Physic with Beta-Beam

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Abstract. A Beta-beam would be a high intensity source of pure $\nu_e$ and/or $\bar{\nu}_e$ flux with known spectrum, ideal for precision measurements. myriad of possible set-ups with suitable choices of baselines, detectors and the beta-beam neutrino source with desired energies have been put forth in the literature. In this talk we present a comparative discussion of the physics reach of a few such experimental set-ups.

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INTRODUCTION

Neutrino physics is now poised to move into the precision regime. A number of high-precision neutrino oscillation experiments have been contrived to shed light on the third mixing angle $\theta_{13}$, the $\sin^2 \theta_{23}$ of $\Delta m^2_{31} = m^2_{3} - m^2_{1}$ (sgn($\Delta m^2_{31}$)) and the CP phase ($\delta_{CP}$), key missing ingredients of the neutrino mass matrix. The $\nu_e \rightarrow \nu_\mu$ transition probability ($P_{\mu\mu}$) depends on all these three parameters and is termed the "golden channel" [1, 2] for long baseline accelerator based experiments[3]. In order to exploit this channel, we need a pure and intense $\nu_e$ (or $\bar{\nu}_e$) beam at the source. The beta-beam serves this purpose. In this talk, we will focus on a few proposed experimental scenarios dealing with beta-beam and discuss the consensus direction for the future.

BETA-BEAM

Zucchelli [4] put forward the novel idea of beta-beam [3, 4, 5, 6, 7, 8, 9, 10, 11, 12], which is based on the concept of creating a pure, well-known, intense, collimated beam of $\nu_e$ or $\bar{\nu}_e$ through the beta decay of completely ionized radioactive ions. It will be achieved by producing, collecting, and accelerating these ions and then storing them in a ring [13]. Feasibility of this proposal and its physics potential is being studied in depth [14], and will take full advantage of the existing accelerator complex and CERN and FNAL. It has been proposed to produce $\nu_e$ beams through the decay of highly accelerated $^{18}$Ne ions and $\bar{\nu}_e$ from $^6$He [4, 13]. More recently, $^8$B and $^8$Li [15] with much larger end-point energy have been suggested as alternate sources since these ions can yield higher energy $\nu_e$ and $\bar{\nu}_e$ respectively, with lower values of the Lorentz boost $\gamma$ [10, 11, 16]. It may be possible to store radioactive ions producing beams with both polarities in the same ring. This will enable running the experiment in the $\nu_e$ and $\bar{\nu}_e$ modes simultaneously. Details of the four beta-beam candidate ions can be found in Table 1 of [9].

THE "GOLDEN CHANNEL" ($\nu_e \rightarrow \nu_\mu$)

The expression for $P_{\mu\mu}$ in matter, up to second order in the small parameters $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ and $\theta_{13}$, is [1, 2]:

$$P_{\mu\mu} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (1 - \hat{A}) \Delta}{(1 - \hat{A})^2} + \alpha \sin 2\theta_{13} \xi \sin \delta_{CP} \sin (\Delta) \frac{\sin (\hat{A}) \sin (1 - \hat{A}) \Delta}{A} + \alpha \sin 2\theta_{13} \xi \cos \delta_{CP} \cos (\Delta) \frac{\sin (\hat{A}) \sin (1 - \hat{A}) \Delta}{(1 - \hat{A})} + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 (\hat{A} \Delta)}{A^2}$$

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \sin 2\theta_{12} \sin 2\theta_{23}$, and $\hat{A} \equiv \pm(2\sqrt{2}G_F n_e L)/\Delta m^2_{31}$, $G_F$ and $n_e$ are the Fermi coupling constant and the electron density in matter, respectively. The sign of $\hat{A}$ is positive (negative) for neutrinos (antineutrinos) with NH and it is opposite for IH. While the simultaneous dependence of this oscillation channel on $\theta_{13}$, sgn($\Delta m^2_{31}$) and $\delta_{CP}$ allows for the simultaneous measurement of all these three quantities, it also brings in the problem of "parameter degeneracies" – the $\theta_{13}$-$\delta_{CP}$ intrinsic degeneracy [17], the sgn($\Delta m^2_{31}$) degeneracy [18] and the octant of $\theta_{23}$ degeneracy [19] – leading to...
an overall eight-fold degeneracy in the parameter values [20]. The degeneracies, unless tackled, always reduce the sensitivity of the experiment.

