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Physics possibilities at India-based Neutrino Observatory

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Abstract. In this talk I review the physics possible at India-based Neutrino Observatory (INO). I discuss the improvement in the precision of currently known quantities and the possibility measuring the presently unknown quantities.

Keywords. Neutrino oscillations; matter effects; mass hierarchy.

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1. Introduction

India-based Neutrino Observatory (INO) is a proposed underground facility at PUSHEP in the Nilagiri Mountains in the Southern part of India. The site is about 240 km south of Bangalore. A cavern of dimensions 120 m × 22 m × 30 m will be constructed at the end of a 1.5-km long tunnel. The location of the cavern is such that there will be about 1 km of rock over burden in all directions (similar to Gran Sasso). INO will house 50 kton Iron CALorimeter (ICAL) capable of detecting atmospheric ν_μ interactions. In addition, it may also host some smaller experiments (such as neutrinoless double beta decay searches) which require low cosmic ray background environments. The ICAL consists of 140 layers of 6 cm iron plates interspersed with 2.5 cm gaps which will house glass resistive plate chambers. The cavern is big enough to double the size of the detector, if necessary. All details of INO can be found in the INO project report available at [1].

2. Physics motivation

The main physics goals of INO are:

1. Reconfirm (with greater statistical significance) the first oscillation dip in (L/E) of the atmospheric neutrinos and measure $|\Delta_{31}|$ and $\sin^2 2\theta_{23}$ precisely.
2. Determine the sign of Δ_{31} and hence the neutrino mass hierarchy.
3. Determine if θ_{23} is maximal or not. If it is not, resolve the octant ambiguity.
4. Search for CPT-violation.

Atmospheric neutrinos are produced in a wide range of energies and they also have a wide range of path lengths varying from 10 km to 10000 km. Thus it is possible to measure their properties over *four orders of magnitude* in (L/E). Thus they are particularly suited to study neutrino oscillation phenomena. Furthermore, the propagation of neutrinos, which travel long distances through earth matter, is modified by the earth matter effects [2]. By a study of these modifications, it is possible to determine the neutrino mass hierarchy [3,4] and the deviation of the mixing angle θ_{23} from $\pi/4$.

2.1 *Precision measurement of* Δ_{31} *and* $\sin^2 2\theta_{23}$

From the current data on solar and atmospheric neutrino experiments, we know that $\Delta_{\rm sol} \ll \Delta_{\rm atm}$. Further, we also know, from CHOOZ data, that the mixing angle $\theta_{13} \leq 12^\circ$ [5,6]. In the three-flavour neutrino oscillation framework [7], we identify $\Delta_{\rm sol} = \Delta_{21} = m_2^2 - m_1^2$ and $\Delta_{\rm atm} = \Delta_{31} = m_3^2 - m_1^2$. In the limit of neglecting Δ_{21} and θ_{13}, the muon neutrino oscillation survival probability is given by

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{1.27\Delta_{31} L}{E} \right), \tag{1}$$

where Δ_{31} is in eV^2, L is in km and E is in GeV. Present atmospheric neutrino data indicate that $\Delta_{31} \sim$ (2–3) $\times 10^{-3}$ eV^2. Thus we find that the downward-going atmospheric neutrinos, with path lengths of a few hundred km, hardly undergo any oscillations at all, whereas the upward-going atmospheric neutrinos, with path lengths of a few thousand km, undergo significant oscillation. The path length is related to the the zenith angle $(\theta_{\rm z})$ by the relation

$$L = \sqrt{(R + L_0)^2 - (R \sin\theta_{\rm z})^2} - R\cos\theta_{\rm z}, \tag{2}$$

where R is the radius of the earth and $L_0 \sim 15$ km is the average height above the surface of the earth at which atmospheric neutrinos are produced. The atmospheric neutrino flux is the same for both positive and negative values of $\cos\theta_{\rm z}$. Therefore the downward-going neutrino events (with positive $\cos\theta_{\rm z}$) give us a measure of the unoscillated neutrino flux whereas the upward-going neutrino events (with negative $\cos\theta_{\rm z}$) give us the oscillated neutrino flux. We define the reference path length for downward-going neutrinos to be that of the associated upward-going neutrinos with zenith angle $\pi - \theta_{\rm z}$ so that the range of (L/E) for both upward- and downward-going neutrinos remains the same. We consider the ratio

$$\mathcal{R}(L/E) = \frac{\text{Upward-going muon neutrinos } (L/E)}{\text{Downward-going muon neutrinos } (L/E)}. \tag{3}$$

