Prospects of using opaque detectors in accelerator neutrino experiments

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Opaque detectors are a recently proposed novel detector concept where an opaque scintillator aligned with wavelength-shifting fibers is used to enable the discrimination of electron neutrinos and antineutrinos with a rather low energy threshold. In this work, we explore the physics reach of using such a neutrino detection technique in accelerator-based neutrino oscillation experiments, where neutrino energies fall into the quasi-elastic regime. Simulating neutrino beams produced via the pion and muon decay, we investigate the prospects of using an opaque detector to search for CP violation in neutrino oscillations at medium and long baseline lengths. We find that a 75% fraction of $\delta_{CP}$ values could be reached for CP violation discovery by 3 $\sigma$ confidence level or better when opaque detectors of 120 kton and 135 kton fiducial masses are used together with neutrino beams from J-PARC and MOMENT, respectively. We also show that opaque detectors could be used to study the light sterile neutrino and reduce its impact on the CP violation sensitivity. We report 0.1 and 0.05 upper limits on $\sin^2 2\theta_{14}$ at 90% confidence level for J-PARC and MOMENT when a 1 kton near detector is used.

Keywords: Scintillator detector, accelerator neutrinos, neutrino oscillations

I. INTRODUCTION

The success of neutrino physics is largely owed to the rapid development of neutrino detection techniques in the recent decades. Dating back to the first observation of neutrinos by Reines and Cowan in 1956 [1], the technologies employed in the neutrino detectors have come a very long way. One of the most established detector technologies to date is the liquid scintillator technique, where neutrino interactions are reconstructed by observing the scintillation light coming from the secondary particles scattering in the detector. Liquid scintillators have facilitated very successful measurements on the neutrino oscillation parameters in reactor neutrino experiments like Daya Bay [2], Double Chooz [3] and RENO [4], solar and geoneutrino detectors Borexino [5] and KamLAND [6], and most recently in the accelerator neutrino experiment NO$\nu$A [7]. Over the next decade liquid scintillators will be exploited on the large-scale in experiments like Jingping [8], JUNO [9] and SNO+ [10]. Other notable detector techniques for accelerator neutrinos are Liquid Argon Time Projection Chambers (LArTPC) and Water Cherenkov detectors (WC), which have been used in e.g. ICARUS [11] and Super-Kamiokande [12].

Most recently, a novel detector concept based on the LiquidO technique has been proposed [13]. In this work, we refer to this technology as the opaque detector. Founded on the same detection principle that was used in the famous experiment by Cowan and Reines, opaque detectors are liquid scintillators with short scattering length and intermediate absorption length. In contrast to the conventional model of liquid scintillators, the working principle of the opaque detectors is based on the observation of stochastic light confinement, where the optical photons emitted upon the scintillation revolve around the energy deposition, creating an image of a light ball. The light is collected with an array of wavelength-shifting optical fibers, which run through the detector vessel. The diverging topologies of the light balls in different event categories allow a clear distinction of electron, positron and gamma events at relatively low energies. The LiquidO technique retains the many advantages of an organic scintillator, while it also introduces the imaging capabilities similar to time projection chambers. Most importantly, the relaxation of the transparency requirements grants opaque detectors an ability to load metal-dopants to unprecedented concentrations, while being a scalable technology.

Opaque detectors offer a wide array of opportunities in neutrino physics thanks to their relaxed constraints on transparency. Applications to opaque detectors have been discussed before in neutrinoless $\beta\beta$-decay measurements [13], CP violation tests in pion decay-at-rest experiments [14] and unitarity tests of the Pontecorvo-Maki-Nagakawa-Sakata matrix in reactor experiments [15]. On the R&D side, the first proof-of-principle experiment on the LiquidO concept has been conducted, and the phenomenon of stochastic light scattering was successfully observed [16, 17].

