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CP Violation and Leptogenesis

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The origin of the baryon asymmetry of the Universe is one of the key open questions to be addressed in particle physics and cosmology. Assuming a negligible initial baryon asymmetry, its dynamical production can happen in presence of non-conservation of the baryon and/or lepton number, violation of the C and CP symmetries and out-of-equilibrium conditions. Leptogenesis is a mechanism, proposed in the context of see-saw models, which can satisfy all these requirements and explain the observed baryon asymmetry. In the simplest case of see-saw type I, in which right handed neutrinos, singlets of the Standard Model, are introduced, lepton number is violated by the heavy Majorana masses, in conjuction with the Yukawa couplings, CP can be violated by complex terms in the Dirac masses and the out-of equilibrium condition is satisfied by the decays of the right handed neutrinos, when the temperature drops below their mass. The interesting question arises if the observable low energy CP violation, parameterised by the δ phase and measurable in long baseline neutrino oscillation experiments, can be responsible for the baryon asymmetry. Although in a model independent way it is not possible to draw such connection, we show that, in presence of flavour effects in leptogenesis, the δ phase enters directly in the lepton, and baryon, asymmetry and thanks to the large value of θ_{13} it may be at the origin of the matter-antimatter asymmetry we observe.

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1. Introduction

After the discovery of neutrino oscillations and the precise measurement of the mass squared differences and of the mixing angles in the past 20 years, the determination of leptonic CP violation (CPV) is one of the most compelling question in particle physics. In the standard three-neutrino mixing scheme, one or three CP violating phases are present in the Pontecorvo–Maki–Nagakawa–Sakata unitary mixing matrix, $U_{\rm PMNS}$, [1]: one phase δ if neutrinos are Dirac particles, and three if they are Majorana ones. δ enters in neutrino oscillations, in particular in the appearance probability in long-baseline neutrino oscillation experiments. Recently, hints in favour of CP violation have been found when one combines the data from the long baseline oscillation experiment T2K (and NOvA) with that from reactor experiments, in particular Daya Bay. In fact, the former reports a rather large neutrino appearance oscillation probability which depends on θ_{13}, θ_{23}, the mass ordering and crucially δ, while the latter constrains very strongly θ_{13} alone. The most recent combined analysis in Ref. [2] gives a best fit value of $-54^o(+30^o,-69^o)$ $(-106^o(\pm 63^o))$ for normal ordering (inverted ordering), while at 3σ all values, including CP conserving ones, are allowed. Current superbeams, i.e. T2K and NOvA, and future long-baseline experiments, e.g. DUNE, T2HK, will allow to test these first hints. If neutrinos are Majorana particles, two additional phases cannot be rotated away and are physical. They enter in lepton number violating processes, the most sensitive of which is neutrinoless double beta decay. In principle, a precise measurement of the effective Majorana mass, combined with an accurate determination of neutrino masses, e.g. from cosmological observations, would allow to test if Majorana CP violation is present. However, this requires not only very sensitive experiments but also a precise computation of the nuclear matrix elements for neutrinoless double beta decay, which is beyond the current state of the art, see e.g. [3].

CP violation, together with the violation of lepton number, can play a crucial role in the generation of the baryon asymmetry of the Universe via the leptogenesis mechanism. In this article we will review the possible connection between the measurable leptonic CP violation at low energy, and in particular δ, and leptogenesis, focussing on see-saw type I models with hierarchical right handed neutrinos.

2. CP violation and the baryon asymmetry

The origin of the matter-antimatter asymmetry in the Universe is one of the most compellings questions in cosmology. Its value has been well measured using the cosmic microwave background (CMB) radiation by Planck [4]

$$Y_B^{\rm CMB} \simeq (8.67 \pm 0.09) \times 10^{-10}\,, \tag{2.1}$$

where Y_B is the baryon to photon ratio at recombination. An independent measurement is given by Big Bang Nucleosynthesis (BBN), $Y_B^{\rm BBN} \simeq (8.10 \pm 0.85) \times 10^{-10}$, in good agreement with the CMB one [5].