Plotting this ratio as a function of (L/E) gives minima at values of (L/E) where the phase $1.27\Delta_{31} L/E = (2p+1)\pi/2$, where p is an integer. Thus accurately locating these minima will enable us to accurately determine $|\Delta_{31}|$. In practise, because of the summation of over wide ranges of L and E, only the first minimum, corresponding to $p = 1$, can be accurately determined. The value of $\mathcal{R}$ at this minimum determines $\sin^2 2\theta_{23}$.

In figure 1, we plot the upward- and downward-muon event distribution at INO, simulated for two different values of $|\Delta_{31}|$. The first minimum in the upward distribution is clearly visible. In figure 2, we plot the ratio $\mathcal{R}$. In generating figure 2, resolutions of 15% in energy E and the path length L are assumed. The position of the minimum is once again clearly defined. The precision with which $|\Delta_{31}|$ and θ_{23} may be measured at ICAL is given in table 1 and in figure 3 alongwith a comparison with current and future experiments.

2.2 *Determination of neutrino mass hierarchy*

The muon neutrino survival probability in vacuum, in the limit of neglecting Δ_{21} but not θ_{13}, is given by

$$P_{\mu\mu}(\text{vac}) = 1 - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\frac{1.27\Delta_{31}L}{E}\right) - \sin^4\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta_{31}L}{E}\right). \tag{4}$$

The angle θ_{13} leads to the mixing between ν_e and ν_μ at the scale of Δ_{31}. Therefore this angle undergoes significant change due to matter effects which arise from the propagation of the neutrinos through earth matter. The matter modified mass-squared difference and mixing angle are given by

$$\Delta_{31}^{\text{m}} = \sqrt{(\Delta_{31}\cos\theta_{13} - A)^2 + (\Delta_{31}\sin\theta_{13})^2}, \tag{5}$$

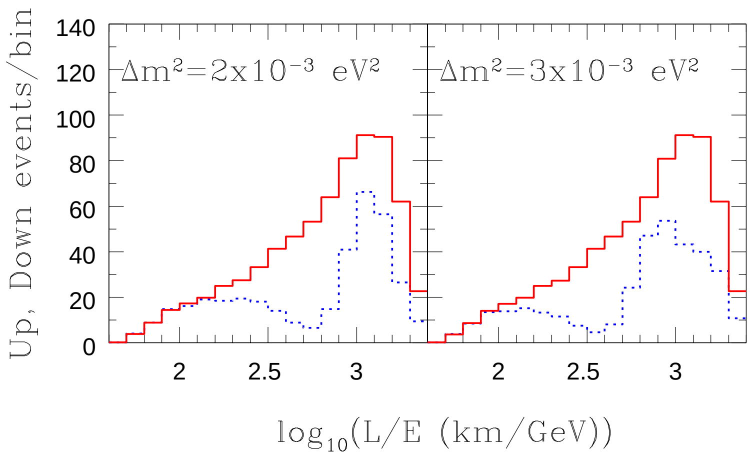

Figure 1. The number of upward-going (broken histogram) and downward–going (solid histogram) muons (of either sign) in (L/E) bins are presented for $|\Delta_{31}| = 0.002$ eV^2, 0.003 eV^2 and $\theta_{23} = \pi/4$ for an exposure of 250 kton-yr at ICAL.

