The objective of this project is to approach the three reasons listed in the previous section and provide a framework that accommodates these established facts into the extended SM with minimum particle content.

1.3 Approach Towards the Model

We start with one of the most popular and interesting mechanisms that generates the hierarchy in fermion masses and their mixings. A brief review of the elements of baryogenesis leads us to the proper path to produce BA from the flavon. Keeping the same order of the DM and baryon energy density in mind, $\frac{\Omega_{DM}}{\Omega_B} \sim 5$, we take an approach similar to cogenesis of DM and BA.

1.3.1 Generating Mass Matrix from Froggatt-Nielsen Mechanism

Among all the ideas proposed to dynamically generate the Yukawa couplings, the most compelling idea was from Froggatt and Nielsen in 1978 [3]. In the Froggatt-Nielsen (FN) mechanism, these hierarchies are generated from a spontaneously broken global or gauge $U(1)_{FN}$ horizontal symmetry. Generally in FN models, the SM is extended with at least a scalar S, known as flavon, having a global $U(1)_{FN}$ charge that couples to the SM particles in effective field theory through higher-dimensional interactions. The flavon and SM fermions are charged under this symmetry whereas Higgs remains uncharged.

$$\mathcal{L}_{FN} = \sum_{i,j=1}^{3} \left[y^{\mathrm{u}}_{\mathrm{ij}} \left(\frac{S}{\Lambda}\right)^{n^{\mathrm{u}}_{\mathrm{ij}}} \bar{Q}_i \tilde{\Phi} u_j + y^{\mathrm{d}}_{\mathrm{ij}} \left(\frac{S}{\Lambda}\right)^{n^{\mathrm{d}}_{\mathrm{ij}}} \bar{Q}_i \Phi d_j \right] + \text{ h.c.},$$

where Φ, Q_i, u_j and d_j denote the Higgs, quark doublets, up-quarks and down-quarks respectively. The dimensionless couplings are denoted as y_{ij}. $n^{\mathrm{u/d}}_{\mathrm{ij}}$ are integer numbers that depend upon the $U(1)_{FN}$ charges of S and SM quarks,

$$n^{\mathrm{u/d}}_{\mathrm{ij}} = H(\bar{Q}_i) + H(u_j/d_j).$$

A similar coupling can be written for the lepton sector of SM. The scalar S gets a VEV v_s and spontaneously break the $U(1)_{FN}$ symmetry leading to the Yukawa couplings and quark masses and mixing. The scalar potential for S can be constructed as,

$$\mathcal{V}_S = -\mu^2_{\mathrm{S}}|S|^2 + \lambda_S|S|^4 + \lambda_{S,\Phi}|S|^2|\Phi|^2 + \text{ U(1) breaking terms.}$$

The flavon-Higgs mixing term is unavoidable. After both the $U(1)_{FN}$ and the EW symmetry are broken, it contributes to the flavon and Higgs mass parameters. This poses a problem unless $\lambda_{S,\Phi}$ is extremely suppressed. A small $\lambda_{S,\Phi}$ points to an unbroken symmetry in the high energy theory of flavon. This is achieved by building explicit models which is beyond the scope of this study.

The flavon acquires a VEV $v_s/\sqrt{2}$ spontaneously breaking the $U(1)_{FN}$

symmetry,

$$\langle S\rangle = \frac{v_s}{\sqrt{2}}, \quad S = \frac{1}{\sqrt{2}}(v_s + \sigma + i\rho).$$

During EWSB, Higgs gets a VEV, $v_\Phi = 246$ GeV. The mass terms for the SM quarks can be written as,

$$\mathcal{L}_{mass} = \sum_{i,j=1}^{3}\left[y^{\rm u}_{\rm ij}\,\frac{v_\Phi}{\sqrt{2}}\,\epsilon^{n^{\rm u}_{\rm ij}}\,\bar{u}_i u_j + y^{\rm d}_{\rm ij}\,\frac{v_\Phi}{\sqrt{2}}\,\epsilon^{n^{\rm d}_{\rm ij}}\,\bar{d}_i d_j\right] + \text{ h.c.}$$

where the parameter ϵ was earlier defined as $\epsilon = \frac{v_s}{\Lambda}$.

The mass hierarchy and the mixing angles depend upon different powers ϵ^n. The powers to ϵ are determined from the horizontal charges of different quark doublets and singlets.

$$|V_{us}| \sim \epsilon^{H(\bar{Q}_1)-H(\bar{Q}_2)}, \; |V_{cb}| \sim \epsilon^{H(\bar{Q}_2)-H(\bar{Q}_3)}, \; |V_{ub}| \sim \epsilon^{H(\bar{Q}_1)-H(\bar{Q}_3)}$$
$$\frac{m_{d_i}}{m_{d_j}} \sim \epsilon^{H(\bar{Q}_i)-H(\bar{Q}_j)+H(\bar{d}_i)-H(\bar{d}_j)} \text{ and } \frac{m_{u_i}}{m_{u_j}} \sim \epsilon^{H(\bar{Q}_i)-H(\bar{Q}_j)+H(\bar{u}_i)-H(\bar{u}_j)}.$$

For a single flavon field, large powers of ϵ is needed to generate the observed hierarchy thus needing more number of intermediate fermions in the fundamental theory which gives rise to the effective Lagrangian of FN. We can reduce the powers by adding more scalar flavons in the theory which will introduce more ϵ parameters in the model.

