The Connection Between Neutrino CP Violation and Leptogenesis

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A major motivation to look for CP violation in neutrino oscillation is that its observation would make it more plausible that the baryon-antibaryon asymmetry of the universe arose, at least in part, through leptogenesis. Leptogenesis, a natural outgrowth of the see-saw theory of why the observed neutrinos are so light, depends on the early-universe decays of very heavy neutrinos. In straightforward versions of leptogenesis, these heavy neutrinos must have masses of 10^9 GeV or more, so that, at least for a long time to come, we will not be able to confirm their existence directly by producing them at an energy-frontier collider. Instead, the hypothesis of leptogenesis must be explored indirectly through intensity-frontier experiments with the light neutrinos ν to which the heavy ones N are related by the see-saw.

The straightforward (type-I) see-saw model adds to the Standard Model (SM) particles only the heavy neutrinos N_i, which are taken to be right-handed electroweak singlets. The N_i are given very large Majorana masses, and Yukawa couplings $\mathcal{L} = y_{\alpha i}\bar{L}_\alpha \bar{H} N_i$ to the SM lepton doublets L_α, with $\alpha = e,\ \mu,\ \tau$, and the SM Higgs doublet H. These Yukawa couplings are responsible for the decays of the N_i. Assuming there are three N_i, to match the number of SM families, there are 9 Yukawa coupling constants $y_{\alpha i}$. If there are CP-violating phases in these Yukawa coupling constants, the decays $N_i \to L_\alpha + H$ and $N_i \to \bar{L}_\alpha + \bar{H}$ have different rates. Thus, in the early universe, these decays would have produced a world with unequal numbers of SM leptons and antileptons. SM processes would then have converted this world into one with unequal numbers of SM baryons and antibaryons, which is what we see today.

The see-saw picture contains 21 leptonic parameters. Of these, only 12 can be measured experimentally without producing the heavy neutrinos N. Since $21 > 12$, current laboratory measurements obviously cannot pin down what happened in the early universe. Oscillation of the light neutrinos ν can violate CP even if there was no leptogenesis. And leptogenesis may have occurred even if light-neutrino oscillation does not violate CP. However, neither of these possibilities is likely [1]. To see why, consider the see-saw relation that follows from the see-saw picture, namely

$$U M_\nu U^T = -\nu^2 (y\, M_N^{-1} y^T) \tag{1}$$

In this relation, $\nu = 174$ GeV is the vacuum expectation value of the Higgs field. All the other quantities are 3×3 matrices. The matrix U is the leptonic mixing matrix, M_ν is a diagonal matrix whose diagonal elements are the masses of the light neutrinos, y is the matrix of Yukawa coupling constants $y_{\alpha i}$, and M_N is a diagonal matrix whose diagonal elements are the masses of the heavy neutrinos. The quantities on the right-hand side of Eq. (1) are inputs to the see-saw model, while those on the left-hand side are consequences of the model. The quantities ν, M_ν, and M_N are all real.

Suppose leptogenesis occurred. Then y, whose CP-violating phases drive leptogenesis, cannot be real. Thus, barring a conspiracy between M_N and y, matrices that represent two presumably-unrelated pieces of the see-saw picture, the right-hand side of Eq. (1) is not real. Then the left-hand side must not be real either. Since M_ν is real, this implies that U is not real. But then, given the well-known relation between light-neutrino oscillation and complex phases in U, one expects that this oscillation will violate CP.

With only a minor caveat, one can reverse this argument: If light-neutrino oscillation violates CP, then, assuming the see-saw picture, leptogenesis probably occurred. We conclude that, generically, leptogenesis and light-neutrino CP violation imply each other.

To be sure, it can be shown that if all the N_i masses exceed 10^{12} GeV, then the phases that drive leptogenesis are independent of those in U [2]. However, there is no need for the N_i masses to be this large. Indeed, supersymmetry suggests that the mass of the lightest N_i must be $\sim 10^9$ GeV [3]. It has been shown that when the smallest N_i mass is below 10^{12} GeV, CP-violating phases in U, which produce CP violation in light-neutrino oscillation and influence the rate for neutrinoless double beta decay, lead also, barring accidental cancellations, to a baryon-antibaryon asymmetry [4].

In summary, assuming the see-saw picture, leptogenesis and light-neutrino CP violation generically do imply each other.

References

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