Assuming that the Universe had no baryon asymmetry to start with, as suggested by inflationary models, the baryon asymmetry can be dynamically generated if the conditions suggested by A. D. Sakharov in 1967 are satisfied [6]:

- Baryon number (or Lepton number, for the leptogenesis mechanism) violation.

- C and CP violation. If CP is conserved, every reaction which produces a particle will be accompanied by an opposite one, with no creation of a net baryon number.
- Departure from thermal equilibrium. This condition is readily satisfied in the Early Universe by its expansion.

Several mechanisms have been proposed as the origin of the baryon asymmetry. A very popular and successfull explanation is leptogenesis [7]. It relies on the fact that, as $B-L$ is conserved both at the perturbative and non-perturbative level, a net $B-L$, (e.g., a lepton number) would induce a net baryon number via sphaleron effects [8].

2.1 The see-saw mechanism and leptogenesis

Leptogenesis is particularly appealing because it naturally occurs in see-saw models [9], which can explain neutrino masses and their smallness. Here, for conciseness we focus on see-saw type I models. Heavy right-handed (RH) Majorana neutrinos, N_i, singlets under the SM gauge symmetry group, are introduced in the theory and the resulting Lagrangian contains a Yukawa term which couples N_i with the Higgs and the leptonic doublet. Once the Higgs gets a vacuum expectation value, a Dirac mass terms arises and the neutrinos mass terms in the Lagrangian read

$$-\mathscr{L}_{\rm mass} = \overline{N_i}\,(m_D)_{ij}\,\nu_{Lj} + \text{h.c.} + \frac{1}{2}\,\overline{(N_i)^c}\,(M_R)_{ij}\,N_j \; , \tag{2.2}$$

where m_D and M_R are the Dirac and Majorana mass matrices, respectively. For $M_R \gg m_D$, light neutrino masses are induced according to the see–saw [9] formula

$$m_\nu = U^*_{\rm PMNS}\, D_m\, U^\dagger_{\rm PMNS} \simeq m_D^T\, M_R^{-1}\, m_D \; . \tag{2.3}$$

Here, D_m is a diagonal matrix containing the three light masses $m_{1,2,3}$.

The see-saw models can satisfy the Sakharov conditions as i) lepton number is violated by the Majorana M_R term; ii) CP violation can be present in the m_D matrix if some of its elements are complex; iii) the departure from equilibrium is due to the N_i decays in the expanding Universe, once the temperature drops below their mass.

2.1.1 The one-flavor approximation

At high temperatures, $T > 10^{12}$ GeV, different leptonic flavors cannot be distinguished as their Yukawa interactions are out of equilibrium. In this case, assuming $M_1 \ll M_2 \ll M_3$, only one CP-asymmetry needs to be considered [7, 10, 11] :

$$\varepsilon_1 = \frac{\Gamma(N_1 \to \Phi^-\,\ell^+) - \Gamma(N_1 \to \Phi^+\,\ell^-)}{\Gamma(N_1 \to \Phi^-\,\ell^+) + \Gamma(N_1 \to \Phi^+\,\ell^-)} \simeq \frac{3}{16\,\pi\,v^2} \sum_{j\neq 1} \frac{{\rm Im}(m_D\, m_D^\dagger)^2_{1j}}{(m_D\, m_D^\dagger)_{11}}\,\frac{M_1}{M_j} \; , \tag{2.4}$$

where Φ and ℓ are the Higgs field and the charged leptons, respectively. v is the electroweak symmetry breaking scale. This CP-asymmetry is partially washed-out by inverse decays and other lepton number violating processes, due to the fact that the lepton asymmetry production in N_1 decays is not instantaneous. These "wash-out" effects are flavor-independent and can be parameterized by $\widetilde{m_1} \propto (m_D\; m_D^\dagger)_{11}$, proportional to the total decay rate of N_1. Finally, the lepton asymmetry is converted into a baryon one by sphaleron effects, $Y_B = c_s Y_{B-L}$, where c_s is a coefficient typically of order 0.2-0.4, depending on the specific model.