In the present work, we investigate the prospects of using an opaque detector in accelerator-based neutrino oscillation experiments. Using the General Long-baseline Experiment Simulator (GLoBES) [18, 19], we simulate the performance of a neutrino beam created through pion and muon decay processes while using a large, $\mathcal{O}$(100 kton) opaque detector as a target. As an example of pion and muon decay based neutrino beams, we simulate the future J-PARC [20, 21] and MOMENT [22] facilities assuming 1.3 MW and 15 MW proton beam powers, respectively. Regarding the neutrino detector, we characterize the detector response by adopting the liquid scintillator model used in the simulation of the NO$\nu$A experiment [1], with modifications based on the special characteristics that have been reported for LiquidO in Ref. [16]. As the capabilities of LiquidO are still under active investiga-

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1 The simulation files used for NO$\nu$A are provided on the GLoBES website [25], whereas the modeling of the detector response is based on Refs. [24, 25].
tion, we take several key parameters in the detector response as unknowns and simulate the results for various scenarios. We present the expected sensitivities in the standard three-neutrino oscillation framework, reviewing the applications of the opaque detector technique in CP violation searches at future accelerator neutrino experiments [26, 27]. We also discuss how much the opaque detector could improve the sensitivity to the active-sterile mixing parameters $\theta_{14}, \theta_{24}$ and $\Delta m^2_{31}$ in the $\Delta m^2_{31} \approx 1 \text{ eV}^2$ regime, which is well-motivated by the recently reaffirmed LSND–MiniBooNE anomaly [28–30] (see also Refs. [31–33] for the related discussion). Finally, we investigate how using opaque detectors can reduce the impact of the $3+1$ mixing on the CP violation sensitivity, which is known to decrease upon the introduction of the new physics [34–46].

This article is organized as follows: In Section II, we briefly describe the key characteristics of an opaque detector and compare its properties with the other notable neutrino detector techniques. We give a brief overview of the neutrino oscillation probabilities in Section III and detail the implementation of the opaque detector and the neutrino sources in GLoBES in Section IV. We present a discussion on the applications of the opaque detector technique in the CP violation and light sterile neutrino searches in Section V. We summarize our findings in Section VI.

II. A COMPARISON OF OPAQUE DETECTOR AND OTHER TECHNIQUES

Liquid scintillators have been widely used as low-energy neutrino detectors, and their use in experiments continues to this day. The advantages of using a transparent liquid scintillator include high purity, low energy threshold and detector homogeneity as well as flexible handling and scalability to large volumes. Though effective, transparent liquid scintillators have several requirements that set limitations to their structure and size.

The main challenge involved in using a transparent liquid scintillator is the inability to identify electrons from positrons and gammas at low energies. Adequate charge-identification can be achieved by applying a magnetic field or loading the scintillator with a metal. The main restrictions in loading a scintillator with heavy elements are given by the strict requirements on the solubility, transparency as well as the chemical stability of the scintillator (see Ref. [47] for a review). In practice, the solubility requirement sets an upper limit for the amount of metal that can be loaded in the scintillator, which can vary from 0.1% through 10% of the detector mass and depends on the specific application. The difficulties of loading the scintillator beyond those levels arise from dissolving highly polar material into non-polar liquid, while maintaining optical and chemical stability over the lifetime of the detector.

Abandoning the requirements for optical transparency has immediate advantages regarding the building costs and physics performance of the detector:

1. An opaque detector is effectively self-segmented. This could increase the light level, thus helping with the calorimetric precision.

2. Opaque detectors can have excellent particle identification for electrons and positrons in MeV energies and above [48].

3. Opaque detectors can be expected to scale to larger fiducial masses, thanks to the absence of segmentation.

4. Opaque detectors can be loaded to high doses of metals. This opens an opportunity to optimize the scintillator composition for various applications.

