Sensitivity of CP Majorana phases using the synergy between cosmological and neutrinoless double beta decay data at high precision era of measures

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Abstract

We study the detectability of Majorana phase of neutrinos through the precision data of the sum of neutrino masses by cosmological observations, lifetime of neutrinoless double beta decay in ton-scale experiments and the effective neutrino mass measured from single beta decay experiments. We found there is a synergy when data of the three experiments is combined, this allow to constraint one of the Majorana phase ($\alpha_{21}$) by excluding $10 - 40\%$ the phase space at the $2\sigma$ level of confidence for the lowest neutrino mass of $0.1$ eV.

INTRODUCTION

In spite that we are in a era where the oscillation parameters are measured with a high precision [1–3], there are some questions in the neutrino sector that remain open. In this work we want to study one of these open questions, it is the CP Majorana neutrino phases [4, 5]. In order to analyze these phases we need to assume that neutrinos are Majorana particles. We are motivated to analyze these parameters because, nowadays, through an unprecedented precision that observables are being measured by experiments, is possible to get valuable information of the parameters when the data of three observables are combined [6]. In order to quantify our results, we have used a function called “exclusion fraction function” ($f_{CPX}$) which is defined as a fraction of the CP Majorana phase space that can be excluded with a certain C.L when the inputs parameters are given [7–9].

THE OBSERVABLES

The effective neutrino mass ($m_{\nu\beta\beta}$) is measured through the half-life time $T_{1/2}^0$ in the neutrinoless double beta decay experiments. Unfortunately this measure have the largest uncertainty in the nuclear matrix element (NME) which introduces an uncertainty with a factor between $2 - 4$ [10] in the $m_{\nu\beta\beta}$. The effective neutrino mass can be related to the oscillation parameters as:

$$m_{\nu\beta\beta} = |m_1c_{13}^2c_{12}^2 + m_2c_{13}^2s_{12}^2e^{i\alpha_{31}} + m_3s_{13}^2e^{i\alpha_{31}}|,$$ (1)

where $m_i$ is the neutrino masses and $c_{ij} = \cos \theta_{ij}$, $s_{ij} = \sin \theta_{ij}$ whereas $\alpha_{31}$, $\alpha_{32}$ represents the CP Majorana phases in the MNS matrix mixing neutrino [11]. The prevision on future neutrinoless double beta decay experiments is that will cover the inverted mass hierarchy band which means $m_{\nu\beta\beta} \approx 10$ meV.
The absolute neutrino mass ($\Sigma$) is related to the oscillation parameters as:

$$\Sigma = m_1 + m_2 + m_3.$$  \hfill (2)

In recent observations by the Planck Collaboration when baryon acoustic oscillation (BAO) is added they obtained the most severe upper bound $\Sigma < 0.23\text{eV}$ (Planck + WMAP + highL+BAO) at 95\% C.L \[12\]. However, we must be careful with those results coming from cosmological analysis because depend on a particular model, in our work we assume that the “Standard Model of Cosmology” is well described by the $\Lambda$CDM model.

The effective neutrino mass $m_\beta$, through the single beta decay process can be measured with the distortion caused by $m_\beta \neq 0\text{eV}$ in the end point of the electron energy spectrum in the Kurie plot. The effective neutrino mass measured by this technique can be written as:

$$m_\beta^2(\nu_e) = c_{12}^2 c_{13}^2 m_1^2 + s_{12}^2 c_{13}^2 m_2^2 + s_{13}^2 m_3^2.$$  \hfill (3)

Currently the best upper limit on $m_\beta$ comes from Mainz \[13\] and Troitsk \[14\] each experiment found a limit of $m_\beta < 2.3\text{eV}$ and $m_\beta < 2.05\text{eV}$ respectively at 95\% CL. There is an experiment called “KATRIN” \[15\] that will improve these bound by one order of magnitude, the upper bound expected with KATRIN is $m_\beta < 0.2\text{eV}$ at 90\% C.L.

