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$\gamma = 350$ Li/B beta beam

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We consider a β-Beam facility where ^{8}Li and ^{8}B ions are accelerated at $\gamma = 350$, accumulated and let decay, so as to produce intense $\bar{\nu}_e$ and ν_e beams. These beams illuminate two magnetized iron detectors located at $L \simeq 2000$ Km and $L \simeq 7000$ Km, respectively. The physics potential of this setup is analysed as a function of the flux. We find that, for the highest flux considered (10×10^{18} ion decays per year per baseline), the sensitivity to θ_{13} reaches $\sin^2 2\theta_{13} \geq 1 \times 10^{-4}$; the sign of the atmospheric mass difference can be identified, regardless of the true hierarchy, for $\sin^2 2\theta_{13} \geq 3 \times 10^{-4}$; and, CP violation can be discovered in 70% of the δ-parameter space for $\sin^2 2\theta_{13} \geq 10^{-3}$, having some sensitivity to CP violation down to $\sin^2 2\theta_{13} \geq 2 \times 10^{-4}$ for $|\delta| \sim 90°$.

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1. Introduction

The results of solar, atmospheric, reactor and accelerator [1] neutrino experiments show that flavour mixing occurs in the leptonic sector. The experimental results point to two mass-squared differences, $\Delta m^2_{\rm sol} \approx 7.9 \times 10^{-5}$ eV^2 and $|\Delta m^2_{\rm atm}| \approx 2.4 \times 10^{-3}$ eV^2. At present, only two out of the four parameters of the three-family leptonic mixing matrix are known: $\theta_{12} \approx 34^\circ$ and $\theta_{23} \approx 42^\circ$ [1]. The other two parameters, θ_{13} and δ, are still unknown: for θ_{13} searches at reactors give the upper bound $\theta_{13} \leq 12.3^\circ$ (3σ), whereas for the leptonic CP-violating phase δ we have no information whatsoever. Another unknown is the sign of the atmospheric mass difference, s_{atm}. These parameters could be measured in "appearance" experiments through $\nu_e \to \nu_\mu, \nu_\mu \to \nu_e$ (the "golden channel" [2]).. However, parametric degeneracies make their simultaneous measurement rather challenging [3]. Here we propose to alleviate this problem with a setup based on ^{8}Li/^{8}B β-Beam accelerated at $\gamma = 350$, aiming at two magnetized iron detectors at $L = 2000$ Km and $L = 7000$ Km [4].

This proposal is the natural conclusion of a series of theoretical, experimental and accelerator achievements. In Ref. [5] the idea of accelerating radioactive ions and store them so as to produce intense $\nu_e(\bar{\nu}_e)$ beams was advanced. ^{6}He/^{18}Ne ions were boosted at $\gamma \sim 100$ using existing infrastructures at CERN, producing $\nu_e(\bar{\nu}_e)$ beams aimed at a 1 Mton water Čerenkov at $L = 130$ Km down the source. In Refs. [6] it was proposed to accelerate the ions at a much higher γ ($\gamma = 350$ and 580, respectively), aiming at a 1 Mton detector water Čerenkov detector at $L = 650$ Km from the source. Such a high Lorentz boost factor could only be attained at CERN using new infrastructures. A new SPS, the SPS+, is actually under discussion in the framework of the planned LHC maintenance and upgrade programme. Alternatively, the TeVatron could be used for the last acceleration stage (see, e.g., Ref. [7]). This setup greatly outperforms the "low"-γ one discussed above and could compete with NF–based setups in the sensitivity to CP violation. In Ref. [8], the "ionization cooling" technique to produce intense ^{8}Li and ^{8}B beams was proposed. In Ref. [9] a "cocktail" of ^{8}Li/^{8}B and ^{6}He/^{18}Ne β-beams at $\gamma = 100$ (the maximum that can be achieved with existing CERN infrastructures) illuminating a 1 Mton water Čerenkov detector located at $L = 650$ Km was proposed so as to solve some of the parametric degeneracies. This setup is only useful in the case of large θ_{13}, due to its statistical limitations. In Refs. [10], the possibility of using a high-γ ^{6}He/^{18}Ne β-Beam illuminating a (MINOS-like) 50 Kton magnetized iron detector located at $L = 732$ Km down the source was explored. Eventually, in Refs. [11] a $\gamma = 350$ ^{8}Li/^{8}B β-Beam illuminating a 50 Kton magnetized iron detector located at $L = 7100$ Km down the source was proposed, The main difference of using ^{8}Li/^{8}B instead of ^{6}He/^{18}Ne ions is that the end-point energy of the ^{8}Li/ ^{8}B β-decays is $Q_\beta \sim 13$ MeV (to be compared with $Q_\beta \sim 3.5$ MeV for ^{6}He/^{18}Ne). With a Lorentz boost factor of $\gamma = 350$, a (relatively) high mean neutrino energy in the laboratory frame, $E_\nu \sim 6$ GeV is achievable, allowing to exploit the resonant enhancement of the oscillation probability. through matter effects, providing excellent sensitivities to s_{atm} and θ_{13}.