THE CERN-INO MAGICAL SET-UP

Interestingly, when $\sin(\Delta \Delta) = 0$, the last three terms in Eq. (1) drop out and the $\delta_{CP}$ dependence disappears from the $P_{e\mu}$ channel. The problem of clone solutions due to the first two types of degeneracies are therefore evaded. Since $\Delta \Delta = \pm (2\sqrt{2}G_F n_e L)/4$ by definition, the first non-trivial solution for $\sin(\Delta \Delta) = 0$ reduces to $pL = \sqrt{2}\pi/G_F Y_e$, where $Y_e$ is the electron fraction inside earth. This gives $\rho_{EC}/|\Delta m_{31}^2| \simeq 32725$, which for the PREM [21] density profile of the earth is satisfied for the “magic baseline” [20, 22, 23], $L_{\text{magic}} \simeq 7690$ km. At this baseline the sensitivity to the mass hierarchy and $\theta_{13}$ is quite significant [22], while the sensitivity to $\delta_{CP}$ is absent.

The large baseline also entails traversal of neutrinos through denser regions of the earth, capturing near-maximal matter contribution to the oscillation probability. In fact, for this baseline, the average earth matter density calculated using the PREM profile is $\rho_{av} = 4.25$ gm/cc, for which the resonance energy

$$E_{res} = \frac{|\Delta m_{31}^2|\cos 2\theta_{13}}{2\sqrt{2}G_F N_e}$$

$$= 7 \text{ GeV},$$

for $|\Delta m_{31}^2| = 2.4 \times 10^{-3}$ eV$^2$ and $\sin^2 2\theta_{13} = 0.1$. Of course neutrino oscillation probability for long baseline experiments depend on the product of the mixing term and the mass squared difference driven oscillatory term inside matter. Largest flavor conversions are possible when both these terms are large [3, 24]. The exact neutrino transition probability $P_{e\mu}$ using the PREM density profile is given in Fig. 1 which has been taken from [9]. For neutrinos (antineutrinos), matter effects for the longer baselines bring a significant enhancement of $P_{e\mu}$ for NH (IH), while for IH (NH), the probability is almost unaffected. This feature can be used to determine the neutrino mass hierarchy (see left panel of Fig. 1). For $L = 7500$ km, which is close to the magic baseline, the effect of the CP phase is seen to be almost negligible. This allows a clean measurement of $sgn(\Delta m_{31}^2)$ and $\theta_{13}$ (see right panel of Fig. 1), while for all other cases the impact of $\delta_{CP}$ on $P_{e\mu}$ is appreciable.

A large magnetized iron calorimeter (ICAL) is all set to come up at the India-based Neutrino Observatory (INO) [25]. ICAL@INO will be a 50 kton detector, capable of detecting muons along with their charge, with good energy and angular resolution. It might be upgraded to 100 kton. If a beta-beam facility is built at CERN, ICAL@INO could serve as an excellent far detector for observing the oscillated $\nu_{\mu}$. The USP of this experimental set-up would be the CERN-INO distance, which corresponds to 7152 km, tantalizingly close to the magic baseline. This would enable an almost degeneracy-free measurement of $sgn(\Delta m_{31}^2)$ and $\theta_{13}$ as discussed above.

In addition, one could exploit the near-maximal matter effects by tuning the beam energy to be close to 6-7 GeV (see Fig. 1).

We consider $^8B$ ($^8\bar{B}$) [15] ion as a possible source for a $\nu_e$ ($\nu_{\mu}$) beta-beam and show the expected flux for our experimental set-up in the left panel of Fig. 2. For the Lorentz boost factor $\gamma = 250 - 650$ the $^8B$ and $^8\bar{B}$ sources have peak energy around $\sim 4 - 9$ GeV. We assume $2.9 \times 10^{18}$ useful decays per year for $^8B$ and $1.1 \times 10^{18}$ for $^8\bar{B}$, for all values of $\gamma$. The expected number of events are shown in the right panel of Fig. 2. We take a detector energy threshold of 1.5 GeV, detection efficiency of 80% and charge identification efficiency of 95%. For discussion on our backgrounds and details of our statistical analysis we refer the readers to [9, 12].

We define the $\sin^2 2\theta_{13}$ sensitivity reach of the CERN-INO beta-beam experiment as the upper limit on $\sin^2 2\theta_{13}$ that can be put at the $3\sigma$ C.L., in case no signal for $\theta_{13}$ driven oscillations is observed and the data is consistent with the null hypothesis. At $3\sigma$, the CERN-INO $\beta$-beam set-up can constrain $\sin^2 2\theta_{13} < 1.14 \times 10^{-3}$ with five years of running of the beta-beam in both polarities with the same $\gamma = 650$ and full spectral information. The $\sin^2 2\theta_{13}(true)$ discovery reach is defined as the minimum value of $\sin^2 2\theta_{13}(true)$ for which we can distinguish the signal at the $3\sigma$ C.L. We present our results in the left panel of Fig. 3, as a function of $\gamma$. The plot presented show the most conservative numbers which have been obtained by considering all values of $\delta_{CP}(true)$ and both hierarchies. We refer the reader to [12] for details. The hierarchy sensitivity is defined as the minimum value of $\sin^2 2\theta_{13}(true)$, for which one can rule out the wrong hierarchy at $3\sigma$ C.L. The results are depicted as a function of $\gamma$ in the right panel of Fig. 3. For NH, true, the $sgn(\Delta m_{31}^2)$ reach corresponds to $\sin^2 2\theta_{13}(true) > 5.51 \times 10^{-4}$, with 5 years energy binned data of both polarities and $\gamma = 650$. Here we had assumed $\delta_{CP}(true) = 0$. However, as discussed before, the effect of $\delta_{CP}$ is minimal close to the magic baseline and hence we expect this sensitivity to be almost independent of $\delta_{CP}(true)$ (see [12] for details).

