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Leptogenesis and Neutrino Physics

SILVIA PASCOLI*

Department of Physics and Astronomy, UCLA, Box 951547
Los Angeles, CA 90095-1547, USA

We review the possible connection between the CP-violating phases which appear in the lepton unitary mixing matrix with the ones which play a role in the leptogenesis mechanism.

Keywords: Neutrinos; Leptogenesis; Leptonic CP-violation.

The origin of the matter-antimatter asymmetry is one of the most important questions in cosmology. The presently observed baryon asymmetry is [1]

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} \simeq 6.5 \times 10^{-10} . \quad (1)$$

In 1967 A. Sakharov suggested that the baryon density can be explained in terms of microphysical laws [2]. Three conditions need to be fullfilled: Baryon number (or Lepton number, for the leptogenesis mechanism) violation, C and CP-violation, and departure from thermal equilibrium. Let us notice that $B - L$ is conserved both at the perturbative and non-perturbative level. This implies that if one creates a net $B-L$, (e.g., a lepton number), the sphaleron processes would leave both baryon and lepton number comparable to the original $B - L$. This idea is implemented in the leptogenesis scenario [3]. Leptogenesis is particularly appealing because it takes place in the context of see-saw models [4], which naturally explain the smallness of neutrino masses. The see-saw mechanism requires the existence of heavy right-handed (RH) Majorana neutrinos, completely neutral under the Standard Theory gauge symmetry group. Introducing a Dirac neutrino mass term, m_D, and a Majorana mass term, M_R, for the right-handed neutrinos leads, for sufficiently large M_R, to the well know see-saw [4] formula

$$m_\nu = U_{\rm PMNS} \; D_m \; U_{\rm PMNS}^T \simeq -m_D \; M_R^{-1} \; m_D^T \; . \quad (2)$$

Here D_m is a diagonal matrix containing the masses $m_{1,2,3}$ of the three light massive Majorana neutrinos and $U_{\rm PMNS}$ is the unitary Pontecorvo–Maki–Nagakawa–Sakata lepton mixing matrix.

*Present address, from 16 October 2004: CERN, Department of Physics, Theory Division, CH-1211 Geneva 23, Switzerland

The CP-violating and out-of-equilibrium decays of RH neutrinos produce a lepton asymmetry [3] that can be converted into a baryon asymmetry through anomalous electroweak processes [5]. The requisite CP violating decay asymmetry, ϵ_1, is caused by the interference of the tree level contribution and the one–loop corrections in the decay rate of the three heavy Majorana neutrinos, N_i, and is proportional to $\text{Im}(m_D^\dagger m_D)^2_{ij}$, $i \neq j$. [6,7] By solving the Boltzmann equations [8] one gets the lepton asymmetry which is then converted into the observed baryon asymmetry[5].

Establishing a connection between the parameters at low energy (neutrino masses, mixing angles and CP-violating phases), measurable in principle in present and future experiments, and at high energy (relevant in leptogenesis) has gathered a great interest in the last few years (see, e.g., Refs. 9, 10, 11, 12). The number of parameters in the full Lagrangian of models which implement the see-saw mechanism is larger than the ones in the low-energy sector: in the case of 3 light neutrinos and three heavy ones, at high energy the theory contains in the neutrino sector 18 parameters of which 12 real ones and 6 phases, while at low energy only 9 are accessible - 3 angles, 3 masses and 3 phases. The decoupling of the heavy right-handed neutrinos implies the loss of information on 9 parameters. In particular, leptogenesis depends only on the mixing in the right handed sector. We can also notice that the PMNS unitary mixing matrix U does not enter esplicitly into the expression for the lepton asymmetry. However it can be shown (see, e.g., Ref. 9) that the phases in U_{PMNS} receive contribution from CP-violation both in the right-handed sector, responsible for leptogenesis, and in the left-handed one, which enters in lepton flavour violating processes. Due to the complicated way in which the high energy phases and real parameters enter in m_ν, if there is CP-violation at high energy, as required by the leptogenesis mechanism, we can expect in general to have CP-violation at low-energy, as a complete cancellation would require some fine-tuning or special forms of m_D and M_R. Let us mention that an observation of CP-violation at low energy, however, does not imply necessarily CP-violation in leptogenesis as it might receive all its contributions from the mixing in the left-handed sector. More specifically, in general, there is no a one-to-one link between low energy CP-violation in the lepton sector and the baryon asymmetry: a measurement of the low energy CP-violating phases does not allow to reconstruct the leptogenesis phases. However most specific models allow for such a connection. In particular if the number of parameter is reduced in m_D, then a one-to-one correspondence between high energy and low energy parameters might be established. This can be achieved in models which allow for CP-violation only in the right-handed sector, or which reduce the number of independent parameters at high energy, for example by requiring only two right-handed neutrinos [11]. Each model of neutrino mass generation should be studied in detail separately to establish the feasibility of the leptogenesis mechanism [12].

In addition, the possible observation of $(\beta\beta)_{0\nu}$-decay would play an important role in understanding the origin of the baryon asymmetry as it would imply that lepton number (one of the main condition for leptogenesis) indeed is not conserved.

Furthermore the Majorana nature of neutrinos would be established: the see-saw mechanism would be regarded as a reasonable explanation of neutrino mass generation. Leptogenesis naturally takes place in this scenario.

In conclusion, the observation of lepton number violation in $(\beta\beta)_{0\nu}$-decay and, in addition, possibly of CP-violation in the lepton sector, would be a strong indication, even if not a proof (as it is not possible to reconstruct in a model indipendent way the high energy parameters from m_ν), of leptogenesis as the explanation for the observed baryon asymmetry of the Universe.

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