Reproducing the masses and mixings of SM quarks constraints the $\epsilon = \dfrac{v_s}{\sqrt{2}\Lambda}$ ratio, $\text{U}(1)_{FN}$ charges and the $y^{\rm u/d}_{\rm ij}$ couplings but leaves the UV scale Λ and scalar mass m_σ as free parameters to some extent [5]. There is no unique choice of the $\text{U}(1)_{FN}$ charges due to the freedom of $y^{\rm u/d}_{\rm ij}$ parameters. The strong bounds from flavour changing neutral current (FCNC) processes limit us to investigate in the range $m_\sigma > 10$ GeV and TeV $< \Lambda < M_{Pl}$, where M_{Pl} is the Planck mass.

1.3.2 Ingredients of Baryogenesis

The Sakharov Conditions

The three conditions given by Sakharov to generate baryon asymmetry dynamically are [1],

- Baryon number violation: Baryon number violation is required as we start from a $B = 0$ universe.

- C and CP violation: Both C and CP must be violated to generate baryon asymmetry as the coupling constants must be complex.

- Departure from thermal equilibrium: In thermal equilibrium the average baryon number $\langle B \rangle_T$ vanishes. So in order to generate baryon asymmetry the out-of-equilibrium condition must be satisfied.

B+L Anomaly and Baryogenesis from Leptogenesis

Since the sphalerons can violate the $B + L$, an asymmetry generated in the lepton sector before the sphalerons froze can be transferred to the quark sector. To get a quantitative relation between the baryon asymmetry and lepton asymmetry, chemical potentials are assigned to each LH quark doublets (q_i), RH quark singlets (u_i, d_i), LH lepton doublets (ℓ_i), RH lepton singlets (e_i) and the Higgs doublet (Φ). There are $5N_f + 1$ chemical potentials for N_f generations of fermions. Considering the particles are weakly coupled in the plasma of temperature T and volume V, the partition function can be written as,

$$Z(\mu, T, V) = \mathrm{Tr}[\exp\{-\beta(H - \sum_i \mu_i Q_i)\}],$$

where H is the hamiltonian and Q_i is the charge operator for the corresponding field. The asymmetry in i^{th} particle anti-particle number density,

$$n_i - \bar{n}_i = -\frac{\partial \Omega}{\partial \mu_i},$$

where the thermodynamic potential $\Omega = -\frac{T}{V} \ln Z(\mu, T, V)$. Assuming the plasma as a non-interacting gas of massless particles,

$$n_i - \bar{n}_i = \frac{1}{6} g_i T^3 \begin{cases} \beta\mu_i + \mathcal{O}((\beta\mu_i)^3) & \text{fermions,} \\ 2\beta\mu_i + \mathcal{O}((\beta\mu_i)^3) & \text{bosons,} \end{cases},$$

where g_i is the internal degrees of freedom of particle i. Quarks and leptons, both being fermion, have an equal number of internal degrees of freedom, $g_q = g_\ell \equiv g$. In a weakly coupled plasma, $\beta\mu_i \ll 1$. Hence, neglecting the higher-order terms, the baryon and lepton number densities,

$$n_B = \frac{1}{6} g B T^2 \quad \text{and} \quad n_{L_i} = \frac{1}{6} g L_i T^2,$$

where, in terms of chemical potentials of SM fermions, the baryon and the lepton numbers can be expressed as,

$$B = \sum_i (2\mu_{q_i} + \mu_{u_i} + \mu_{d_i}) \;\text{ and }\; L_i = \sum_i (2\mu_{\ell_i} + \mu_{e_i})$$
$$\text{with } \; L = \sum_i L_i.$$

L_i represents individual lepton number of each generation. The 2-factors arise due to the two fields present in the LH doublets, q_i (contains LH up-type and LH down-type quark) and ℓ_i (contains LH charged lepton and LH neutrino).

The SM fermions and Higgs interact via Yukawa and gauge couplings and also, via non-perturbative sphaleron processes. In thermal equilibrium, the chemical potentials of the SM particles are constrained by these interactions [6].