5. The opaque detector can be magnetized, which could further improve the particle identification.

6. The opaque detector does not need cryogenics.

In summary, neutrino detectors filled with opaque scintillators can provide the imaging capabilities of a time projection chamber and the low energy threshold of a transparent liquid scintillator. With the additional option for magnetization, opaque detectors make an attractive candidate for accelerator-based neutrino experiments.

It should be noted that when the neutrino energies are above the critical value $E_\nu \sim 100 \text{ MeV}$, some of the more energetic electron and positron events lead to electromagnetic showering [14], reducing the $e^-/e^+$ particle identification performance both in efficiency and rejection. This loss could be mitigated with a magnetic field.

Opaque detectors may also provide a good alternative to large Water Cherenkov detectors. A traditional Water Cherenkov detector of $\mathcal{O}(100 \text{ kton})$ mass scale requires a huge tank and high photo-coverage in light collection. Water Cherenkov detectors receive directional information from the Cherenkov light with a good efficiency and relatively low light yield. This information is used to reconstruct tracks created by muon neutrinos and shower Cherenkov rings by electron neutrinos. Water Cherenkov detectors are not sensitive to the particle charge, but in quasi-elastic processes charge identification can be achieved by doping the water with gadolinium. On the other hand, a typical scintillator detector offers a good light yield, which is transmitted by energy losses as neutrinos interact with detector medium. This is the main advantage of liquid scintillators. Further development on combining the Cherenkov and scintillation signals in a single detector have been made in e.g. the proposed THEIA [49] experiment. As the detector size goes up to 100 kton and beyond, the attenuation of light sets high requirements on the transparency of the detector medium. In the LiquidO detector, this problem is partly mitigated as the light is collected via wavelength-shifting fibers.

III. NEUTRINO OSCILLATIONS

In this section, we review the neutrino oscillation probabilities relevant to the accelerator neutrino experiments considered in this work. We discuss the potential applications in
the CP violation searches in subsection IIIA and in constraining active-sterile neutrino parameters in the $\Delta m_{41}^2 \approx 1 \text{ eV}^2$ regime in subsection IIIB.

In the standard three-neutrino paradigm, neutrino oscillations are governed by the so-called Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [50–54], which describes the mixing with three rotation angles $\theta_{12}$, $\theta_{13}$, $\theta_{23}$ and the Dirac CP phase $\delta_{\text{CP}}$:

$$U_{\text{PMNS}} = R_{3 \times 3}(\theta_{23}, 0) \times R_{3 \times 3}(\theta_{13}, \delta_{\text{CP}}) \times R_{3 \times 3}(\theta_{12}, 0)$$

(1)

where $R_{3 \times 3}(\theta_{ij}, \delta_{ij})$ is a $3 \times 3$ rotation matrix with the rotation angle $\theta_{ij}$ and the CP phase $\delta_{ij}$ $(i, j = 1, 2, 3)$, whilst $s_{ij}$ and $c_{ij}$ denote the functions $\sin \theta_{ij}$ and $\cos \theta_{ij}$, respectively.

The probability for the oscillation $\nu_\alpha \rightarrow \nu_\beta$ $(\alpha, \beta = e, \mu, \tau)$ to take place in vacuum is given by

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha \beta} - 4 \sum_{k>j} \text{Re}[U_{\alpha k}^* U_{\beta j} U_{\beta j}^* U_{\alpha k}^*] \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E}\right) + 2 \sum_{k>j} \text{Im}[U_{\alpha k}^* U_{\beta k} U_{\beta j}^* U_{\alpha j}^*] \sin \left(\frac{\Delta m_{ij}^2 L}{4E}\right),$$

(2)

where $U_{ij}$ are the matrix elements of Eq. (1), $\Delta m_{ij}^2 \equiv m_{i}^2 - m_{j}^2$ are the so-called mass-squared differences, whereas $E$ is the energy of the neutrino and $L$ is the distance it has traveled.