THE CERN-MEMPHYS PROJECT

The CERN-MEMPHYS proposal comprises of sending a low gamma beta-beam from CERN to the envisaged MEMPHYS, which would be a 440 kton fiducial mass water detector located in Fréjus, at a distance of 130 km
from CERN. The major advantage of this set-up is that one needs very reasonable values of the Lorentz Boost $\gamma = 100$ and $^{18}$Ne and $^{6}$He ions for producing the beta-beam. The current accelerator capabilities at CERN are expected to be enough for producing a beta-beam with $\gamma = 100$ without requiring any upgrades and affecting the running of LHC. The band between the red solid lines in Fig. 4 show the $3\sigma$ “discovery reach” for $\sin^2 2\theta_{13}$ using the combined 5 years run in $\nu_e$ and $\bar{\nu}_e$ polarities. The band corresponds to changing the systematic errors from 2% to 5%. The $3\sigma$ $\sin^2 2\theta_{13}$ discovery reach is defined as the minimum value of $\sin^2 2\theta_{13}$ which could produce a $3\sigma$ unambiguous signal at the detector. The strongest point of this experiment is its tremendous sensitivity to CP violation. Maximal CP violation can be observed at the $3\sigma$ C.L. if $\sin^2 2\theta_{13} > 2 \times 10^{-4}$. Another major advantage of this set-up is that if the SPL is built at CERN, then it could serve as a superbeam experiment as well. In that case, one could run could combine simultaneous 5 years of running of $\nu_e$ beta-beam with 5 years of running of the SPL superbeam, without having to run the experiment in the $\bar{\nu}_e$ mode.

COMPARING DIFFERENT SET-UPS

The authors of [5] studied the physics potential of beta-beams, using $^{18}$Ne and $^{6}$He as the source ions and allowing for different values of $\gamma$ and $L$. Table 1 describes the details of the three illustrative set-ups analyzed in details in [5]. Fig. 5 shows the $\sin^2 2\theta_{13}$ sensitivity reach of these three set-ups and compares them with the corresponding potential of that expected from two standard neutrino factory set-ups. We note that the sensitivity of...
\[
\sin^2 2\theta_{13}^{(\text{true})} = 13 - 2 + \text{Li}_8 (\gamma) B_8 (\gamma + ) \text{Li}_8 (\gamma / 1.67)
\]

FIGURE 3. Left panel shows the 3σ discovery reach for \(\sin^2 2\theta_{13}^{(\text{true})}\) for which the wrong inverted hierarchy can be ruled out at the 3σ C.L., as a function of the Lorentz boost \(\gamma\). The red solid lines in both the panels are obtained when the \(\gamma\) is assumed to be the same for both the neutrino and the antineutrino beams. The blue dashed lines show the corresponding limits when the \(\gamma\) for the \({}^8\text{Li}\) is scaled down by a factor of 1.67 with respect to the \(\gamma\) of the neutrino beam, which is plotted in the x-axis.

FIGURE 4. 3σ discovery reach for \(\sin^2 2\theta_{13}^{(\text{true})}\) for \(\beta\)-beam, Super Beam and T2HK (phase II of the T2K experiment) as a function of \(\delta_{\text{CP}}^{(\text{true})}\). The running time is \((5\nu + 5\bar{\nu})\) year for \(\beta\)-beam with twice the standard luminosity and \((2\nu + 8\bar{\nu})\) years for the Super Beams (4 MW).

the CERN-INO beta-beam experiment is better than that quoted for the set-up 2 of Table 1. The set-up 3 is better, but it needs \(\gamma = 1000\). While none of these three set-ups are competitive with the neutrino factory at magic baseline or the CERN-INO beta-beam set-up as far as the hierarchy sensitivity is concerned, the CP sensitivity of the three set-ups is extremely good. For CP studies the performance of beta-beam is comparable with neutrino factory at \(L = 3000 - 4000\) km.