- **Yukawa and Gauge Interactions:** The Yukawa interactions, supplemented by the gauge interactions, give rise to the following relations among the chemical potential of the Higgs and fermions,
$$\mu_{q_i} + \mu_\Phi - \mu_{u_j} = 0 \;,\; \mu_{q_i} - \mu_\Phi - \mu_{d_j} = 0 \text{ and } \mu_{\ell_i} - \mu_\Phi - \mu_{e_j} = 0.$$
- **Hypercharge Conservation:** At all temperatures, the total hypercharge of the plasma is zero. This leads to the relation,
$$\mu_{q_i} + 2\mu_{u_i} - \mu_{d_i} - \mu_{\ell_i} - \mu_{e_i} + \frac{2}{N_f}\mu_\Phi = 0.$$
- **$\mathbf{SU(2)_{\mathbb{L}}}$ Instantons:** The effective interactions among LH fermions, $\prod_i (q_i q_i q_i \ell_i)$ induced by EW instanton processes yields the relation,
$$\sum_i (3\mu_{q_i} + \mu_{\ell_i}) = 0.$$
- **$\mathbf{SU(3)_{\mathit{c}}}$ Instantons:** The QCD instantons, $\prod_i (q_i q_i u_i^{\mathrm{c}} d_i^{\mathrm{c}})$ lead to,
$$\sum_i (2\mu_{q_i} - \mu_{u_i} - \mu_{d_i}) = 0.$$

These relations hold until the sphalerons decouple. When $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_{\mathbb{L}} \times \mathrm{U}(1)_Y$ symmetry is intact, all the Yukawa interactions are in thermal equilibrium. The sphalerons violate the baryon and lepton number conservation but preserve the $L_i - \dfrac{B}{N_f}$ asymmetry. Thus different generations of SM fermions are in equilibrium, $\mu_q \equiv \mu_q$ and $\mu_{\ell_i} \equiv \mu_\ell$. Now, there are $5N_f + 1$ chemical potentials and $5N_f$ constraints for N_f generation of fermions. Choosing μ_ℓ as the independent potential,

$$\mu_e = \frac{2N_f + 3}{6N_f + 3}\mu_\ell \ , \ \mu_d = -\frac{6N_f + 1}{6N_f + 3}\mu_\ell \ , \ \mu_u = \frac{2N_f - 1}{6N_f + 3}\mu_\ell \ ,$$

$$\mu_q = -\frac{1}{3}\mu_\ell \ \text{ and } \ \mu_\Phi = \frac{4N_f}{6N_f + 3}\mu_\ell .$$

Substituting these relations into the expression of B and L, we get the connection between B and L asymmetry:

$$B = -\frac{4}{3}L\left(\frac{6N_f + 3}{14N_f + 9}\right).$$

So the analysis shows that a violation of the lepton number can lead to a violation of the baryon number which, in turn, satisfies Sakharov's first condition. The relation holds until the sphalerons decouple.

Dirac Leptogenesis

The motivation behind Dirac leptogenesis was to give the active neutrinos Dirac mass and simultaneously produce the BA [13]. If an asymmetry can be generated in the left-handed (LH) leptons, it can be transferred to the quark sector via sphaleron. Since the sphaleron only couples the LH quark doublets to the LH lepton doubles, a non-zero BA can be produced without lepton number violation (except of course by the spharelon). The small Yukawa couplings of neutrinos, $\lambda \lesssim 10^{-11}$, implies that the lepton number stored in LH and RH neutrinos will not reach equilibrium until the temperature falls well below EWSB [14, 15, 16].

The idea can be implemented in the following way. The decay of a heavy particle; i.e. the flavon in the present scenario; produces non-zero lepton number for the LH lepton doublets and an equal but opposite lepton number in RH lepton singlets keeping the total lepton number zero. The Yukawa interaction rate, $\Gamma_\lambda \sim \lambda^2 T$ [17] becomes significant when it reaches the expansion rate, $H \sim \dfrac{T^2}{M_{Pl}}$ where M_{Pl} is the Planck mass. So the left-right LR equilibration happens around the temperature $T \sim \dfrac{\lambda}{10^8} T_{EWSB}$. Before EWSB a fraction of the LR asymmetry has already been transferred to the baryon sector by sphaleron interactions. At much lower temperature, when the sphalerons are frozen, the LR asymmetry equilibrates but a net baryon and lepton number remain.

The non-zero LH lepton number can be produced from an initial flavon asymmetry. Since the flavon is a scalar field, it is possible to generate a non-zero flavon number from the Affleck Dine mechanism as we discuss below.

Baryogenesis from Affleck-Dine Mechanism:
A Non-supersymmetric Scenario

The recent experiments lead us to a position where the existence of supersymmetry is the least possible. We look forward to a non-supersymmetric scenario that generates an asymmetry in a complex scalar field.

Consider the Lagrangian of a single complex scalar field ϕ,

$$\mathcal{L} = \frac{1}{2}|\partial_\mu \phi|^2 - \frac{1}{2}m^2\phi^2.$$

The Lagrangian has a global $U(1)$ symmetry, $\phi \to e^{i\alpha}\phi$, with the corresponding conserved current,

$$j^\mu = i(\phi^* \partial^\mu \phi - \phi \partial^\mu \phi^*).$$

The Lagrangian also possesses a CP symmetry: $\phi \leftrightarrow \phi^*$.