**ANALYSIS METHOD**

We analyze the CP Majorana phases minimizing the $\chi^2$ function which is defined as:

$$\chi^2 \equiv \min \left\{ \left[ \frac{\Sigma(0) - \Sigma^{\text{fit}}}{\sigma_\Sigma} \right]^2 + \left[ \frac{m_\beta(0) - m_\beta^{\text{fit}}}{\sigma_\beta} \right]^2 + \left[ \frac{\xi m_{\nu e \beta \beta}(0) - m_{\nu e \beta \beta}^{\text{fit}}}{\sigma_{\nu e \beta \beta}} \right]^2 \right\},$$  \hfill (4)

where we have assumed that each observable have a central value ($\Sigma^{0}, m_\beta^{0}, m_{\nu e \beta \beta}^{0}$) and 1\% of uncertainty ($\sigma_\Sigma = 0.05\text{eV}, \sigma_\beta = 0.06\text{eV}, \sigma_{\nu e \beta \beta} = 0.01\text{eV}$) \((\text{for more details see Appendix A in} [9])\) whereas the functions $\Sigma^{\text{fit}}(m_0), m_\beta^{\text{fit}}(m_0), m_{\nu e \beta \beta}^{\text{fit}}(m_0, \alpha_{12}, \alpha_{13})$ must be fitted varying the parameters $m_0, \alpha_{13}$ and $\alpha_{12}$. In this work is imperative a special attention to the NME uncertainty which is represented by $\xi$ in the equation (4) and is quite similar to the one in \[16\]. \textit{See also} \[9\]. We explore four different values of NME uncertainty parameter, $r_{\text{NME}} = 1.1, 1.3, 1.5, 2.0$ where $\xi$ is bounded as $1/\sqrt{r_{\text{NME}}} \leq \xi \leq \sqrt{r_{\text{NME}}}$. In order to quantify our results, we have used “the exclusion fraction function” see FIG. 1, it is a useful function which shows us how much the parameters can be excluded.
FIG. 1. In (a), (b), (d), (e) Contours of \( f_{\text{CPX}} \) determined at 3 \( \sigma \) C.L for the Inverted and Normal Hierarchy (IH, NH). (1 DOF) projected into the plane of the true values of \( \alpha_{21}/\pi \) and the lightest neutrino mass \( m_0 \) for the cases where true value of \((\sigma_\Sigma, r_{\text{NME}})\) = \((0.05 \text{ eV}, 1.3)\), \((0.05 \text{ eV}, 1.1)\), \((0.02 \text{ eV}, 1.3)\) and \((0.02 \text{ eV}, 1.1)\) are shown. In (c) and (f), we show, respectively, for \( \sigma_\Sigma = 0.05 \text{ eV} \) and \( 0.02 \text{ eV} \), the iso-contours of \( \Delta f_{\text{CPX}}(r_{\text{NME}}) \equiv f_{\text{CPX}}(r_{\text{NME}} = 1.1) - f_{\text{CPX}}(r_{\text{NME}} = 1.3) \) whereas in (g) and (h), we show, respectively, for \( r_{\text{NME}} = 1.3 \) and \( 1.1 \), the iso-contours of \( \Delta f_{\text{CPX}}(\Sigma) \equiv f_{\text{CPX}}(\sigma_\Sigma = 0.02 \text{ eV}) - f_{\text{CPX}}(\sigma_\Sigma = 0.05 \text{ eV}) \). In (i) we show the iso-contours of \( \Delta f_{\text{CPX}}(\Sigma, r_{\text{NME}}) \equiv f_{\text{CPX}}(\sigma_\Sigma = 0.02 \text{ eV}, r_{\text{NME}} = 1.1) - f_{\text{CPX}}(\sigma_\Sigma = 0.05 \text{ eV}, r_{\text{NME}} = 1.3) \).

**SUMMARY AND REMARKS**

- The dependence of \( m_{0\beta\beta} \) on \( \alpha_{13} \) is very weak due to the small value of \( s^2_{13} \) and there is a very weak dependence between \( \alpha_{12} \) and \( \alpha_{13} \). For more details see [9],

- The best and worse sensitivities to \( \alpha_{12} \) is when the true value of \( \alpha_{12} \) are 0 or \( \pi \) and \( 3\pi/2 \) respectively. See figure (1),

- The sensitivity to \( \alpha_{12} \) increase to low values of true \( m_0 \) in the inverted ordering case, whereas for larger values of \( m_0 \) there is an increase of the sensitivity for any value of NME. See figure (1),
• The sensitivity to $\alpha_{12}$ increases when the uncertainty of the NME decreases and also when the uncertainty of the $\Sigma$ decreases, See figure (1). In this point, we expect that in the near future, with the cosmological data coming with an unprecedent precision, the interest of the Cosmology on the neutrino sector be renewed.

• There is a synergy between $m_{0e/\beta\beta}$ and $\Sigma$ data which play a interesting role to constraint the CP Majorana phase $\alpha_{12}$. As we can see in the equation (2) even without dependence of $\Sigma$ on $\alpha_{12}$, we found that when the cosmological data are added to equation (4) the sensitivity to $\alpha_{12}$ increases. For more details see [9].

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