The observed baryon asymmetry is then given by

$$Y_B \simeq -c_s \frac{\varepsilon_1}{g_*} \eta\left(\widetilde{m_1}\right), \tag{2.5}$$

where $\eta\left(\widetilde{m_1}\right)$ accounts for the washing out due to inverse decays.

It should be noted that the resulting baryon asymmetry depends on the trace of the CP asymmetries over flavours, ε_1, times a function of the trace over flavours of the decay rate of N_1.

2.1.2 Flavor effects

Once the interactions due to the charged lepton Yukawa couplings get into equilibrium, at $T \ll 10^{12}$ GeV for τ leptons and at $T \sim 10^9$ GeV for muons, different flavours become distinguishable and the asymmetry and wash-out effects become flavour-dependent. The total baryon asymmetry is obtained summing three contributions [12, 13, 14, 15]: the CP asymmetry in each lepton flavor l, washed-out by the same-lepton number violating processes. The asymmetry in each flavor l is given by

$$\varepsilon_l = \frac{3}{16\pi v^2} \frac{1}{(m_D m_D^\dagger)_{11}} \operatorname{Im}\Big(\sum_j \Big((m_D)_{1l} (m_D m_D^\dagger)_{1j} (m_D^*)_{jl}\Big)\Big) \frac{M_1}{M_j}. \tag{2.6}$$

Similarly, one has to consider the "wash-out mass parameter" for each flavour l [13, 15], $\widetilde{m_l} \propto |(m_D)_{1l}|^2$, which depends on the decay rate of N_1 to the leptons of flavour l.

As an example, here we will consider temperatures $(10^9 \leq T \sim M_1 \ll 10^{12})$ GeV, for which only the interactions mediated by the τ Yukawa coupling are in equilibrium. The final baryon asymmetry is well approximated by [15]

$$Y_B \simeq -\frac{12}{37 g_*} \left(\varepsilon_2\, \eta\left(\frac{417}{589}\widetilde{m_2}\right) + \varepsilon_\tau\, \eta\left(\frac{390}{589}\widetilde{m_\tau}\right)\right), \tag{2.7}$$

where $\varepsilon_2 = \varepsilon_e + \varepsilon_\mu$, $\widetilde{m_2} = \widetilde{m_e} + \widetilde{m_\mu}$. It should be noted that, differently from the "one-flavor approximation", the total baryon number is not proportional to ε_1.

3. Testing the ingredients for leptogenesis: leptonic CP violation

The appearance channel $\nu_\mu \to \nu_e$ in long-baseline neutrino oscillation experiments depends on the δ phase and offers the opportunity to hunt for leptonic CP violation. The probability can be approximated, expanding to second order in the small parameters $\sin\theta_{13}$ and $\Delta m^2_{21}/\Delta m^2_{31}$, as [16]:

$$\begin{aligned} P_{\nu_\mu \to \nu_e} \approx\ & 4 \sin^2\theta_{13} \sin^2\theta_{23} \frac{\sin^2 \Delta(1-A)}{(1-A)^2} + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A^2} \\ & + 2\alpha \sin\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta \pm \delta) \frac{\sin \Delta A}{A} \frac{\sin \Delta(1-A)}{1-A}, \end{aligned} \tag{3.1}$$

where the following definitions hold

$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}, \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}, \quad A \equiv \frac{2EV}{\Delta m^2_{31}}. \tag{3.2}$$

Here, L is the baseline, E is the neutrino energy, and V is the effective matter potential [17], taken to be constant over these baselines. The plus (minus) sign holds for neutrinos (antineutrinos), and for antineutrinos V needs to be changed to $-V$, i.e. $A \to -A$.

The first term in the probability is being referred to as “atmospheric term" given the dependence on Δm^2_{31} and is dominant due to the observed large value of θ_{13}, $\sin^2\theta_{13} \approx 0.022$. This term provides the strongest sensitivity to matter effects and allows to determine the neutrino mass ordering with the present generation and future long-baseline oscillation experiments, such as NOvA, DUNE, and a neutrino factory. The second term is typically very small as it is suppressed by two powers of α. The third term, usually called the “CP violating" term, depends on the δ phase and is suppressed due to Δm^2_{21}, although it depends only linearly on $\sin\theta_{13}$. This implies that the determination of CP violation is challenging as it requires the measurement of the probability at the few percent level.