Now thinking of a field constant throughout the space $\phi(\vec{x}, t) = \phi(t)$, we can picturise the behavior of the function as isotropic harmonic oscillator throughout the space from Klein-Gordon (KG) equation. If we consider the charge corresponding to the U(1) symmetry as F-number, the initial flavon number remains unchanged through time. Adding more U(1)-symmetric term, i.e. $\lambda|\phi|^4$, would not change the case. We can not produce baryon asymmetry unless we break the symmetry from a "symmetric origin" [7].

In terms of amplitude and phase the complex field, $\phi = re^{i\theta}$, has a conserved charge,

$$F = i\int \mathrm{d}^3x(\phi^*\dot{\phi} - \phi\dot{\phi}^*) = -2\int \mathrm{d}^3x\; r^2\dot{\theta}.$$

If initially $F = 0$, the phase θ remains frozen with time and no asymmetry is generated. Now let us add some soft-symmetry breaking terms to the U(1)-symmetric Lagrangian,

$$\mathcal{L}_{breaking} = \epsilon\phi^3\phi^* + \delta\phi^4 + \text{c.c.}$$

These interactions are clearly violating F and also CP for a general complex

ϵ and δ. In order to generate an appreciable amount of F asymmetry from these couplings, the field needs to be very large at early times. Since flavon as a complex scalar field can decay to the SM particles, any asymmetry generated in flavon can be transferred to the baryons.

1.3.3 Extending by Dark Matter Candidate in Cogenesis Scenario

The same order of the DM and baryon energy densities suggests a common origin to these. The asymmetric flavon can decay into SM producing a left-right (LR) asymmetry which in turn generates the BA. The recent study [11] was able to produce the correct amount of BA of the universe. We aim to minimally extend the SM by appropriate $U(1)_{FN}$ charged DM candidates which can simultaneously incorporate the puzzle of dark matter. The model has been thoroughly discussed in chapter 2.

1.4 The Quantitative Way of Determining Particle Abundance: The Boltzmann Equation

In the early stages of the universe, all the particles present in the plasma were in thermal equilibrium and their evolution could be easily described to a good approximation. However, the universe cooled down with the expansion and particles decoupled from the plasma with the rough criterion, $\Gamma \lesssim H$. When a particle decouples from the plasma, its number density simply decreases as a^{-3}, and momenta decreases as a^{-1} with a being the scale factor [28]. To properly treat the evolution of a species during the epoch of its decoupling, we must use the Boltzmann Equation (BE) which governs the microscopic evolution of the particle's phase-space distribution.

In a quantitative analysis, a species in plasma is assumed to follow the Maxwell-Boltzmann statistics. A particle of mass m_i has the equilibrium phase space density,

$$f_i^{eq}(E_i, T) = \exp(-\frac{E_i}{T}).$$

The density of the i^{th} particle,

$$n_i(T) = \frac{g_i}{2\pi^3} \int \mathrm{d}^3 p_i f_i,$$

where g_i is the internal degrees of freedom of the species. A higher rate of elastic scatterings than inelastic scatterings implies kinetic equilibrium. Hence, the phase space density can be written as,

$$f_i(E_i, T) = \frac{n_i}{n_i^{eq}} \exp\left(-\frac{E_i}{T}\right).$$

In the thermal bath, the entropy of a comoving volume remains constant, $sR^3 =$ constant, where s is the entropy density and R is the scale factor of the expanding universe. The fiducial quantity, entropy density, $s = g_* T^3 \sqrt{\frac{2\pi^2}{45}}$ is used to eliminate the effects of the expansion. The number of particles in a comoving volume is defined as $Y_i = \frac{n_i}{s}$. Imposing the variable $x = \frac{m}{T}$ as the independent variable, where m is any convenient mass scale (usually of the particle of interest), the BE describing the evolution of Y_i is given by [18, 19],

$$\frac{\mathrm{d}Y_i}{\mathrm{d}x} = -\frac{x}{sH(m)} \sum_{j,a,b,...} \left[\frac{Y_i Y_j ...}{Y_i^{eq} Y_j^{eq} ...} \gamma^{eq}(i + j + ... \to a + b + ...) - \frac{Y_a Y_b ...}{Y_a^{eq} Y_b^{eq} ...} \gamma^{eq}(a + b + ... \to i + j + ...) \right],$$

where $H(m) = \pi \sqrt{\frac{g_*}{90}} \frac{m^2}{M_{Pl}}$ is the Hubble parameter at $T = m$ with Planck mass M_{Pl}.