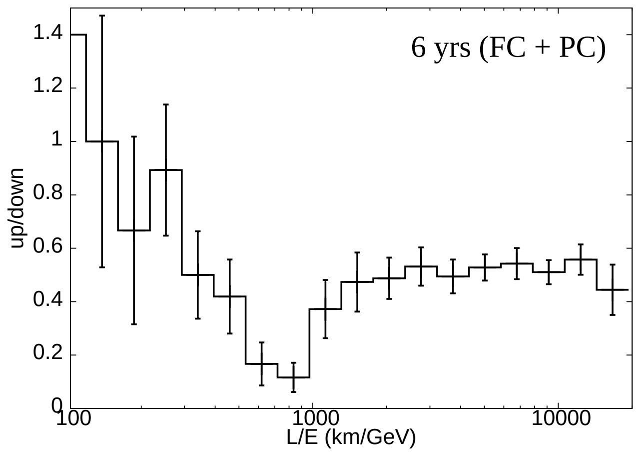

Figure 2. The ratio of upward-going to downward-going muon events for six years of data simulation. The input values are $|\Delta_{31}| = 2 \times 10^{-3}$ eV^2 and $\theta_{23} = 45°$. The position of the dip is sensitive to the magnitude of Δ_{31} whereas the value of the ratio at the dip is sensitive to $\sin^2 2\theta_{23}$.

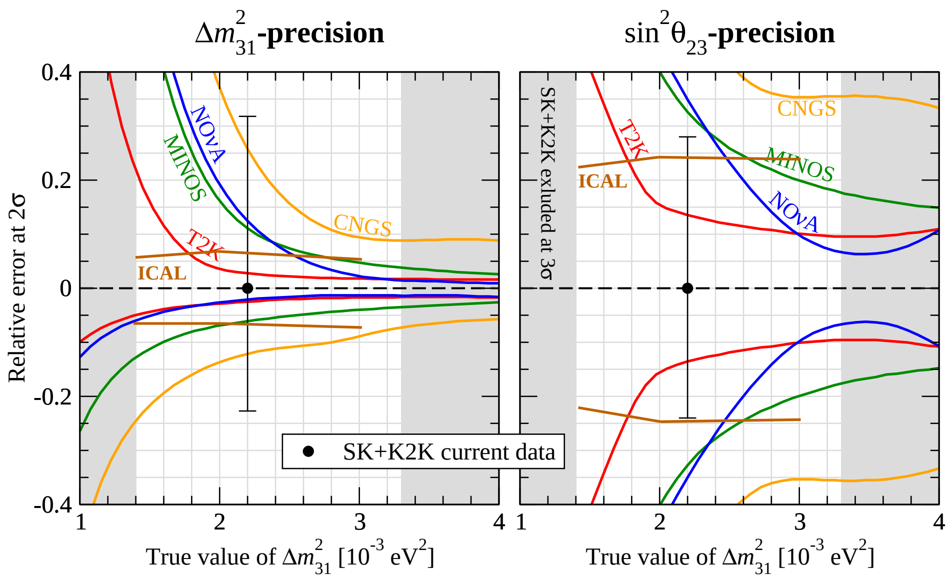

Figure 3. The relative error on $|\Delta_{31}|$ and $\sin^2\theta_{23}$ as a function of the input value of $|\Delta_{31}|$ at 2σ level. The figure is adopted from P Huber *et al*, hep-ph/0412133, with the curve for ICAL overlaid.

$$\sin 2\theta_{13}^{\rm m} = \sin 2\theta_{13}\frac{\Delta_{31}}{\Delta_{31}^{\rm m}}, \tag{6}$$

where A is the Wolfenstein term. In terms of these, the matter modified muon neutrino survival probability is given by [2,4]

Table 1. Precision for $|\Delta_{31}|$ and $\sin^2\theta_{23}$ if the true values are $|\Delta_{31}| = 0.002$ eV^2 and $\theta_{23} = \pi/4$. The table is adopted from P Huber *et al*, hep-ph/0412133, with the information of ICAL added.

Experiment	Δ_{31} (%)	$\sin^2\theta_{23}$ (%)
Current data	88	79
MINOS + CNGS	26	78
T2k (SK, 0.75 MW, 5 yrs)	12	46
NOνA (30 kton, 0.6 MW, 5 yrs)	25	86
ICAL (50 kton, atm. nu, 5 yrs)	20	60

$$P_{\mu\mu}(\mathrm{mat}) = 1 - \cos^2\theta_{13}^{\mathrm{m}} \sin^2 2\theta_{23} \sin^2\left[1.27(\Delta_{31} + A + \Delta_{31}^{\mathrm{m}})L/2E\right] \\ - \sin^2\theta_{13}^{\mathrm{m}} \sin^2 2\theta_{23} \sin^2\left[1.27(\Delta_{31} + A - \Delta_{31}^{\mathrm{m}})L/2E\right] \\ - \sin^4\theta_{23} \sin^2 2\theta_{13}^{\mathrm{m}} \sin^2\left(1.27\Delta_{31}^{\mathrm{m}} L/E\right). \tag{7}$$

