Exploring leptonic CP violation with a Li/B β-beam from CERN to Gran Sasso

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Abstract. We have considered a β-beam setup which tries to leverage at most existing European facilities to boost high-Q ions aiming at a far detector located at $L = 732$ km in the Gran Sasso Underground Laboratory. The average neutrino energy obtained from ^{8}Li and ^{8}B ions boosted at $\gamma \sim 100$ is in the range $E_\nu \in [1, 2]$ GeV, high enough to use a large iron detector of the MINOS type. We perform, then, a study of the neutrino and antineutrino fluxes needed to observe CP violation and to establish the neutrino mass hierarchy in a significant part of the parameter space.

Keywords: Beta decay, CP violation, neutrino oscillations
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THE SETUP

In a β-beam, a pure electron neutrino beam is produced from the decay of beta unstable ions in the straight sections of a decay ring aiming at a far detector. The original β-beam design was conceived to leverage at most the CERN accelerator complex and profit of the high isotope production yield reachable by ISOL techniques [1]: the terminal booster was the SPS, which can accelerate ions up to a maximum Lorentz $\gamma \sim 450\ Z/A$, while the choice of the ions was ^{6}He and ^{18}Ne . Since their Q-values are around 3-4 MeV, the mean neutrino energy of the beam was between 0.5 and 0.9 GeV. Such low energies require the construction of a very massive low-density detector, with the consequent technical difficulties related to its accomodation in an underground facility located at an appropriate baseline matching the first oscillation peak. On the other hand, employing neutrinos in the multi-GeV range exhibits an additional advantage: the oscillation signal can be observed and effectively separated from the background in high density detectors, such as an iron calorimeter[1]. Such a detector could be hosted in much smaller underground halls, such as the Gran Sasso Undergound Laboratory in Italy or the Canfranc Underground Laboratories in Spain.

One option in order to achieve a larger mean neutrino energy would be to increase the maximum γ. In principle, this would also be beneficial since larger γ provide larger fluxes at the detector. However, the decay rate at the storage ring would decrease due to a larger ion lifetime in the lab frame. Conversely, Lorentz contraction of the bunches would allow, in principle, for a larger number of ions to be injected into the ring. Therefore, an increase of γ would be profitable provided that the ion decay rate does not drop faster than γ^{-1}. The major disadvantage of this option is that a new terminal booster (such as the proposed SPS+) and a larger storage ring[2] would be needed.

None of these challenges has to be faced if the increase in neutrino energy is achieved employing isotopes with larger Q-values: the SPS can still be used as the terminal booster, and the decay ring size does not need to be increased. The only assumption which has to be made is the replacement of the Proton Synchroton with a new machine (PS2) injecting protons at an energy of 50 GeV into the SPS[3]. Moreover, a new technique to produce low-Z, high-Q ions was proposed in 2006 by C. Rubbia [2] and Y. Mori [3] and specifically adapted to high-Q β-beams

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[1] In principle, magnetization is not required for a β-beam detector, since it is a pure source of electron neutrinos. However, magnetization could be used to reduce the background of punch-through pions.

[2] Larger curved sections are needed in order to bend the ions, which implies a smaller fraction of useful ion decays in the straight sections of the ring.

[3] Such a replacement is presently envisioned to grant the reliability of the LHC injection complex and for the luminosity upgrade of the LHC itself.

in Refs. [2, 4] through the production of ^{8}Li and ^{8}B as $\overline{\nu}_e$ and ν_e sources, respectively.

Either using the ionization cooling technique or standard ISOL methods, a signiticant ^{8}Li flux can be produced. The ionization cooling technique should be able to guarantee a similar production rate for ^{8}B. In this case, however, the problem resides in the extraction and recollection of ^{8}B ions, as they are very reactive and therefore difficult to manipulate. The nominal fluxes proposed in the EURISOL project for ^{18}Ne (^{6}He) are $1.1\ (2.9) \times 10^{18}$ useful decays per year. Significant larger fluxes are expected from the use of ionization cooling for high-Q isotopes. Therefore, we will study the performance of our setup as a function of the achievable neutrino and antineutrino fluxes, F and $\overline{F}$, with respect to a nominal flux F_0 which we have set at $F_0 = 3 \times 10^{18}$ useful decays per year for both ^{8}Li and ^{8}B .