Neglecting the CP violation allows us to take the rates of forward and backward processes to be equal. In a dilute gas, we only need to consider the decay and two-body scatterings. For decay processes,

$$\gamma^{eq}(i \leftrightarrow a + b + ...) = n_i^{eq} \frac{K_1(x)}{K_2(x)} \Gamma_0,$$

where Γ_0 is the usual decay rate of particle i and the ratio of the modified Bessel functions comes from the finite temperature correction [19]. For two-body scattering we have,

$$\gamma^{eq}(i + j \leftrightarrow a + b + ...) = \frac{T}{64\pi^4} \int_{(m_i + m_j)^2}^{\infty} \mathrm{d}s' \hat{\sigma}(s') \sqrt{s'} K_1(\frac{\sqrt{s'}}{T}),$$

where $s' = (p_i + p_j)^2 = (E_i + E_j)^2$ is the total energy squared. The reduced cross-section $\hat{\sigma}(s')$ can be expressed in terms of usual cross-section $\sigma(s')$ as,

$$\hat{\sigma}(s') = \frac{8}{s'}\left[(p_i.p_j)^2 - m_i^2 m_j^2\right]\sigma(s').$$

The evolution of a species departing from thermal equilibrium while decaying can be analysed approximately using the Boltzmann equation. These useful relations will be used for determining the BA and DM abundance in our model.

Chapter 2

Asymmetric DM and Baryogenesis from Flavon Asymmetry

The study of DM in various mass ranges is one of the most popular areas to examine in particle physics phenomenology. An encounter with the hierarchy problem, BA and the DM in one model is rarely studied in the cogenesis scenario.

We propose a model based on the standard FN mechanism with one flavon field S and two fermionic fields χ_a and χ_b representing DM extends the SM of particle physics with a global $\mathrm{U}(1)_{FN}$ symmetry. The generally used $\mathrm{U}(1)_{FN}$ charge of the flavon is -1. χ_a is charged $+1$ and χ_b is uncharged under $\mathrm{U}(1)_{FN}$. The SM fermions are also charged under the $\mathrm{U}(1)_{FN}$ symmetry but the Higgs is uncharged. The interaction terms of the flavon to the DM particle field do not contain the Higgs field,

$$\mathcal{L}_{Flavon-DM} \supset d_{ab} S \bar{\chi_b} \chi_a + \text{h.c.}$$

A $\mathcal{Z}_2$ symmetry is introduced to prevent DM decays into the SM particles. Only the DM candidates χ_a and χ_b are charged odd under this symmetry. The flavon and the DM fields are not charged under the SM gauge group.

In order to successfully generate the mass hierarchy and the mixing, we have to roughly aim,

$$\epsilon \sim |V_{us}|,\ \epsilon^2 \sim |V_{cb}|, \frac{m_d}{m_s}, \frac{m_s}{m_b}, \frac{m_b}{m_t},\ \text{and}\ \epsilon^3 \sim |V_{ub}|, \frac{m_u}{m_c}, \frac{m_c}{m_t},$$

In section 1.3.1 the powers of ϵ are already listed as the horizontal charge differences of different quark doublets and singlets. We choose $H(\bar{Q}_3) = 0$ and the other charges of the quark doublets can be determined equating the powers to proper charge differences. From the mixing angles, $H(\bar{Q}_1) - H(\bar{Q}_2) = 1$ and $H(\bar{Q}_2) - H(\bar{Q}_3) = 2 \implies H(\bar{Q}_2) = 2, H(\bar{Q}_1) = 3$. Now to have non-zero flavon to quark coupling for each quark type we choose $H(u_3) = 1$ and $H(d_3) = 1$. From the mass ratios,

$$\begin{aligned} H(\bar{Q}_i) - H(\bar{Q}_j) + H(u_i) - H(u_j) &= 3 \\ \text{and } H(\bar{Q}_i) - H(\bar{Q}_j) + H(d_i) - H(d_j) &= 2, \end{aligned}$$

the $U(1)_{FN}$ charges of the singlet right-handed quarks can be calculated. The charges of the flavon, quarks and DM candidates are listed below.

Field	S	$\bar{Q}_1$	$\bar{Q}_2$	$\bar{Q}_3$	u_1	u_2	u_3	d_1	d_2	d_3	χ_a	χ_b
$U(1)_{FN}$	-1	$+3$	$+2$	0	$+4$	$+2$	$+1$	$+2$	$+1$	$+1$	$+1$	0
$\mathcal{Z}_2$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$-$	$-$

Table 2.1: $U(1)_{FN}$ and $\mathcal{Z}_2$ charge of the particles.

2.1 Flavon Asymmetry

In this scenario, a large flavon asymmetry is required to generate the BA and DM abundance. The scalar dynamics is achievable in the Affleck Dine scenario. The S-number violating terms can provide a kick to the field to oscillate. If the U$(1)_{FN}$ is local, the Goldstone mode gets eaten and the only real scalar does not allow us to introduce U$(1)_S$ and define S-number. For the case of global U$(1)_{FN}$, explicit models [8, 9] allow us to consider an approximate U$(1)_S$ symmetry.

The asymmetric flavon number density, n_S is related to the initial flavon asymmetry parameter η_S by,

$$n_S = \eta_S \frac{\rho_S}{m_\sigma},$$

where ρ_S is the flavon energy density. For a benchmark scenario, we will use $\eta_S = 1$.