Moreover, the extraction of the unknown parameters, i.e. the sign of Δm^2_{31}, δ, the octant of θ_{23}, is complicated by the fact that they enter the probability in a complex manner. This leads to the well known problem of degeneracies [18], so that, even if the probabilities were measured to a high precision, there would remain uncertainties in the reconstruction of the unknown parameters. A particularly relevant degeneracy, highlighted in [19], is the one between θ_{23}–δ–θ_{13}, for which the synergy between the appearance and disappearance channels can have a relevant role. Generically, having information at different energies, combining oscillation channels and using inputs from other experiments, such as reactor or atmospheric neutrino ones, helps solving this problem and improve significantly the reach of long baseline experiments.

Experimentally long baseline neutrino oscillation experiments exploit beams sourced in pion and muon decays and large detectors. Specifically in superbeams, the muon neutrino (and antineutrino) beam is produced at an accelerator complex in which high energy protons are impinged on a target. The collisions produce large quantities of pions which are focussed and decay sourcing to a collimated beam of muon neutrinos. The latter travels and can interact in large detectors, which have the capabilities to reconstruct ν_e and ν_μ. Typical choices are Water Cherenkov, for $E_\nu < 1$ GeV, Liquid Argon (LAr) or scintillator (LSc) ones. Important backgrounds to the appearance channel are: i) mis-identified π^0 produced in neutral current interactions, as one of the γs from the pion decay $\pi^0 \to \gamma\gamma$ is not reconstructed; ii) intrinsic ν_e from the beam, usually coming from kaon decays, at a level of 0.5%–1%; iii) mis-reconstructed muon neutrinos. Systematic errors, both on the signal and on the backgrounds, due to the beam and the detector, such as e.g. the cross sections, overall normalisation, are crucial to establish the sensitivity of the setup. In this, the near detector will play an important role.

Two long-baseline neutrino experiments, T2K and NOvA, are currently taking data. Thanks to the large value of θ_{13} they will be able to provide some information on the mass ordering and on CP violation, when combined with a precise measurement of θ_{13} from reactor neutrino experiments.

T2K [20]. The beam from the J-PARC accelerator complex has a nominal power of 750 kW and has recently reached 350 kW. The detector is the 22.5 kton Super-Kamiokande Water Cerenkov detector located at a distance of 295 km and at an off-axis angle of 2.5^o. A combination of the neutrino and antineutrino runs, together with a precise value of θ_{13} will allow to reach a 2σ sensitivity for maximal CPV in the favorable region $\delta < 0$, see e.g. Refs. [21]. Interestingly, in July 2015 T2K reported the first results for its antineutrino run.

NOvA [22]. This experiment uses the NuMI beam with 700 kW and a 14 kton totally active plastic scintillator detector located 810 km away off-axis. NOvA presented the first results from the neutrino run in August 2015. It has been shown that NOvA has a similar sensitivity to CPV as T2K, at a 1.5-2 σ for a broader range of values [23], and that the combination of these two experiments could even reach a 3 σ result for particularly favourable values of δ.

The prospective sensitivity significantly depends on the value of θ_{23} worsening going from lower to higher values of θ_{23}. For these experiments, the sensitivity is statistics-limited and additional years of running would lead to significant improvements.

DUNE [24, 25]. The DUNE experiment, exploiting the LBNF facility at Fermilab, is a proposal in the US which uses a beam sourced at the Main Injector at Fermilab with 1.2 MW of power. Differently from T2K and NOvA, this experiment would have the advantage of a broad energy spectrum and consequently the ability to get information on the probability at different energies. The chosen detector comprises 4 10 kton modules of LAr TPC, located at the Sanford Underground Research Facility site, at a distance of 1300 km from Fermilab. A recent optimisation of the beam has allowed to improve significantly the reach in CP violation: DUNE will achieve a sensitivity > 3 σ for 75% of the values of δ in 1320 kton MW years and reach a 5 σ discovery for 50% of the values in 810 kton MW years (for the most recent analysis see DUNE CDR document in Ref. [25]).

