Leptogenesis

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Abstract. Leptogenesis [1] is one of the leading mechanisms for explaining the observed baryon asymmetry in the universe. In this proceeding I review the basic features of leptogenesis, before discussing some recent developments in the theoretical computation of the resulting baryon asymmetry. Finally I comment on the possible connection with low energy neutrino data and testability of the mechanism.

1. Introduction

The baryon asymmetry of the universe (BAU) has been measured precisely both from observations of the cosmic microwave background (CMB), and from the abundances of light elements in the universe which depend on the baryon density at the time of big bang nucleosynthesis (BBN). Today the entropy normalised baryon asymmetry is known to be [2]

$$Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s} = (8.59 \pm 0.13) \times 10^{-11} \,, \tag{1}$$

where the relation to the baryonic energy density is given by $Y_{\Delta B} \approx 3.89 \times 10^{-9} \Omega_B h^2$ [3]. To generate such an asymmetry the three Sakharov conditions have to be satisfied: 1. Baryon number (B) must be violated; 2. C and CP must be violated; 3. The universe must depart from thermal equilibrium at some early time.

Within the standard model (SM) the first two conditions are satisfied, namely B is violated at high temperatures in the early universe by non-perturbative sphaleron processes, and C and CP are violated by the weak interactions and the quark Yukawa couplings. However the electroweak phase transition within the SM is not strong enough to allow departure from equilibrium, and no other strong phase transition is expected at higher temperatures, while at lower temperatures B violation is no longer active.

Leptogenesis is based on the see-saw mechanism, which explains the smallness of neutrino masses by introducing heavy right-handed neutrinos N_i. Yukawa couplings between the left-handed doublets lepton doublets and the right-handed neutrinos then induce masses for the SM neutrinos ν_i which are parametrically of the order $m_\nu \sim y^2 v^2/M$, where y is the neutrino Yukawa coupling, v is the Higgs vacuum expectation value and M is the right-handed neutrino mass scale. Sub-eV neutrino masses are then possible with order one couplings provided that the right-handed neutrino masses are of order 10^{9-15} GeV.

When the temperature in the early universe drops below the mass M_1 of the lightest right-handed neutrino, N_1, it will decay a lepton and a Higgs doublet, or their corresponding anti-particles. Complex phases in the neutrino Yukawa couplings can lead to CP violation in the decay rates, such that more leptons than anti-leptons can be produced in those decays. If the decay rate Γ is slower than the expansion rate of the universe $H(T)$ at temperatures $T \sim M_1$, the right-handed neutrino distributions will depart from thermal equilibrium, such that a net lepton asymmetry can be generated. This asymmetry is then partially transferred to the baryon sector through electroweak sphalerons, thus producing a baryon asymmetry in agreement with Sakharov's conditions. The departure from equilibrium of N_1 depends on the same combination of parameters as the resulting light neutrino masses, and it turns out that the observed neutrino masses are exactly consistent with the requirement $\Gamma/H(T = M_1) \approx \mathcal{O}(1)$.

2. Theory Progress

In order to understand whether the observed neutrino masses and mixing angles are consistent with the observed BAU, one has to be able to compute $Y_{\Delta B}$ as function of the Yukawa couplings and masses. In recent years a lot of progress has been made to formulate the problem using non-equilibrium quantum field theory, see e.g. [4, 5, 6], and references therein for earlier work.

The main advantage of this approach is that it provides a robust framework for deriving and studying quantum effects like CP-violation and flavour oscillations in transport equations. Furthermore it also allows a systematic inclusion of thermal effects on the CP asymmetry and on scattering rates, which can be significant in particular at early times $T \gtrsim M_1$.

In strong washout scenarios, which are characterised by $\Gamma \gtrsim H(T = M_1)$, inverse decays $\ell\phi$, $\bar{\ell}\phi^\dagger \to N_1$ efficiently wash out asymmetries produced at earlier times.The final asymmetry is determined at the time when the inverse decays freeze out, $T \ll M_1$, and does not depend significantly on either the initial conditions or on thermal corrections, which mostly affect the asymmetry at earlier times. Since strong washout is also favoured by our current knowledge of the neutrino mass parameters, we will in the following focus on recent developments that affect the final asymmetry in that regime.