2.2 Flavon Cosmology

Flavon is a weakly coupled complex scalar field. It can perform coherent oscillations around the zero temperature minimum of its potential. The flavon gets driven away from its $T = 0$ minima due to the soft symmetry-breaking terms [8] or thermal corrections to its potential [5]. Also it is a sufficiently long-lived particle. It decays while dominating the energy density of the universe. The energy density of the oscillation, ρ_S falls as a^{-3} but the energy density of radiation, ρ_{rad} drops as a^{-4} where a is the scale factor. The SM and DM particles produced from the flavon decay thermalises quickly and contributes to the radiation energy density. At time t_* and temperature T_* during the evolution of the universe the energy stored in the oscillations begins to dominate over the radiation energy, $\rho_S = \rho_{rad}$. The energy densities evolve as,

$$\frac{\mathrm{d}\rho_S}{\mathrm{d}t} + 3H\rho_S = -\Gamma_S \rho_S$$
$$\frac{\mathrm{d}\rho_{rad}}{\mathrm{d}t} + 4H\rho_{rad} = \Gamma_S \rho_S,$$

where Γ_S is the total decay width of the flavon and the Hubble constant, H is governed by the Friedmann equation,

$$H^2 = \frac{8\pi}{3M_{\mathrm{Pl}}^2}(\rho_S + \rho_{rad}).$$

The temperature of the radiation is related to the radiation energy density, $\rho_{rad} = \frac{\pi^2}{30} g_* T^4$. The flavon decays reheat the universe by producing the SM and DM particles in the thermal bath.

The coupled equations can be solved simultaneously with the yield equations numerically to estimate the abundances of the flavon, DM and baryons.

2.3 Left-Right Asymmetry in Lepton Sector

The flavon couplings to lepton sector can be realised as the decays,

$$S \to \bar{\ell}_{\mathbb{L}_i} \Phi \, e_{\mathbb{R}_j} \text{ and } S^* \to \ell_{\mathbb{L}_i} \Phi^\dagger \bar{e}_{\mathbb{R}_j},$$

where $\ell_{\mathbb{L}}$ and $e_{\mathbb{R}}$ are the LH lepton doublet and RH lepton singlet respectively. Clearly, lepton number is not violated in these interactions but a left-right asymmetry can be generated from an initial flavon-antiflavon asymmetry. The EW sphalerons only act on the left-handed particles. Before EWSB this asymmetry can be partially transferred to the baryons through sphaleron processes. This scenario is similar to Dirac Leptogenesis where a non-zero BA can be produced without violating $B - L$ as long as the right-handed lepton asymmetry survives after EWSB [14][26]. Right-handed electrons can equilibrate with SM particles via Higgs coupling or 2-to-2 scatterings with a rate $\Gamma_{LR} = 10^{-2} y_e^2 T$ [17]. Comparing this rate to the Hubble rate of a radiation-dominated universe, the equilibrium temperature for $e_{\mathbb{R}}$ is $T \sim 10^5$ GeV which is much before the EWSB at $T \sim 160$ GeV. However, for a scenario where the energy density is dominated by flavon until EW transition, this scenario may change and an asymmetry can remain in the right-handed electron after decoupling of the sphalerons.

2.4 Asymmetry in Dark Sector

The flavon decays into the dark sector and produces more χ_a and $\bar{\chi}_b$ than $\bar{\chi}_a$ and χ_b,

$$S \to \chi_a \bar{\chi}_b \text{ and } S^* \to \bar{\chi}_a \chi_b.$$

We consider that there exists an annihilation process into a hidden photon-like particle fast enough to eliminate the symmetric part of χ_a and χ_b,

$$\chi_a \bar{\chi}_a \to \gamma_D \gamma_D \text{ and } \chi_b \bar{\chi}_b \to \gamma_D \gamma_D.$$

The process was in equilibrium at the time when flavon decays were out-of-equilibrium. The excess χ_a and $\bar{\chi}_b$ survived to become the DM content of the universe.

2.5 Flavon Decay Rates

The two-body decay processes of flavon to DM particles, $S \to \chi_a \bar{\chi}_b$ and $S^* \to \bar{\chi}_a \chi_b$ have same decay rates in the tree level. The rate can be calculated easily to be,

$$\Gamma_{\rm DM} = \frac{1}{16\pi}|d_{ab}|^2 m_\sigma \left[1 - \left(\frac{m_a + m_b}{m_\sigma}\right)^2\right] \times \left[1 + \left(\frac{{m_a}^2 - {m_b}^2}{{m_\sigma}^2}\right)^2 - 2\left(\frac{{m_a}^2 + {m_b}^2}{{m_\sigma}^2}\right)\right]^{1/2}.$$

For the case $m_{a,b} \ll m_\sigma$, the decay rate can be approximated to be $\Gamma_{\rm DM} = \frac{1}{16\pi}|d_{ab}|^2 m_\sigma$. Since we have considered a single flavon for this model, the

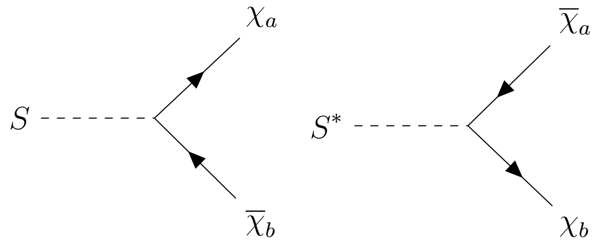

Figure 2.1: Flavon Decays to DM particles.

rates are also equal at the loop level.