We will consider, therefore, a β-beam produced through the acceleration of ^{8}Li and ^{8}B ions up to $\gamma \sim 100$ aimed at an iron calorimeter detector located at the Gran Sasso Underground Laboratory, at 732 km from CERN [5]. Since for this configuration the mean neutrino and antineutrino energies are both 1.5 GeV, we employ the same selection both for ν_μ CC and $\overline{\nu}_\mu$ events: an interaction is classified as a $\nu_\mu (\overline{\nu}_\mu)$ CC if both the event lenght and the total number of hits in the detector are larger than 12. The efficiency of identifying a CC interaction averaged out over the whole spectrum is $\sim 60\%$. Conversely, the probability for the background to be identified as a CC-like event is slightly less than 1%. Efficiencies and background contamination as a function of the neutrino energy are the ones shown in Fig. 4 from Ref. [6]. Finally, a mass of 100 kton is assumed for the detector, together with 5 years of data taking both for neutrino and antineutrino modes.

RESULTS

In this section we will present the performance of the proposed setup in terms of two observables, defined as:

the CP discovery potential: for a given point in the parameter space, we will say that CP violation can be established if we can rule out the CP-conservation hypothesis ($\delta = 0, \pi$) at 3σ 1 d.o.f., after marginalizing over all the remaining parameters for both hierarhies.

the sgn(Δm^2_{23}) reach: this is defined as the region of the $(\sin^2 2\theta_{13}, \delta)$ plane for which the wrong hierarchy can be ruled out at 3σ 1 d.o.f.

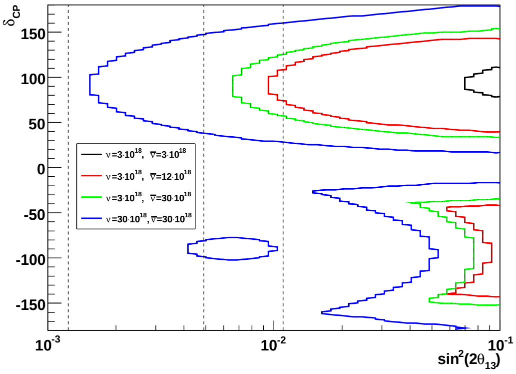

FIGURE 1. CP discovery potential as a function of $\sin^2 2\theta_{13}$ and δ, for several values of both neutrino and antineutrino fluxes, as indicated in the legend. Dotted vertical lines indicate, from left to right, the values of $\sin^2 2\theta_{13}$ corresponding to $\theta_{13} = 1^\circ, 2^\circ$ and 3°, respectively. For the points to the left of each curve, CP violation cannot be established at 3σ 1 d.o.f. after marginalizing over the rest of parameters.

CP discovery potential

In Fig. 1, we present the results for the CP discovery potential as a function of $\sin^2 2\theta_{13}$ and δ, for several values of the neutrino and antineutrino fluxes. Notice the verical dotted lines, which indicate, from left to right in the plot, the values of $\sin^2 2\theta_{13}$ corresponding to $\theta_{13} = 1^\circ, 2^\circ$ and 3°, respectively. A remarkable feature in this plot is the lack of sensitivity around $\sin^2 2\theta_{13} \sim 10^{-2}$ for negative values of δ. This effect is the so-called “π-transit” effect [7]: matter effects mimic CP violation and, for this particular value of θ_{13}, the so-called “sign clones” move from true CP-violating values to CP-conserving ones. As a consequence, in this region of the parameter space CP violation cannot be established even though it is maximal for $\delta \sim -90^\circ$.