2.1. Flavour Effects

While it was always clear that the lepton asymmetry produced by N_1 decays is produced in a linear combination of flavour eigenstates, it was only realised in [7, 8] that this could have a significant impact on the final asymmetries, if leptogenesis takes place at a time where one or more charged lepton Yukawa couplings are in thermal equilibrium.

Roughly, this can be understood as follows: When the interactions mediated by the tau Yukawa coupling are in equilibrium (i.e. faster than the Hubble rate), the produced asymmetry is projected onto either the tau lepton flavour or an orthogonal linear combination. In general each flavour combination has a different washout rate, while the overall asymmetry production rate stays the same. This can result in a sizeable increase of the final lepton asymmetry in scenarios with moderate to strong washout.

In order to properly understand the transition regime where the flavour interactions enter thermal equilibrium, the quantum kinetic equations of motion for the flavoured lepton number densities, including flavour off diagonal correlations, were derived from non-equilibrium quantum field theory in [9]. In Fig. 1 it can be seen that the total asymmetry smoothly increases form the unflavoured to the flavoured limit (dotted and dashed lines) as the leptogenesis scale decreases, and there is a broad transition regime where neither approximation yields an accurate result.

2.2. Scattering Rates

An important ingredient for a precise treatment of flavour effects is the flavour relaxation rate, i.e. the rate of processes mediated by the charged lepton Yukawas. The leading processes, namely decays and inverse decays of the Higgs boson into left- and right-handed leptons appearing at $\mathcal{O}(y_\tau^2)$, are not allowed kinematically in the early universe where all particles are approximately massless. Instead one has to consistently compute all processes at order $g^2 y_\tau^2$ in order to arrive at

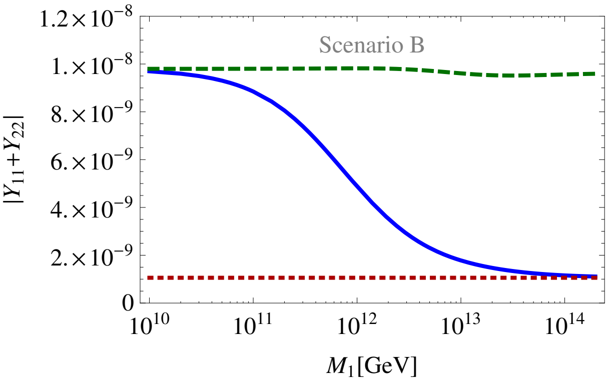

Figure 1. Total lepton asymmetry as a function of the Leptogenesis scale M_1. Shown are the solutions of the exact flavoured equations of motion (solid, blue) as well as the fully flavoured (dashed, green) and unflavoured (dotted, red) approximations. Taken from Ref. [9].

a reliable leading order result. At finite temperature, this not only includes scattering processes involving electroweak gauge bosons and top quarks, but also $1 \to 2$ decay processes that become allowed once thermal masses are included, and processes with multiple soft scatterings of gauge bosons which have to be resummed [10].

A first calculation of the charged lepton Yukawa equilibration rate was performed in [11]. For the temperature range relevant to leptogenesis, the charged lepton flavour relaxation rate was found to be $\Gamma^{\text{fl}}_{\alpha} \approx 5 \times 10^{-3} y_{\alpha}^2 T$, where α labels the different lepton flavours. This rate is dominated by scattering processes of the form $\ell A \leftrightarrow \phi e_R$ and $\ell \bar{e}_R \leftrightarrow A\phi$, where a lepton is exchanged in the t-channel. Here A denotes an electroweak gauge boson, and e_R a right-handed charged lepton.