During that time when the horizontal $U(1)_{FN}$ symmetry is broken and the electroweak symmetry remains intact, the flavon couplings to SM fields are realised through non-renormalisable interactions. The flavon field is expanded about its VEV. We have,

$$\mathcal{L}_{\Lambda>T>T_{EWSB}} \supset \sum_{i,j=1}^{3}\left[\frac{g^{\rm u}_{\rm ij}}{\Lambda}\sigma\bar{Q}_i\tilde{\Phi}u_j + \frac{g^{\rm d}_{\rm ij}}{\Lambda}\sigma\bar{Q}_i\Phi d_j\right] + \text{ h.c.},$$

where $g^{\rm u/d}_{\rm ij} \simeq \frac{y^{\rm u/d}_{\rm ij}}{\sqrt{2}}\, n^{\rm u/d}_{\rm ij}\, \epsilon^{n^{\rm u/d}_{\rm ij}-1}$.

In this time-range, the scalar σ can decay into three SM particles, $\sigma \longrightarrow \bar{Q}_i\Phi u_j$ or $\sigma \longrightarrow \bar{Q}_i\Phi d_j$. The decay width is given by [5],

$$\Gamma^{\rm u/d,UV}_{\rm ij} = \frac{N_c}{3}\frac{|g^{\rm u/d}_{\rm ij}|^2}{64\pi^3}\frac{{m_\sigma}^3}{\Lambda^2}.$$

In the lepton sector, flavon decays dominantly into the heaviest lepton τ. As a benchmark scenario, we will use only the first generation. The branching fraction of flavon decay to the RH electron, $B_e \sim \left(\frac{n_e y_e}{n_\tau y_\tau}\right)^2 \sim 7.5\times 10^{-7}$.

Neglecting the masses of leptons and Higgs, the decay width of S to the first generation leptons has a form,

$$\Gamma_{\rm SM} \simeq \frac{1}{2\epsilon^{2-2n_{ij}}}\frac{|n_e y_e|^2}{64\pi^3}\frac{{m_\sigma}^3}{\Lambda^2}.$$

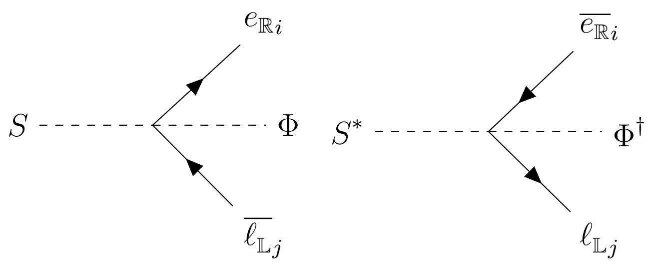

Figure 2.2: Flavon Decays to SM Leptons.

2.6 Washout and Transfer Processes

All the 2-to-3 scattering processes are listed below. The u-channel washout processes can change the DM and LR asymmetry by 1 unit each. Whereas the s-channel transfer processes can only transfer the asymmetry between two sectors.

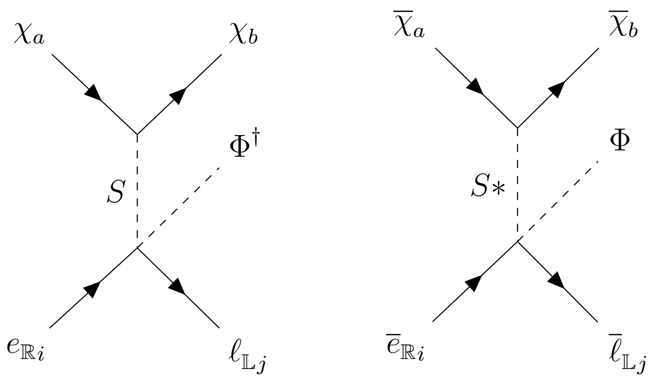

Figure 2.3: Feynman Diagrams of the Washout Processes.