When the energy is such that the resonance condition

$$\Delta_{31}\cos\theta_{13} = A = 2\sqrt{2}G_{\mathrm{F}}N_e E \tag{8}$$

is satisfied, the matter modified mixing angle θ_{13}^{m} becomes equal to $\pi/4$ [8] and ν_μ survival probability can be significantly modified. However, at resonance Δ_{31}^{m} takes its minimum value of $\Delta_{31}\sin\theta_{13}$. Thus the large change in $P_{\mu\mu}$ at resonance energies, occurs only when the path length satisfies the condition [3,4]

$$[\rho \mathrm{L}]_{\mu\mu} \simeq p\,\pi\ \times 10^4\,(\cos 2\theta_{13})\ \mathrm{km\ gm/cc}. \tag{9}$$

Thus we can expect matter effects to induce a large change in $P_{\mu\mu}$ for select energies and path lengths. In figure 4 we show the change in $P_{\mu\mu}$ as a function of energy for a path length of 7000 km. For $\Delta_{31} = 2\times 10^{-3}$ eV^2, the resonance in the earth's mantle occurs at an energy of about 5 GeV. From figure 4, we see that, at this resonance energy, $P_{\mu\mu}$ drops by as much as 40%.

In the case of anti-neutrinos the matter term A is replaced by $-A$ because the interaction potential has opposite sign. Thus, if Δ_{31} is positive, then θ_{13} for neutrinos undergoes resonance, whereas that of the anti-neutrinos is essentially unaffected. This is illustrated in figure 4. The situation is reversed when Δ_{31} is negative. Thus we expect matter effects to cause a large change in the muon neutrino event rates if Δ_{31} is positive and leave the muon anti-neutrino event rates to be unaffected. The situation is reversed if Δ_{31} is negative. For $\sin^2 2\theta_{13} = 0.1$, the number of muon neutrino event rates, in the energy range 5–10 GeV and path length range 6000–9000 km, changes from **261** (vacuum) to **204** (matter), the number of anti-muon event rate remains unchanged at **105** for both vacuum and matter [3,4].

The difference in the up/down ratio for neutrinos and anti-neutrinos,

$$\mathcal{A} = \frac{U}{D} - \frac{\bar{U}}{\bar{D}}$$

as a function of (L/E) is very sensitive to the sign of Δ_{31} [9,10]. This asymmetry is an oscillating function of (L/E) as can be seen in the left panels of figure 5.

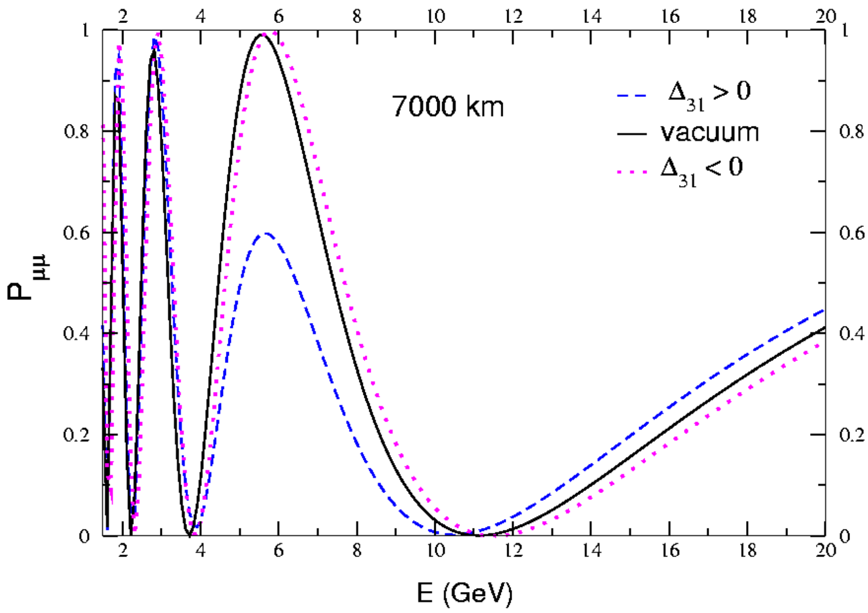

Figure 4. Variation of $P_{\mu\mu}$ vs. E for a path length of 7000 km, for vacuum, for matter effects with positive Δ_{31} and for matter effects with negative Δ_{31}. The input parameters used are $|\Delta_{31}| = 2 \times 10^{-3}$ eV^2, $\theta_{23} = \pi/4$ and $\sin^2 2\theta_{13} = 0.1$.