These processes diverge when the momentum exchange goes to zero, and the divergence is regulated by the thermal mass of the exchanged lepton. Using the 2PI formalism for calculating these rates in non-equilibrium QFT, this regularisation is implemented automatically since the corresponding scattering processes arise from self energy diagrams involving resummed fermion propagators, which include both thermal masses and widths. A calculation of the corresponding neutral lepton Yukawa interactions was presented in [12] using different techniques, and we have explicitly shown that we reproduce the same logarithmic enhancement of the rate, however a discrepancy in the $\mathcal{O}(g^2)$ contribution remains to be resolved.

2.3. Spectator Effects

The washout, and thus the final asymmetry, can also be affected by interactions that do not change the lepton asymmetry themselves, so called *spectator effects*. To understand this it is important to notice that Leptogenesis not only produces an asymmetry in lepton doublets, but also in the Higgs doublets. This asymmetry is then partially transferred into a chiral asymmetry between third generation quark doublets and right-handed top quarks, since top Yukawa interactions are always in thermal equilibrium. This overall redistribution of the asymmetry leads to an effective reduction of the washout rate.

Depending on the Leptogenesis scale, different SM interactions may reach thermal equilibrium during the leptogenesis process. Possible candidates include interactions mediated by third and second generation Yukawa couplings and the strong and electroweak sphaleron processes. The usual approach to deal with this was to assume that for a given scale, a process is either fully equilibrated or inactive. In our discussion of flavour effects above however we have seen that the transition regime for an interaction to reach equilibrium can span more than an order of magnitude, and this is similarly the case for spectator effects.

In [13] we have therefore considered the case of spectators reaching thermal equilibrium during Leptogenesis, by including additional degrees of freedom in the Boltzmann equations. As a simple toy example we have considered the case where the tau Yukawa interaction reaches thermal equilibrium, while neglecting any lepton flavour effects. What happens then is that parts of the asymmetry are transferred to an asymmetry in right-handed leptons, where it is protected from washout.

While we again observed a smooth interpolation between the limiting cases at high and low scales, for strong washout there is an intermediate regime where the final asymmetry is larger than in either limit. The reason for this is that for strong washout, the asymmetry at intermediate stages is much larger than the final freeze out asymmetry. Now parts of this larger asymmetry are transferred to the right-handed leptons, but since the spectator interaction is not fully equilibrated yet, this asymmetry is only transferred back to the lepton doublets after the washout ends, thus protecting some asymmetry from being washed out.

In the toy example this enhancement of the asymmetry can reach up to 60%, while in more realistic examples where either the sphalerons or the bottom Yukawa enter thermal equilibrium it only provides corrections at the 10% to 20% level. Another important consequence here is that the spectator "remembers" the asymmetry at earlier times, therefore it can reintroduce a dependence on initial conditions and on thermal corrections even in the strong washout regime.

3. Thoughts on Testability

Due to the high scales involved, it is unlikely that the right-handed neutrino sector can ever be accessed experimentally. It is therefore reasonable to ask what can be learned from low energy neutrino observations, and to which extend this mechanism can be probed.

One would expect that a measurement of the low energy neutrino CP phase should have some impact on Leptogenesis. In general this is not the case however: In the absence of flavour effects, the lepton asymmetry is independent of the entries in the $U_{\rm PMNS}$ matrix. Including flavour effects reintroduces some dependence, however without further restrictions on the high-scale parameters Leptogenesis can still work for any value of the neutrino mixing parameters.

On the other hand the LHC could have severely disfavoured the Leptogenesis mechanism. The reason is that it relies on the existence of the SM, or a perturbative extension thereof (like the MSSM), up to the Leptogenesis scale. The discovery of a SM-like Higgs boson in a mass range that is consistent with vacuum stability up to very high scales, and nothing else (yet), can therefore be taken as positive evidence that indeed Leptogenesis could be the mechanism responsible for our existence.

In the future a confirmation of the Majorana nature of neutrinos and of a non-vanishing CP phase could provide further evidence for Leptogenesis. Instead an observation or large lepton number violating processes at the LHC or elsewhere would be problematic, since the new washout processes induced by such interactions would erase any lepton asymmetry produced by Leptogenesis [14].

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