J-PARC to Hyper-Kamiokande long-baseline experiment (T2HK) [26, 27]. This facility uses a beam sourced at the JPARC accelerator and aimed at a 0.99 Mton Water Cherenkov detector located 2.5^o off-axis at 295 km in the Kamiokande mine. Considering a total exposure of 7.5 MW times 10^7 seconds, leptonic CP violation can be established at 3 σ for 76% of the values of δ and discovered at 5 σ for 58% of them. The advantages of this proposal are the excellent energy resolution for quasi-elastic interactions at these energies, the large number of events and the low intrinsic background.

ESSνSB [28]. Differently from other options, this 10 MW beam, sourced at the European Spallation Source, is peak around the second oscillation maximum in order to maximise the sensitivity to CP violation. It is aimed at a 500 kton Water Cherenkov detector which could be located at a distance between 300 and 550 km. This setup has the ability to discover CP violation at 5σ for up to 50% of the values of δ. Additional studies are currently ongoing in order to further optimize this facility.

Neutrino factory [29, 30, 31, 32, 33]. Neutrinos are produced by high energy muons which decay producing a collimated beam of muon neutrinos and electron antineutrinos. A magnetised detector, a 100 kton iron MIND, is needed in order to distinguish the muon produced by interacting ν_μ from $\nu_\mu \to \nu_\mu$ oscillations, from the antimuons arising from the interactions of $\bar{\nu}_\mu$ from the appearance channel. The baseline configuration uses 10 GeV muons and 2000 km. Thanks to the high number of events, very low backgrounds and the wide and well known energy spectrum, this setup achieves a superior performance with CP violation which could be discovered for over 70% of the values of δ.

Other type of setups. For the sake of completeness, we note that there are non-long-baseline strategies to search for leptonic CP violation. DAEδALUS (Decay-At-rest Experiment for δ CP studies At the Laboratory for Underground Science) [34] uses a cyclotron-driven muon antineutrino beam and a very large detector optimised for low energies, such as a 50 kton liquid scintillator one, e.g. LENA, or a megaton scale Water Cherenkov one, e.g. a gadolinium-doped 300 kton or Hyper-K detectors. Placing the source at different distances, e.g. 1.5 km, 8 km and 20 km, CP violation can be searched for. Finally, very large detectors for atmospheric neutrinos, e.g. SuperPINGU, can provide information on CP violation using subGeV energy neutrinos. Depending on the specific detector performance achievable, maximal CP violation could be distinguished from the CP conserving value $\delta = 0$ with a significance between 3σ and 8σ, see Ref. [35].

When comparing the sensitivities of different setups, a word of caution is in order: the precise physics reach of each configuration is strongly dependent on the assumption made on the beam, detector, oscillation parameters and systematic errors.

4. The connection between low-energy leptonic CPV and the baryon asymmetry

Establishing a connection between the parameters at low energy (in particular, the CP violating phases and the presence of lepton number violation), and at high energy (relevant in leptogenesis) is very interesting. Here, we focus the discussion on see-saw type I models with 3 hierarchical N_i masses. We ask the following question: could the CP violating phase δ be responsible for the baryon asymmetry?

In a generic model, the number of parameters in the see-saw Lagrangian is larger than that of the measurable ones: for three heavy neutrinos, at high energy the theory contains 3 heavy masses, 9 real parameters and 6 phases in the Dirac mass matrix, while at low energy only 9 are in principle accessible - 3 angles, 3 masses and 3 phases (of these only one Dirac and potentially one Majorana phase could ever be measured). This implies that a "one-to-one connection" between the low-energy and the high energy parameters, specifically the phases, cannot be established in a model independent way. However, typically, models implementing symmetries, textures or other tools to explain the low energy flavour structure, have a reduced number of parameters and might allow such a connection.