A. Searching CP violation with $\nu_\mu$ source

One of the main goals for the next-generation of neutrino experiments is to search for the CP violation arising from $\delta_{\text{CP}}$ and to determine its size. In accelerator-based neutrino experiments, CP violation can be tested by comparing probabilities for $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ (both pion and muon decay based beams) and for $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\tau$ (only muon decay based beams).

Taking $\xi \equiv \Delta m_{31}^2$ to be small and $s_{13}^2 = \sin^2 \theta_{13} \sim \mathcal{O}(\xi)$, this probability can be expressed as

$$P(\nu_\mu \rightarrow \nu_\mu) = P_1 + P_2 + \mathcal{O}(\xi^2),$$

(3)

where the first two terms are given by

$$P_1 = \frac{4}{(1 - r_A)^2} s_{23}^2 s_{13}^2 \sin^2 \left(\frac{(1 - r_A)\Delta_{31}}{2}\right),$$

(4)

$$P_2 = 8 J_r \frac{\xi}{r_A (1 - r_A)} \cos (\delta_{\text{CP}} + \frac{\Delta_{31}}{2}) \sin \left(\frac{\xi + \Delta_{31}}{2}\right) \times \sin \left(\frac{1 - r_A) \Delta_{31}}{2}\right),$$

(5)

where $J_r = c_{12} s_{12} c_{23} s_{23} s_{13}$, $r_A = a_\nu / \Delta m_{31}^2$ and $\Delta_{31} \equiv \Delta m_{31}^2 L/2E$. Here $a_\nu \equiv 2\sqrt{2} E G_F N_c$, where $G_F$ is the Fermi coupling constant and $N_c$ is the electron number density in the Earth.

As one can see from Eqs. (3–5), the Dirac CP phase $\delta_{\text{CP}}$ appears in the order of $\mathcal{O}(\xi^{1/2})$ inside a cosine function together with $\Delta_{31}/2$. This function reaches its first maximum at $\Delta_{31}/2 = \pi/2$ and second maximum at $3\pi/2$, respectively. Experiments covering either or both of these oscillation maxima can therefore be expected to be sensitive to $\delta_{\text{CP}}$.

B. Probability with the active-sterile mixing

Another well-motivated question to be investigated at the future experiments is LSND-MiniBooNE anomaly and the effect of a light sterile neutrino of $\mathcal{O}(1 \text{ eV})$ mass in the neutrino oscillation probabilities. When a light sterile neutrino is considered, the PMNS matrix becomes a submatrix of a $4 \times 4$ mixing matrix, which is given by

$$U_{3+1} = R_{4 \times 4}(\theta_{14}, \delta_{14}) R_{4 \times 4}(\theta_{24}, \delta_{24}) R_{4 \times 4}(\theta_{13}, \delta_{\text{CP}}) R_{4 \times 4}(\theta_{12}, 0),$$

(6)

with three new mixing angles $\theta_{14}$, $\theta_{24}$, and $\theta_{23}$, and two new phases $\delta_{14}$ and $\delta_{34}$. To calculate oscillation probabilities, we also need to include a new mass-squared splitting $\Delta m_{41}^2 \sim 1 \text{ eV}^2$.

In the following, we apply the so-called short-baseline approximation $\Delta_{41} \equiv \Delta m_{41}^2 L/2E \gg \Delta_{31}$ on Eq. (2). For measuring active-sterile mixing parameters in a near detector, the probabilities are given by [55]

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4 \cos^2 \theta_{14} \sin^2 \theta_{24} \times (1 - \cos^2 \theta_{14} \sin^2 \theta_{24}) \sin^2 (\Delta m_{31}^2 L/4E)$$

(7)

and

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{14} \cos^2 \theta_{24} \times \sin^2 \theta_{14} \sin^2 (\Delta m_{41}^2 L/4E).$$

(8)

Near detectors can be optimized for the measurement of the active-sterile mixing parameters. In a beam experiment with $E \sim \mathcal{O}(100 \text{ MeV})$, baseline lengths of $L \sim \mathcal{O}(100 \text{ m})$ are the most sensitive to the $\Delta m_{41}^2 \sim 1 \text{ eV}^2$ scale.

