Intermediate $\gamma$ beta beams with a cluster of detectors

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Abstract. The acceleration of radionuclides in a beta beam provides an alternative experimental design to superbeam and neutrino factory long baseline neutrino oscillation experiments. Only single baseline beta beam scenarios have been considered thus far although a storage ring could source at least two baselines. The multitude of possible detector sites in Europe potentially allows for numerous baselines for future long baseline experiments sourced at CERN. Here, we will consider an example taking the CERN-Canfranc and CERN-Boulby baselines. We present results that indicate good sensitivity to the mass hierarchy for values of $\sin^2 2\theta_{13}$ as small as $10^{-3}$ and CP-violation discovery for $\sin^2 2\theta_{13}$ down to $10^{-4}$. These results are achieved with a single helicity since the second baseline provides the synergies usually associated with an anti-neutrino run.

1. Introduction

First introduced by Zucchelli [1], the beta-beam proposes to source a clean, well collimated neutrino beam through the acceleration and subsequent decay of stored $\beta$-emitting ions. The initial study [1] considered a “low-$\gamma$” machine which experimentally had three stages: nuclide production via the ISOL technique; acceleration using existing technology such as the PS and SPS before being stored in a decay ring. The feasibility of such a scheme has been demonstrated [2], the current magnetic rigidity of the SPS allowing a maximum $\gamma \sim 150$. Current beta-beam studies [3, 4] focus primarily on the use of existing or near future technology and expertise, e.g. the EURISOL project at CERN. The choice of isotope is determined by the need for a high count rate - a condition that points to isotopes with low Z and a lifetime $(0.8 - 1)$ secs. Most discussion in the literature has focussed on the use of $^6$He for the anti-neutrinos and $^{18}$Ne for neutrinos. These choices were mainly based on the studies and techniques developed by the ISOLDE group at CERN - they are gaseous at room temperature and offer simple diffusion out of the target. The typical $\gamma$ considered for these ions is 100 although higher $\gamma$ have been considered for an upgraded SPS [7, 8, 9, 10]. Although it is expected that these higher $\gamma$ can be experimentally achieved, there is no guarantee that the intensities needed can be obtained. It is then natural to consider higher Q-valued $^8$B and $^8$Li as alternatives [5] provided a factor 15-20 increase in decays can be achieved to compensate for the lower $\gamma$. These ions would allow the reach of higher energies without the need of very high $\gamma$. After acceleration, the ions are accumulated in a storage ring with the straight section decays sourcing a clean $\nu_e/\bar{\nu}_e$ beam. Only single baseline scenarios have been considered up to now whilst any decay ring can source at least two baselines. Although an increase in sensitivity is a trivial consequence of introducing a
second baseline, the addition must be chosen in such a way as to maximise the physics potential of the setup. In a long baseline neutrino oscillation experiment, our inability to determine unambiguously $(\theta_{13}, \delta)$ by the measurement of the neutrino oscillation probabilities presents a further problem. This is the problem of degeneracies. Addition solutions might appear due to our ignorance of $(\theta_{13}, \delta)$, $\text{sign}(\Delta m_{13}^2)$ and unknown octant of $\theta_{23}$. In general, the neutrino oscillation probabilities allow for a second pair $(\theta_{13}', \delta')$ that may fit data; this is the ‘intrinsic degeneracy’. With the sign of $\Delta m_{13}^2$ and unknown octant of $\theta_{23}$ there are up to eight sets of possible values $(\theta_{13}, \delta, \Delta m_{13}^2, \theta_{23})$ that could fit the data.

In this paper we shall be examining intermediate $\gamma$ beta beams with a baseline $L < 1000$ km and a flux equivalent to $^{18}\text{Ne} \gamma < 550$. The overall sensitivity to the mass hierarchy and CP-violation is expected to be good for these configurations; the aim should then be to use synergies to break the degeneracies to improve the CP-violation and mass hierarchy reach for a broader range of $\theta_{13}$ and $\delta$.

2. Formalism

The oscillation probability for $\nu_\mu \rightarrow \nu_e$ can be expanded in the small parameters $\theta_{13}, \Delta_{12}/\Delta_{13}$, $\Delta_{12}/A$ and $\Delta_{12}L$ [6], where the shorthand $\Delta_{ij} \equiv \Delta m_{ij}^2/(2E)$ is being used

$$
P_{\nu_\mu \rightarrow \nu_e}(L) \simeq s_{23}^2 \sin^2 2\theta_{13} \left( \frac{\Delta_{13}}{A + \Delta_{13}} \right)^2 \sin^2 \left( \frac{A + \Delta_{13}L}{2} \right)$$

$$
+ J \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{A + \Delta_{13}} \sin \left( \frac{AL}{2} \right) \sin \left( \frac{A + \Delta_{13}L}{2} \cos \left( \frac{\delta}{A + \Delta_{13}L} \right) \right)$$

$$
+ c_{23}^2 s_{12}^2 \frac{\Delta_{12}}{A} \left( \frac{\Delta_{13}}{A} \right)^2 \sin^2 \left( \frac{AL}{2} \right)
$$

(1)

where $J$ is the Jarlskog invariant $J = \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$ and the $\mp$ corresponds to neutrinos/anti-neutrinos. Here we are using $A = \sqrt{2}G_F n_e(L)$ (the constant density approximation for the index of refraction) where $n_e = 1/L \int_0^L n_e(L')dL'$ is the average electron density and $n_e(L)$ is the electron density along the baseline. The probability $P_{\nu_\mu \rightarrow \nu_e}$ is found via the transformation $T(\delta)P_{\nu_\mu \rightarrow \nu_e}$ which takes $\delta \rightarrow -\delta$.