In the basis in which both M_R and the charged lepton mass matrix are real and diagonal, the orthogonal parametrization for the Dirac mass [36] turns out to be very useful, as it allows to separate measurable parameters from high energy unknown ones:

$$m_D \simeq \sqrt{M_R}\,\mathbf{R}\,D_m^{1/2}\,U_{\rm PMNS}^{\dagger}\,, \tag{4.1}$$

where $\mathbf{R}$ is a complex orthogonal matrix, which contains 3 unknown real parameters and 3 unkown phases.

Using this parameterisation, in the "one-flavor" approximation, the CP asymmetry can be rewritten as:

$$\varepsilon_1 = -\frac{3M_1}{16\pi v^2}\,\frac{\mathrm{Im}\left(\sum_{\alpha\beta\rho} m_\rho^{1/2} m_\beta^{3/2} U^*_{\alpha\rho} U_{\alpha\beta} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2} = -\frac{3M_1}{16\pi v^2}\,\frac{\mathrm{Im}\left(\sum_\rho m_\rho^2 R_{1\rho}^2\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}\,. \tag{4.2}$$

It is apparent that the unitary mixing matrix $U_{\rm PMNS}$ does not enter directly into the expression for the lepton asymmetry. Therefore, in general an observation of CP violation at low energy would not provide any information on the generation of a baryon asymmetry in the Early Universe.

This conclusion does not hold if leptogenesis takes place at $T \ll 10^{12}$ GeV. In this case flavors are distinguishable and each flavor asymmetry must be considered separately:

$$\varepsilon_\alpha = -\frac{3M_1}{16\pi v^2} \frac{\mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\alpha\beta} U_{\alpha\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}. \tag{4.3}$$

Since each flavour CP asymmetry is weighted by the corresponding wash out parameter, the total lepton number depends directly on the CP violating phases at low energy [37, 38, 14, 15].

Asking if the δ phase can be responsible for the baryon asymmetry can be analysed by imposing that the matrix R is real and setting the Majorana phases to CP-conserving values [37, 38]. In this case, the flavor CP asymmetries $\varepsilon_2 = -\varepsilon_\tau$ and, consequently, the baryon asymmetry depend *exclusively on the low energy phases*, specifically δ. It is now necessary to recast the baryon asymmetry in terms of δ and to check that the obtained values can be compatible with the observations. For concreteness, we consider the normal hierarchical mass spectrum for light neutrinos, $m_1 \ll m_2 \ll m_3$. We take the simplest case of decoupling of the heaviest right-handed neutrino, $R_{11} = 0$. Detailed results for generic R and for other choices of neutrino mass spectrum can be found in Ref. [38]. The baryon asymmetry is given by [38]:

$$|Y_B| \cong 2.4 \times 10^{-11} \, |\sin\delta| \left(\frac{s_{13}}{0.15}\right) \left(\frac{M_1}{10^{11}\ \mathrm{GeV}}\right). \tag{4.4}$$

Here, we have taken $R_{12} = 0.92$ and $R_{13} = 0.39$ which approximately maximize the CP asymmetry. We have used the current best fit values for the oscillation parameters. In order to generate the observed baryon asymmetry, $|Y_B| \simeq 8.59 \times 10^{-10}$, for maximal CP violation, $|\sin\delta| \sim 1$, in the case analised, we should have $M_1 \sim 3.5 \times 10^{11}$ GeV [38]. Recalling that flavour effects in leptogenesis are developed for $M_1 \leq 5 \times 10^{11}$ GeV, this implies that CP needs to be violated maximally, or nearly maximally. These values are in agreement with current hints and will be at reach of future long baseline neutrino oscillation experiments.

5. Conclusions

The observation of lepton number non-conservation and of leptonic CP violation in long baseline neutrino oscillations, at reach in current and future experiments, would have important implications for our understanding of the origin of the baryon asymmetry. They would constitute a strong indication (even if not a proof) in favour of leptogenesis as the mechanism of generation of the baryon asymmetry of the Universe.

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