The amplitude of oscillation is a function of θ_{13} (shown in figure 5 for $\theta_{13} = 5°$ and $11°$), because this asymmetry arises due to matter effects and these, at atmospheric neutrino scale, are dependent on θ_{13}. Inclusion of the detector resolution functions dilutes this asymmetry. The right panels of figure 5 are generated with 15% resolution in energy and 15% resolution in path length. We see that only the envelope with $(L/E) = 1000$–1500 range has appreciable asymmetry. We define

$$\mathcal{A}_n^H = \sum_{i=1}^{n} (-1)^i \mathcal{A}^{H,i}, \tag{10}$$

where i stands for each envelope of oscillation and H is the hierarchy which is either normal N or inverted I. We take the alternating sum defined in eq. (10) so that the total asymmetry summed over all the envelopes does not get washed out. We also note that beyond the third envelope, the asymmetry is very small, so we terminate the sum at $n = 3$. We now define a discriminating quantity

$$\delta\mathcal{A} = \mathcal{A}_3^{\rm N} - \mathcal{A}_3^{\rm I}. \tag{11}$$

Table 2 gives the values of $\delta\mathcal{A}$ for two values of θ_{13}, two different exposure times and two different resolution factors. Our ability to distinguish between the two hierarchies improves with increasing θ_{13} and exposure time and with improving resolutions. In particular, we note from table 2, that increasing the resolution in L and E from 15% to 10% at 480 Ktyr exposure has the same effect as increasing the exposure from 480 Ktyr to 1120 Ktyr for a resolution of 15%.

Table 2. Significance of the asymmetry for different exposures in kton-yr as function of θ_{13} for E and L resolutions of 15% (upper) and 10% (lower).

Exposure (kton-yr)	θ_{13}	$\Delta\mathcal{A}$	Significance
480	$7°$	0.167 ± 0.230	$0.7\sigma, 51.6\%$
1120	$7°$	0.167 ± 0.151	$1.1\sigma, 72.9\%$
480	$11°$	0.415 ± 0.230	$1.8\sigma, 92.8\%$
1120	$11°$	0.415 ± 0.150	$2.8\sigma, 99.6\%$
480	$7°$	0.232 ± 0.220	$1.1\sigma, 72.9\%$
1120	$7°$	0.232 ± 0.144	$1.1\sigma, 89.0\%$
480	$11°$	0.565 ± 0.220	$2.6\sigma, 99.1\%$
1120	$11°$	0.565 ± 0.144	$3.9\sigma, 99.99\%$

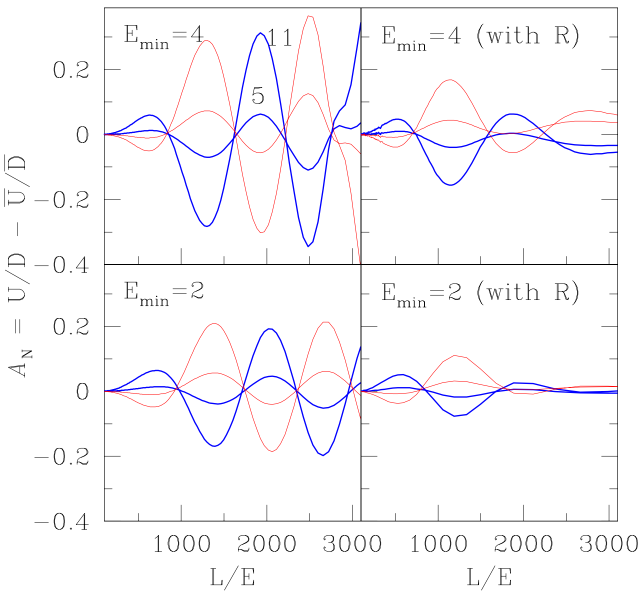

Figure 5. A comparison of the difference asymmetry without and with the resolution functions for the input values of $|\Delta_{31}| = 0.002$ eV^2 and $\theta_{13} = 5°, 11°$. The thick (blue) curves correspond to normal and the thin (red) curves correspond to the inverted hierarchy. Two cases, with $E > 2$ GeV and $E > 4$ GeV are shown. The higher energy emphasizes the asymmetry but the event rates are approximately halved.