It is also important to pay attention to the dependence on the fluxes. Strong improvement takes place when the antineutrino flux is increased from $F_0 \rightarrow 4F_0$, even though we keep the neutrino flux fixed at F_0. However, once we have reached this point, we have saturated statistics for antineutrino events, and no additional improvement will be achieved by further increasing the antineutrino fluxes unless the neutrino flux is also increased. This can be easily seen from the comparison of red and green lines in the plot: even if the antineutrino flux has been increased over a factor of 2, the improvement in the CP discovery potential is only marginal. This is due to the fact that, in order to achieve sensitivity to the CP-violating phase, a comparison between neutrino and antineutrino events at the detector is mandatory: even if we continued increasing the antineutrino flux, the CP dis-

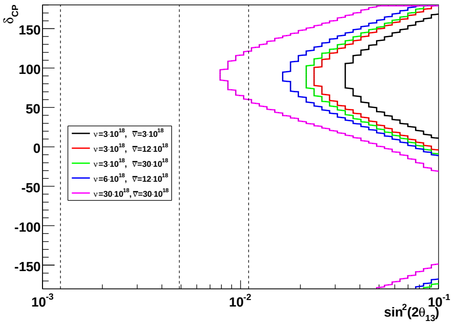

FIGURE 2. The $\mathrm{sgn}(\Delta m^2_{32})$ sensitivity as a function of $\sin^2 2\theta_{13}$ and δ for several values of neutrino and antineutrino fluxes, assuming normal hierarchy. Dotted vertical lines indicate, from left to right, the values of $\sin^2 2\theta_{13}$ corresponding to $1^\circ, 2^\circ$ and 3°, respectively. For the points to the left of the curve, the correct hierarchy cannot be established at 3σ 1 d.o.f. after marginalizing over the rest of parameters.

covery potential will not improve accordingly as there are not enough neutrino events to compare with. On the other hand, if we compare the green and blue lines in the plot a remarkable improvement has taken place in this case (though only the neutrino flux has been enhanced) because now all the antineutrino events are useful.

Sensitivity to the mass hierarchy

As the baseline of the setup is relatively "short", matter effects turn out to be quite mild and therefore we are sensitive to the mass hierarchy only in a small region of the parameter space. The sensitivity to the mass hierarchy is depicted in Fig. 2 as a function of $\sin^2 2\theta_{13}$ and δ for several values of neutrino and antineutrino fluxes, assuming normal hierarchy. Vertical dotted lines indicate, from left to right, the values of $\sin^2 2\theta_{13}$ corresponding to $1^\circ, 2^\circ$ and 3°, respectively. For the points located to the left of each curve, the correct hierarchy cannot be established at 3σ 1 d.o.f., after marginalizing over the rest of parameters. Notice the lack of sensitivity in the region for $\delta < 0$: in the vaccuum limit, the sensitivity to the mass hierarchy comes only through the CP-violating term in the golden channel probablity, which is maximal for $\delta > 0$ for neutrinos in the normal hierarchy case. However, sign clones appear for $\delta < 0$ which avoid the joint measurement of δ and the hierarchy, thus leading to a strong lack of sensitivity in this region.

We have also considered the case of inverted hierarchy, which yields very similar results to those for normal hierarchy, but changing $\delta \to -\delta$. Finally, we have studied how the combination of data from the β-beam and from atmospheric neutrinos could improve the sensitivity to the mass hierarchy. We found that, for large values of θ_{13}, such combination can be of value for the present setup in the region of null sensitivity in Fig. 2, bringing the sensitivity of the setup down to $\sin^2 2\theta_{13} \simeq 3 \times 10^{-2}$.

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REFERENCES

1. The study of this option has been carried out in the framework of the EURISOL Design Study. Information available at `http://beta-beam.web.cern.ch/`
2. C. Rubbia, A. Ferrari, Y. Kadi *et al.*, Nucl. Instrum. Meth. **A568** (2006) 475-487. [hep-ph/0602032].
3. Y. Mori, Nucl. Instrum. Meth. **A562** (2006) 591-595.
4. C. Rubbia, arXiv:hep-ph/0609235.
5. P. Coloma, A. Donini, P. Migliozzi *et al.*, [arXiv:1004.3773 [hep-ph]].
6. A. Donini, E. Fernandez-Martinez, P. Migliozzi *et al.*, Eur. Phys. J. **C48** (2006) 787-796. [hep-ph/0604229].
7. P. Huber, M. Lindner, W. Winter, Nucl. Phys. **B645** (2002) 3-48. [hep-ph/0204352].