In the far detectors, the oscillations are dominated by $\Delta m_{31}^2$ and $\Delta m_{41}^2 \sim \mathcal{O}(1 \text{ eV}^2)$ are averaged out. After taking $s_{14}^2 \sim s_{24}^2 \sim s_{34}^2 \sim s_{13}^2 \sim \mathcal{O}(\xi^2)$ to be small, the oscillation
probabilities for \( \nu_\mu \rightarrow \nu_\mu \) and \( \nu_\mu \rightarrow \nu_e \) can be approximated as [55]

\[
P(\nu_\mu \rightarrow \nu_\mu) \approx \sin^2(\Delta_{31}) (1 - 2s_{24}^2) + 8s_{24}^2 \sin^2(\Delta_{31})
+ 2s_{34}^2 \cos(\theta_{34}) \sin(2\Delta_{31})
- s_{13}^2 \sin(\Delta_{31}) \times (\Delta_{31} - \theta_{24}) (\Delta_{31} - \theta_{24})
+ \frac{1}{2} s_{24}^2 (3 + \cos(2\Delta_{31}))^2
\]

(9)

and

\[
P(\nu_\mu \rightarrow \nu_e) \approx 1 - \left\{ \cos^2(\Delta_{31}) (1 - 2s_{24}^2) + 2s_{13}^2 \Delta_{31} \cos(\Delta_{31}) \times \sin(\Delta_{31} - \theta_{24}) \sin(\Delta_{31}) \times (\Delta_{31} - \theta_{24}) + s_{24}^2 (1 - s_{24}^2)
- s_{13}^2 \Delta_{31} \sin(\Delta_{31} - \theta_{24}) (\sin(\Delta_{31}) - \sin(\Delta_{31} - \theta_{24}))
+ \frac{1}{2} s_{24}^2 (3 + \cos(2\Delta_{31})) \right\}
\]

(10)

where \( s_{24}^2 = \sin^2 \theta_{24} - 1/\sqrt{2}, \Delta_{e(n)} = a_{e(n)} L/4E \) and \( a_{e(n)} = 2 \sqrt{2} E G F N_n \), whereby \( N_n \) is the neutron number density in the Earth.

As was pointed out in Ref. [55], a resonance takes place in Eqs. (9) and (10) when \( \Delta m^2_{31} \sim \Delta m^2_{24} \). In principle, far detectors with \( L \sim O(100 \text{ km}) \) suitable for measuring the sterile mixing angles. However, it is unavoidable that the new angles \( \theta_{24} \) and \( \theta_{34} \) will hinder their measurement [34]. The presence of the sterile phases could also reduce the sensitivity to discover CP violation [35–37].

### IV. IMPLEMENTATION IN GLOBES

In this work, we study the physics prospects of sending a neutrino/antineutrino beam from an accelerator facility to a detector employing the LiquidO technique. We focus on the energy range relevant to medium and long-baseline experiments, \( E_{\nu, \bar{\nu}} \sim O(100 \text{ MeV}) \), where neutrinos and antineutrinos interact with the scintillator predominantly via quasi-elastic scattering. We obtain our results using the General Long-baseline Experiment Simulator (GLoBES) [18, 19].

We consider two different neutrino beams as the source, one based on the pion decay and the other on the muon decay. For the pion-decay-based neutrino beam, we simulate the JHF beam from the J-PARC facility [20], which will operate at 1.3 MW proton beam power after its next upgrade [21]. The JHF beam is currently proposed to be used in the Tokai-to-HyperKamiokande (T2HK) experiment, which includes a Water Cherenkov detector. As for the muon decay based neutrino beam, we consider the MOMENT facility [22] with its 15 MW proton beam power. The properties of the neutrino beams are summarized in Table 1. We assume these beam configurations in our simulations throughout this work, unless otherwise stated.