In Table 2 we present a quantitative comparison of the potential of the different set-ups. The first two rows of the table shows the sensitivity reach of the the neutrino factory experiments at 3000 km and 7500 km respectively. The third and fourth rows show the physics reach of the CERN-INO and CERN-MEMPHYS beta-beam proposal. The remaining entries have been taken from various papers on beta-beam and their arXiv numbers are mentioned in the first column of the Table. The second column shows the \(\gamma\) value considered, the third column gives the \(L\) taken, fourth column the type of detector considered\(^4\), while the fifth column shows the time of running of the experiment in the neutrino (\(T_{\nu}\)) and antineutrino (\(T_{\bar{\nu}}\)) modes. The cases shown as 10(S) correspond to simultaneous running of the \(\nu_e\) and \(\bar{\nu}_e\) beams for a period of 10 years, with the \(\gamma\) corresponding to the \(\bar{\nu}_e\) beam suppressed by a factor of 1.67. The last three

\(^4\) The detector type (MI) stands for magnetized iron.
columns show the (approximate) $3\sigma$ $\theta_{13}$ discovery (or sensitivity reach), the hierarchy sensitivity and CP sensitivity respectively. The entries in square brackets correspond to 99% C.L. sensitivity. The results correspond to assumed true normal hierarchy. Since the $\theta_{13}$ and hierarchy reach of the experiment in general depends on $\Delta m^2$ (true), we give the most conservative value. Note that for the CERN-MEMPHYS project the hierarchy sensitivity comes mainly from adding the atmospheric neutrino data in the megaton MEMPHYS detector.

FIGURE 5. The $\sin^2 2\theta_{13}$ sensitivity limits for the different setups and other representatives. Here $n = 0$ (decays per year fixed) and the 3$\sigma$ confidence level are chosen. The final sensitivity limits are obtained as the right edges of the bars after successively switching on systematics, correlations, and degeneracies.

TABLE 2. Comparison between the different experimental set-ups. See the text for details.

| $\nu_{\mu}$ V (km) | Detector | $T_{\nu_{\mu}}/T_{\nu_{\tau}}$ | $\sin^2 2\theta_{13}$ | $\Delta m^2$ | Max CPV |
|-------------------|-----------|-----------------|-----------------|-------------|--------|
| NF03000          | 3000      | 50 (MI)         | 4/4             | $1.5 \times 10^{-3}$ | $10 \times 10^{-4}$ | $7 \times 10^{-5}$ |
| NF07500          | 7500      | 50 (MI)         | 4/4             | $2 \times 10^{-4}$ | $2 \times 10^{-4}$ | No sens |
| CERN              | 350       | 7152 (MI)       | 5/5             | $1 \times 10^{-3}$ | $1 \times 10^{-3}$ | No sens |
| CERN-MEMPHYS     | 100/100   | 130 440 (WC)    | 10/10           | $5 \times 10^{-4}$ | $2 \times 10^{-4}$ | $2 \times 10^{-4}$ |
| hep-ph/          | 200/200   | 520 400 (WC)    | 8/8             | $1 \times 10^{-4}$ | $2 \times 10^{-4}$ | $2 \times 10^{-4}$ |
| G062127          | 500/500   | 450 320 (TASD)  | 8/8             | $2 \times 10^{-4}$ | $4 \times 10^{-4}$ | $1 \times 10^{-4}$ |
| 1000/1000        | 1300 500 (TASD) | 8/8 | $1 \times 10^{-4}$ | $7 \times 10^{-4}$ | $7 \times 10^{-4}$ | |
| hep-ph/          | 100/50    | 130 400 (WC)    | 10 (S)          | No sens        | $\leq 1 \times 10^{-4}$ | $\leq 1 \times 10^{-4}$ |
| 0312068          | 580/350   | 732 400 (WC)    | 10 (S)          | Given          | $\leq 1 \times 10^{-4}$ | $\leq 1 \times 10^{-4}$ |
| 3500/3500        | 1300 400 (WC) | 10 (S) | $5 \times 10^{-4}$ | Not           | $\leq 1 \times 10^{-4}$ | $\leq 1 \times 10^{-4}$ |
| hep-ph/          | 120/120   | 130 440 (WC)    | 10 (S)          | Given          | $\leq 1 \times 10^{-4}$ | $\leq 1 \times 10^{-4}$ |
| 0503212          | 150/150   | 300 440 (WC)    | 10 (S)          | $6 \times 10^{-4}$ | $\leq 1 \times 10^{-4}$ | $\leq 1 \times 10^{-4}$ |
| 3500/3500        | 1300 440 (WC) | 10 (S) | $4 \times 10^{-4}$ | Not           | $\leq 1 \times 10^{-4}$ | $\leq 1 \times 10^{-4}$ |

CONCLUSIONS

In this talk, we discussed the expected physics reach of selected experimental set-ups using a beat-beam. Beta-beams are seen to have extremely good physics reach which are comparable to those expected in neutrino factories.

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