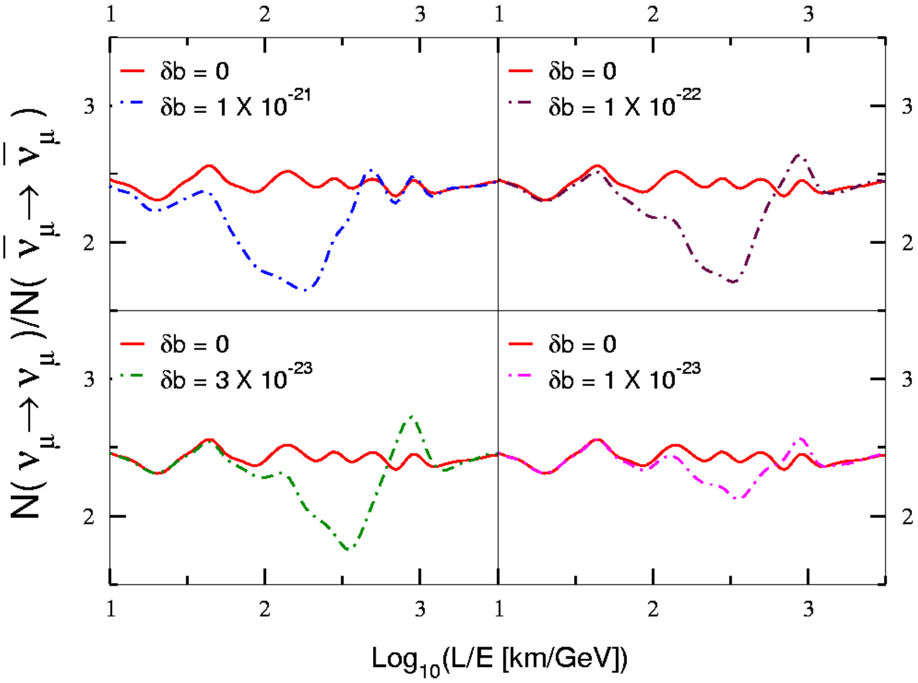

Figure 6. The ratio of total (up+down) muon to anti-muon events plotted against $\log_{10}(L/E)$ for different values of CPT-violating parameter δb (in GeV).

2.3 *Resolution of the octant ambiguity of* θ_{23}

The dominant matter-dependent term in $P_{\mu\mu}$ also goes as $\sin^4\theta_{23}$. By appropriate cuts on energy and path length this term can be isolated and one can determine if θ_{23} is greater or less than $\pi/4$. The procedure for doing this is described in [11,12]. At present $|D = 0.5 - \sin^2\theta_{23}|$ is constrained to be about 0.16 at 3σ. If $\sin^2\theta_{13} = 0.02$, then 1000 kton-yr exposure can measure a non-zero value for $|D| \sim 0.09$ at 3σ. The same exposure can determine sign of D (and the octant of θ_{23}) if $|D| \geq 0.12$.

2.4 *Search for CPT-violation*

Since charge determination is possible at ICAL, one can measure both $P_{\mu\mu}$ and $P_{\bar{\mu}\bar{\mu}}$ independently. This leads to the possibility of searching for signals of CPT-violation. With an exposure of about 400 kton-yr, CPT-violation parameter $\delta b \sim 10^{-23}$ GeV can be probed [13] as shown in figure 6.

3. Conclusions

A large magnetized iron calorimeter can achieve a number of important goals of neutrino physics. It can determine the atmospheric neutrino oscillation parameters to a precision comparable to that of T2K or Noνa experiments, with about 5 years of data-taking. In addition, with about 1000 Ktyr of exposure, it can determine the neutrino-mass hierarchy and the octant of θ_{23}, if $\sin^2 2\theta_{13} \geq 0.07$. In addition, because of the ability to determine the charge of the muon, such a detector can also search for signals of CPT-violation.

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