Regarding the implementation of the far detector, we assume a large opaque detector with the fiducial masses of 50 kton...500 kton. In the case of the J-PARC beam facility, we assume the detector to be placed at 295 km with 2.5° off-axis angle, which corresponds to the configuration where the JHF beam reaches the first oscillation maximum. In the case of MOMENT, the opaque detector is taken to be 150 km from the beam facility, facing the neutrino/antineutrino beam on-axis. We assume both configurations to operate 10 years in total, which is divided in 1:3 and 1:1 ratios in order to provide similar rates for neutrino and antineutrino events from J-PARC and MOMENT beams, respectively.

As there is currently very little known about the detector response of an opaque detector, we simulate the opaque detector following the example set by the NO\(\nu\)A far detector, which is based on a 14 kton segmented liquid scintillator. To account for the improvements that can be introduced using an opaque detector, we assume a 80% detection efficiency for muon-like events and 50% efficiency for electron-like events\(^2\). Further details on the detector simulation are shown in Table 2.

Thanks to their improved imaging capabilities, opaque detectors can help to constrain the number of background events in both pion- and muon-decay-based neutrino beams. In the JHF beam generated in J-PARC, the background to the \( \nu_\mu \) and \( \bar{\nu}_\mu \) beams consists of the intrinsic beam background, flavour mis-identification and neutral current events, of which the beam background is irreducible. The beam-related backgrounds in J-PARC are modeled after Refs. [24, 25]. MOMENT on the other hand produces neutrinos and antineutrinos in \( \nu_\tau, \bar{\nu}_\tau \) and \( \nu_\mu, \bar{\nu}_\mu \) pairs, which have negligible beam-related backgrounds. Instead, it accumulates background

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\(^2\) It has been suggested that in the LiquidO detector the efficiencies can be as high as 100% for both e and \( \mu \)-like events [56]. In our simulations, we maintain the conservative choices of 50% and 80%, respectively.
Table 3. The best-fit values and 1 σ confidence level uncertainties for the neutrino oscillation parameters reported by the NuFit group [60]. The values are shown for both normal ordering (NO) and inverted ordering (IO), where $\Delta m^2_{32}$ corresponds to $\Delta m^2_{31}$ (NO) and $\Delta m^2_{32}$ (IO), respectively.

| Parameter | Central value ± 1 σ (NO) | Central value ± 1 σ (IO) |
|-----------|--------------------------|--------------------------|
| $\theta_{12}$ ($^\circ$) | 33.82 ± 0.78 | 33.82 ± 0.78 |
| $\theta_{13}$ ($^\circ$) | 8.60 ± 0.13 | 8.64 ± 0.13 |
| $\theta_{23}$ ($^\circ$) | 48.6 ± 1.4 | 48.8 ± 1.2 |
| $\delta_{\text{CP}}$ ($^\circ$) | 221 ± 39 | 282 ± 25 |
| $\Delta m^2_{31}$ (10$^{-5}$ eV$^2$) | 7.39 ± 0.21 | 7.39 ± 0.21 |
| $\Delta m^2_{32}$ (10$^{-3}$ eV$^2$) | 2.528 ± 0.031 | -2.510 ± 0.031 |

V. PHYSICS PROSPECTS

In this section, we discuss the prospects of using a large-scale opaque detector in establishing CP violation in accelerator neutrino experiments, and in constraining the active-sterile mixing parameters in the so-called 3+1 neutrino model by using a near detector containing opaque scintillator. We present the sensitivities for the CP violation discovery using beams from the MEnTe beam factory and the J-PARC facilities, and the 90% confidence level (C.L.) exclusion limits to $\sin^2 2\theta_{14}$, $\sin^2 2\theta_{34}$ and $\Delta m^2_{31}$, respectively.

