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Appearance and disappearance signals at a β-beam and a super-beam facility

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Abstract

In this Letter we present the study of the eightfold degeneracy in the (θ_{13}, δ) measurement including both appearance and disappearance channels. We analyse, for definiteness, the case of a standard low-γ β-beam and a 4 MW SPL super-beam facility, both aiming at a UNO-like Mton water Čerenkov detector located at the Fréjus laboratory, $L = 130$ km. In the β-beam case, the ν_e disappearance channel does not improve the (θ_{13}, δ) measurement when a realistic (i.e., $\geqslant 2\%$) systematic error is included. In the super-beam case, the ν_μ disappearance channel could, instead, be quite useful in reducing the impact of the eightfold degeneracy in the (θ_{13}, δ) measurement, especially once the error on the atmospheric mass difference is fully taken into account in the fit.

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1. Introduction

After more than 30 years of successful neutrino oscillation experiments [1] two parameters still remain undetermined in the three-family Pontecorvo–Maki–Nakagawa–Sakata [2] mixing matrix: the mixing angle θ_{13}, for which only a upper limit has been set [3], and the CP-violating phase δ that is still completely unknown. The full understanding of the leptonic mixing matrix constitutes, together with the discrimination of the Dirac/Majorana character and the measure of the neutrino absolute mass scale, the main neutrino-physics goal for the next decade(s).

It is well known that the best way to simultaneously measure (θ_{13}, δ) is the (golden) $\nu_e \to \nu_\mu$ appearance channel [4] (and its T and CP conjugate ones). Unfortunately this measure is, in general, severely affected by the presence of degeneracies. When a measurement of the two unknown parameters is performed using

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a beam able to produce both neutrinos and antineutrinos, the following four systems of equations must be solved:

$$\begin{cases} N_{l^+}(\bar\theta_{13}, \bar\delta; \bar s_{\rm atm}, \bar s_{\rm oct}) = N_{l^+}(\theta_{13}, \bar\delta; \pm\bar s_{\rm atm}, \pm\bar s_{\rm oct}), \\ N_{l^-}(\bar\theta_{13}, \bar\delta; \bar s_{\rm atm}, \bar s_{\rm oct}) = N_{l^-}(\theta_{13}, \bar\delta; \pm\bar s_{\rm atm}, \pm\bar s_{\rm oct}), \end{cases} \tag{1}$$

where $s_{\rm atm} = {\rm sign}(\Delta m^2_{\rm atm})$ and $s_{\rm oct} = {\rm sign}(\tan 2\theta_{23})$ are two discrete unknowns, the sign of the atmospheric mass difference and the θ_{23}-octant. The r.h.s. of this equation implies that four different models (each of them with a definite $(s_{\rm atm}, s_{\rm oct})$ choice) must be used to fit the data on the l.h.s. The eight solutions form what is known as the *eightfold degeneracy* [5–8]. Various methods have been considered to get rid of degeneracies (using spectral analysis [5], combination of experiments [9] and/or different channels [10]). In principle, the eightfold degeneracy can be completely solved if a sufficient number of independent informations is added. At the cost, of course, of increasing the number of detectors and/or beams and consequently the budget needs.

In this Letter we try to understand if the effect of degeneracies can be reduced using informations from both the appearance and the disappearance channels at a given experiment. We consider, as reference, the proposal for two CERN-based facilities, the standard[1] low-γ β-beam [11] and the super-beam based on the 4 MW SPL 2.2 GeV proton driver [15]. Both beams are directed from CERN toward the underground Fréjus laboratory, where it has been proposed to locate a 1 Mton UNO-like [16] water Čerenkov detector with a 440 kton fiducial mass. The considered baseline is $L = 130$ km. To be at the first peak in the leading oscillation probability term, the average neutrino energy for both beams has been chosen of the order of a few hundreds MeV. Of course, many other similar setups could be considered, instead the "standard" ones adopted in this Letter. Anyway our considerations are quite general and will hold for any comparable low-γ β-beam and super-beam setup.

Needless to say that a similar analysis can be performed in any experiment where disappearance and appearance channels are simultaneously available. At the neutrino factory, for example (see [17,18]), the $\bar\nu_\mu$ disappearance channel can be certainly used together with the appearance channel $\nu_e \to \nu_\mu$, whereas the ν_e disappearance channel is extremely difficult to exploit (due to the need to measure the electron charge to distinguish $\nu_e \to \nu_e$ from $\bar\nu_\mu \to \bar\nu_e$).

The eightfold degeneracy for these two facilities has been comprehensively studied in [19] and we refer to that paper for all the technical details regarding the used cross-sections, efficiencies and backgrounds. The results of [19] show that to run the two facilities simultaneously does not help in solving the degeneracies, mainly because the two beams, running on the same baseline and with approximately the same energy, are not complementary at all. The only effect is to increase the statistics by roughly a factor two and to reduce some of the systematics, but leaving practically unaffected the main systematic error that it's due to the definition of the fiducial volume of a Mton water detector. In this sense no real *synergy* is achieved adding these two experiments (if not for using the same detector, thus halving the corresponding costs). For this reason, in the following we will analyse the performance (in the appearance and disappearance channels) of the two facilities separately.[2]

2. β-beam appearance and disappearance channels

The considered β-beam setup consists of a $\bar\nu_e$-beam produced by the decay of ^{6}He ions boosted at $\gamma = 60$ and of a ν_e-beam produced in the decay of ^{18}Ne ions boosted at $\gamma = 100$. The γ-ratio has been chosen to store both ions simultaneously into the decay ring. A flux of 2.9×10^{18} ^{6}He decays/year and 1.1×10^{18} ^{18}Ne decays/year, as discussed in [20], will be assumed. The average neutrino energies of the $\nu_e, \bar\nu_e$ beams corresponding to this configuration are 0.37 and 0.23 GeV, respectively. Although the boosting factor has been chosen to maximize the oscillation probability at $L = 130$ km, a severe drawback of this option is

[1] Other β-beam proposals with different choices of the boosting factor can be found in [12–14].

[2] We will not consider here the possibility of using the β-beam or super-beam facility for other measures beyond appearance and disappearance oscillation ones. The interested reader can find a detailed description of these other possible measurements in, for example, [11,12,20].