2.1. Mass hierarchy

From equation 1 it is clear that the presence of a non-negligible matter effect modifies the amplitude of the oscillatory parts of the neutrino oscillation probability - enhancement for the normal hierarchy and suppression for the inverted hierarchy. It is therefore expected that the $\text{sign}(\Delta m_{23}^2)$ sensitivity is greatest at energies around oscillation maxima and least around the oscillation minima where the effect cannot be accentuated as much. To demonstrate this we study the quantity

$$
D_H = \frac{P(NH) - P(IH)}{P(NH) + P(IH)}
$$

(2)

where $P(NH)$ and $P(IH)$ are the neutrino oscillation probabilities for the normal hierarchy and inverted hierarchy respectively. In figure 1(a) we have taken $\sin^2 2\theta_{13} = 0.001$ and fixed the other parameters to the current experimental values for the CERN-Boulby baseline (1050km). First oscillation maximum is at $E_\nu \approx 2.1$ GeV. The plot clearly shows that the difference between normal and inverted hierarchies is greatest around the oscillation maxima with the least sensitivity expected around the minima. This suggests that, in order to solve the degeneracies and improve the sensitivity to the type of hierarchy, the second baseline should have its maxima in the regions of the minima for the CERN-Boulby baseline. The closest option available is the CERN-Canfranc baseline (650 km) which has its first oscillation maximum at $E_\nu \approx 1.3$ GeV.
Figure 1. Projection of $D_H$ onto the $(E_\nu, \delta)$ plane for a) CERN-Boulby: dashed = 0.002, dotted = 0, thin dashes = -0.002 b) CERN-Canfranc: dashed = 0.004, dotted = 0, thin dashes = -0.004. $\sin^2 2\theta$ is fixed at 0.001

2.2. CP-violation

The standard technique to extract the CP-violating phase $\delta$ is to run in $\nu$ and $\bar{\nu}$ channels then use spectral information to resolve the intrinsic degeneracy. With two distinct baselines it should be unnecessary to run in both $\nu$ and $\bar{\nu}$ as the energy spectra will be different for each case. To solve the intrinsic degeneracy one needs to locate and eliminate the clone solutions in different points in the parameter space ($\sin^2 2\theta_{13}, \delta$). For a single baseline this is achieved by using the spectral information from the two channels, the clone being located at different ($\sin^2 2\theta_{13}, \delta$) for each energy bin thus reducing their statistical significance. With two baselines and a single helicity the different energy spectra at each detector should position the clone solutions at different points in the parameter space again resolving this degeneracy.

3. Results

We have studied in detail the performance of a neutrino beta beam with 2 baselines. We have considered a single $\beta^+$ emitter, $^{18}$Ne; the beam being sourced from CERN and directed at Canfranc (650 km) and Boubly (1050 km). We have assumed the following statistics a) Canfranc: $2.5 \times 10^{20}$ decays $\times$ kton $\times$ yr b) Boulby: $5 \times 10^{20}$ decays $\times$ kton $\times$ yr. For example, the Boulby statistics could be realised for 10 years of data with a 100 kton detector and $5 \times 10^{18}$ useful ion decays. The sensitivities to the mass hierarchy and CP discovery are presented in figure 2 both with the statistics quoted above and with a factor 5 reduction. The results have a 2 % systematic error included and backgrounds including a) atmospheric background and efficiencies assuming a $10^{-3}$ duty cycle and b) intrinsic beam background taken as 0.1 % of the unoscillated events. The signal was divided into 200 MeV energy bins. Zero efficiencies were assumed under 400 MeV and 100% otherwise. 99 % confidence level hierarchy resolution can be achieved down to $\sin^2 2\theta_{13} \sim 2 \times 10^{-4}$ whilst this setup has sensitivity to CP-violation for values
Figure 2. a) 99 \% confidence level hierarchy resolution (2 d.o.f). The solid line depicts the results for the statistics quoted in the text, the dotted line corresponds to a reduction by a factor of 5. b) 3\( \sigma \) confidence level for CP-violation extraction. The line scheme is the same as a).

of \( \sin^2 2\theta_{13} \) as small as 2 \( \times \) 10\(^{-5} \). The use of two baselines has compensated for only running in the single helicity.

4. Conclusions
Degeneracies present a challenging problem for future long baseline neutrino oscillation experiments. In this work we have considered using two baselines from a single beta beam source to resolve some of the degeneracy and improve overall sensitivities. A future long baseline experiment should utilise as many synergies as possible to maximise physics reach. A European network of detectors could realise this for the beta beam with upgraded SPS.

Acknowledgments
CO is funded under a STFC studentship to which thanks is given. The authors would like to thank the organisers for the stimulating scientific atmosphere of the conference.

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