A further consequence of having an energetic neutrino flux is that we can safely use dense detectors with a good muon identification efficiency, as an alternative to the water Čerenkov technology. We will therefore consider the neutrino beam to be aimed at two 50 Kton magnetized iron detectors of the MIND-type, located at $L = 2000$ Km (at the oscillation peak) and at the "magic baseline", $L \simeq 7000$ Km, as in the NF [12].

The near baseline, tuned to the oscillation peak, provides the sensitivity to CP violation that the "magic baseline", at which matter effects cancel the dependence of the oscillation probability on δ, lacks. This sensitivity is, however, spoiled by degeneracies, specially by the ones related to the mass hierarchy. which are effectively solved with the combination with the longer baseline with its nearly resonant sensitivity to s_{atm}.

2. Signal and backgrounds

Lacking a detailed study of the achievable ^{8}Li and ^{8}B fluxes, in ref [4] three possible values for the β-beam flux were considered: "nominal flux" of 2×10^{18} decays per year per baseline for both ^{8}Li and ^{8}B (these fluxes are close to the "standard fluxes", i.e. 2.9×10^{18} and 1.1×10^{18} decays per year for ^{6}He and ^{18}Ne); "medium flux" of 5×10^{18} and "ultimate flux" of 10×10^{18} decays per year per baseline for both ions. The comparison of the physics performance achievable with each of these fluxes was presented in ref [4], here we will show the results for the "ultimate flux". An increase of the ion flux up to the "ultimate flux" is believed to be possible (see the talk by M. Lindroos). Notice, moreover, that due to the higher energy of this setup compared to standard He/Ne options, the atmospheric neutrino background is expected to be significantly lower and a larger number of bunches can be thus injected into the storage ring.

A full simulation of the response of a magnetized iron detector to the beam proposed in this paper is lacking. In the framework of the ISS report [13], a detailed study of the MIND detector exposed to the Neutrino Factory beam (i.e. for a neutrino energy around 30 GeV) has been presented, finding a ν_μ identification efficiency in the energy range of interest as high as 70%. The fractional backgrounds were found to be around or below 10^{-4} for the region around 5 GeV. Since in our setup there is no such a strong down-feed of the background from high energy neutrinos, we expect 10^{-4} to be a pessimistic upper limit for the beam-induced background.

In the numerical analysis below, event rates have been divided into nine bins between 1.5 and 10.5 GeV, with $\Delta E = 1$ GeV. The detector energy resolution has been implemented through a gaussian resolution function with $\sigma = 0.15 \times E$. We have considered a constant $\nu_\mu/\bar{\nu}_\mu$ identification efficiency of 65% and a constant fractional background equal to 10^{-5} of the unoscillated events per bin. In ref [4] the impact of the beam background on the physics performance of the setup increasing the fractional background up to 10^{-4} was also studied, showing explicitly that the effect is small for any of the considered observables.

We have, eventually, considered a 2.5% and 5% systematic errors on the signal and on the beam-induced background, respectively. They have been included as "pulls" in the statistical χ^2 analysis. The effect of increasing these errors to 10% and 20%, respectively, was also considered in ref [4]. It has been found that the impact is negligible.

The following 1σ errors for the oscillation parameters were also considered: $\delta\theta_{12} = 1\%$, $\delta\theta_{23} = 5\%$, $\delta\Delta m^2_{21} = 1\%$ and $\Delta m^2_{31} = 2\%$. If θ_{23} turns out to be maximal the error on θ_{23} could be larger than the 5% we assumed. We studied the effect of increasing the error to 10%, which is almost the present uncertainty, given that this parameter will not be measured by the proposed setup. We have checked that our results are not significantly affected by considering such an error. Eventually, an error $\delta A = 5\%$ has been considered for the Earth density given by the PREM model.