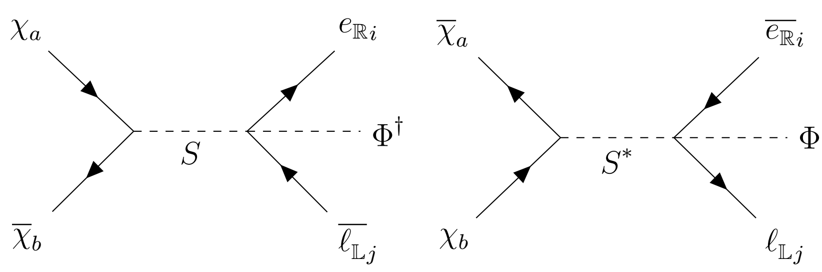

Figure 2.4: Feynman Diagrams of the Transfer Processes.

In addition to the decay and inverse decays, these scattering processes also have a role in the BA and DM abundance observed today.

2.7 Boltzmann Equations for LR Asymmetry and DM Abundance

Let us use the variables $Y_R = Y_{e_\mathbb{R}} - Y_{\bar{e}_\mathbb{R}}$ and $Y_D = Y_{\chi_a} = Y_{\bar{\chi}_b}$ for the asymmetric part of RH electrons and $\chi_{a,b}$. The BEs for Y_R and Y_D will contain the contributions from decay, inverse decay and transfer processes. In addition to these, the LR equilibration processes contribute only to the BE for Y_R. SM Lepton doublets and the Higgs are assumed to be in thermal equilibrium via the sphaleron process. Let us take the masses of the DM candidates are chosen to be equal for simplicity, $m_a = m_b$. The fast annihilation process in the dark sector allows us to consider $\bar{\chi}_a$ and χ_b to be in equilibrium and hence reduces the number of BEs to work with. The asymmetry in the number density of RH electrons and DM candidates can be found by solving these coupled BEs.

$$\frac{sH(m_\sigma)}{x}\frac{\mathrm{d}Y_R}{\mathrm{d}x} = -\left\{\frac{Y_R}{Y_\mathrm{R}^\mathrm{eq}} - \frac{Y_S}{Y_\mathrm{S}^\mathrm{eq}}\right\}\gamma_\mathrm{SM}^\mathrm{eq} - \frac{Y_R}{Y_\mathrm{R}^\mathrm{eq}}\gamma_\mathrm{LR}^\mathrm{eq} + (2 \leftrightarrow 3 \text{ washout } + \text{ transfer})$$

$$\frac{sH(m_\sigma)}{x}\frac{\mathrm{d}Y_D}{\mathrm{d}x} = -\left\{\left(\frac{Y_D}{Y_\mathrm{D}^\mathrm{eq}}\right)^2 - 1 - \frac{Y_S}{Y_\mathrm{S}^\mathrm{eq}}\right\}\gamma_\mathrm{DM}^\mathrm{eq} + (2 \leftrightarrow 3 \text{ washout } + \text{ transfer}),$$

where

$$\gamma_\mathrm{SM}^\mathrm{eq} = \gamma^{eq}(S, S^* \leftrightarrow \mathrm{SM}) = sY_\mathrm{R}^\mathrm{eq}\frac{K_1(x)}{K_2(x)}\Gamma_\mathrm{SM}$$

$$\text{and } \gamma_\mathrm{DM}^\mathrm{eq} = \gamma^{eq}(S, S^* \leftrightarrow \mathrm{DM}) = sY_\mathrm{D}^\mathrm{eq}\frac{K_1(x)}{K_2(x)}\Gamma_\mathrm{DM}.$$

- **Narrow-width Approximation:** We have already discussed that the flavon dominates the energy density of the universe due to its longer lifetime, $\Gamma_S \ll m_\sigma$ and ${\Gamma_S}^2 \ll m_\sigma H$. In this scenario the dominant source of washout is the inverse decay and the contributions from $2 \leftrightarrow 3$ processes can be ignored [25]. Hence the two BEs decouple and the asymmetries evolve independent of each other. Each equation can be solved simultaneously with the equations for ρ_S and ρ_{rad} evolution and hopefully the expected BA and DM relic density can be produced.

2.8 Summary and Conclusion

The Froggatt-Nielsen mechanism in single flavon scenario and the ingredients to generate baryon asymmetry was revisited as the first part of this work. Cogenesis of baryon and DM abundances is our motive in the latter part of the project. Generating the hierarchy in SM fermion masses and mixings by extending the SM with single scalar demands high powers of $\epsilon = \frac{v_S}{\Lambda}$ thus increasing the number of intermediate fermions in the UV theory. But it simplifies the study of abundances by restricting the CP violation only to its finite temperature potential. More than one flavon scenario can potentially make the decay rates of S and S^* different in the loop-level considering the couplings to be complex. Also the weak couplings of flavon to SM and DM particles causes its longer lifetime and domination in the energy density for an intermediate period in the evolution of the universe.

Due to the small decay width of flavon, the yield equations for LR and DM asymmetry decouple from each other and the abundances evolve independently in two sectors. Our plan in the future is to numerically solve the BEs and find the range of the decay rates Γ_{SM} and Γ_{DM} which can produce the correct baryon and DM relics.

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