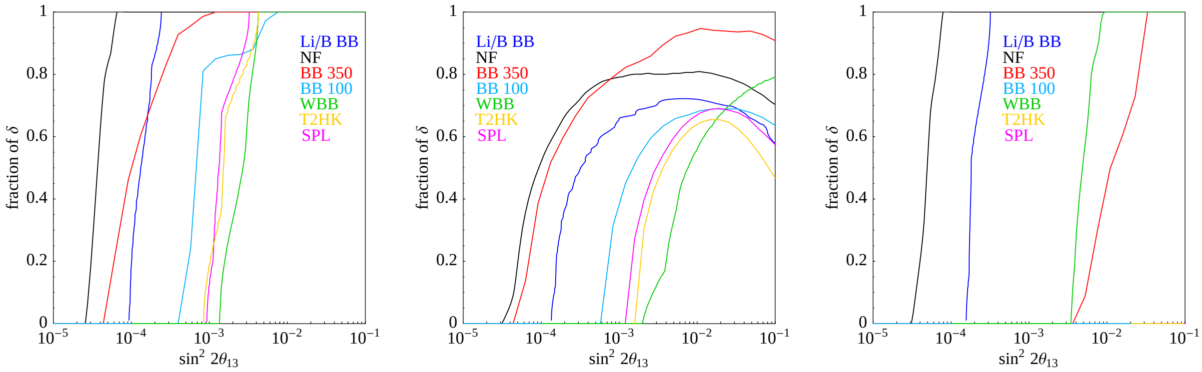

Figure 1: *Comparison of the physics performance of the facilities studied in [15] with the* ^{8}*Li/*^{8}*B* β*-Beam.*

Marginalization over these parameters has been performed for all observables. The Globes 3.0 [14] software was used to perform the numerical analysis.

3. Results

Fig. 1 shows the discovery potential to θ_{13} (first panel), CP violation (second panel) and a normal mass hierarchy (third panel) for the ^{8}Li/^{8}B β-Beam compared with the results of the comparison performed in [15]. The blue curve depicts the sensitivities that would be achieved with the proposed setup and “ultimate” fluxes. The effect of increasing the background and systematic errors is small and was studied in [4]. Decreasing the fluxes down to the “medium” or “nominal” fluxes has a greater impact in the physics performance and was also shown in [4]. The two best facilities in the comparison study performed in were the NF (black curve) and the high γ He/Ne β-Beam (red curve). The former has excellent sensitivity to θ_{13} and to the mass hierarchy (due to its long baselines and to the combination of the two detectors, that allows to measure s_{atm} down to $\sin^2 2\theta_{13} \geq 3 \times 10^{-5}$). The latter has excellent sensitivity to CP violation, being located on-peak and with very small matter effects that can mock true CP violation, it could detect a non-vanishing δ for more than 80% or even 90% of the parameter space if θ_{13} is not too small. The (too) short baseline, however, spoils its sensitivity to the mass hierarchy.

Using the “ultimate flux” (10×10^{18}), the sensitivity to θ_{13} is $\sin^2 2\theta_{13} \geq 2 \times 10^{-4}$, regardless of the value of δ. For specific values of δ close to maximal CP violation, $|\delta| \sim 90^\circ$, the sensitivity reaches $\sin^2 2\theta_{13} \geq 10^{-4}$, thus outperforming any Super-Beam or low-γ β-Beam setup and being competitive with the $\gamma = 350$ He/Ne scenario. for extremely small values of θ_{13} the NF, with its high statistics, provides the best sensitivity.

The CP-violating phase δ can be measured in approximately 70% of the δ parameter space for $\sin^2 2\theta_{13} \simeq 10^{-2}$. Some sensitivity to δ is achieved for $|\delta| \sim 90^\circ$ down to $\sin^2 2\theta_{13} \geq 10^{-4}$. We again find that this setup outperforms all Super-Beams and low-γ β-Beam scenarios. It is, however, outperformed by the high-γ He/Ne β-Beam and by the NF. In this case the best sensitivity is achieved by the high-γ He/Ne β-Beam covering more than 90% of the δ parameter space for $\sin^2 2\theta_{13} \simeq 10^{-2}$ and with some sensitivity down to $\sin^2 2\theta_{13} \geq 5 \times 10^{-5}$.

As for the sensitivity to the mass hierarchy, we find that the true hierarchy could be identified if $\sin^2 2\theta_{13} \geq 3 \times 10^{-4}$ for any value of δ, with some sensitivity down to $\sin^2 2\theta_{13} \geq 10^{-4}$ for

$|\delta| \sim 90^\circ$. Only the NF (with sensitivity down to $\sin^2 2\theta_{13} \geq 6 \times 10^{-5}$ for any value of δ) can in this case beat the high-γ Li/B β-Beam.

The combination of the two baselines, thus, provides good sensitivity to the three observables. Notice that, if the "medium" or the "ultimate flux" can be achieved, this would be the only β-Beam-based setup capable of simultaneously probing CP violation and the neutrino mass hierarchy in the range $\sin^2 2\theta_{13} \in [3 \times 10^{-4}, 1 \times 10^{-2}]$. The main drawback is its low statistics compared to the He/Ne setup (with a shorter baseline and larger detector) or to the NF-RS (whose flux is two orders of magnitude above the most optimistic ion flux considered here).

In summary, we think that the combination of the "on peak" and "magic" baselines at a high-γ Li/B β-Beam is a very powerful tool to solve degeneracies and find good sensitivities to the most relevant unknown parameters of the leptonic flavour sector. This setup is, however, limited by the statistical error and would strongly benefit of any improvement on the neutrino flux, detector mass or efficiency.

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