A. Sensitivity to CPV discovery

One of the most important missions of the next-generation accelerator neutrino experiments is to establish CP violation in the leptonic sector and to measure the value of the Dirac CP phase $\delta_{\text{CP}}$. The typical challenge in measuring $\delta_{\text{CP}}$ arises from the need to collect sufficient number of events from both neutrino and antineutrino channels. In a pion-decay-based neutrino beam experiment, the sensitivity to CP violation discovery is mainly acquired from $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, which places importance on the reconstruction of electron...
Fig. 1. CP discovery potential in an accelerator neutrino experiment using muon and pion decay beams. Left: the detector masses and efficiencies for which the CP-conserving values $\delta_{\text{CP}} = 0^\circ$, $180^\circ$ can be ruled out at $3 \sigma$ confidence level (C.L.) or better for 70% and 75% of the $\delta_{\text{CP}}$ values, respectively. Right: the masses and efficiencies required to reach $4 \sigma$ and $5 \sigma$ C.L. statistical significance for CP violation discovery when the true value is $\delta_{\text{CP}} = 270^\circ$. The approximate position of T2HK in this map is indicated with a black dot.

Fig. 2. The same as in Fig. 1, but the CP fractions and statistical significances are presented as a function of detector mass and signal-to-background ratio in the configuration. The number of signal events in $\nu_\mu \to \nu_e$ and $\nu_e \to \nu_\mu$ are fixed at 397 and 172 per 100 kton in pion and muon decay beams, respectively. The results are shown for signal-to-background ratios 1–30. The approximate position of T2HK in this map is indicated with a black dot.

and positron events and on the background suppression$^3$. In this subsection, we show how using opaque detectors could improve the sensitivity to CP violation through the particle identification in electron-like events.

We have calculated the CPV discovery potential simulating opaque detector of various sizes with muon and pion decay based beam setups. The $\chi^2$ fitting has been done by marginalizing over all parameters except $\delta_{\text{CP}}$. The results are presented in Figures 1 and 2.

In Figure 1, the sensitivity to CP violation has been presented in two different aspects. On the one hand, we studied the fraction of the theoretically allowed $\delta_{\text{CP}}$ values for which CP violation can be established by at least $3 \sigma$ C.L. The results are obtained for 70% and 75% coverages and they are presented in the left panel of the figure. We also calculated the statistical significance to rule out the CP-conserving values $\delta_{\text{CP}} = 0^\circ$ and $360^\circ$. The results are plotted in the right panel of the figure for $4 \sigma$ and $5 \sigma$ C.L., while assuming the true value of $\delta_{\text{CP}}$ to be $270^\circ$. In both panels, the results are shown as a function of the fiducial mass as well as of the efficiency to reconstruct electron-like events in the opaque detector.

We also considered the effect of background suppression by assuming different values for the signal-to-background ratio in the simulated experiments. The expected CP fractions and statistical significances are shown for 70% and 75% coverages as well as for $4 \sigma$ and $5 \sigma$ C.L. statistical significances as a function of the detector mass and the value of the signal-to-background ratio. The results are shown in Figure 2.

We make the following observations from simulation results: The detection efficiency for $e$-like events appears to have only a mild correlation with the CPV discovery potential at 70% and 75% fractions, as is apparent from Figure 1. With the conservative assumption of 50% detection efficiency for $e$-like events, improving CPV coverage from 70% to 75% at 3 $\sigma$ C.L. requires only a slightly larger increment in the fiducial mass than with the optimistic assumption of 70% efficiency. Similar dependence is found for the CPV discovery potential at $\delta_{\text{CP}} = 270^\circ$. We note that the difference becomes larger for higher sensitivities. Figure 2 on the other hand indicates that the size of the background only becomes relevant in the CPV coverage and discovery potential if the detector mass is sufficiently large. For a 100 kton detector, for example, no improvement in signal-to-background ratio can increase the sensitivity to CP violation due to low statistics, whereas a 300 kton detector is already very sensitive to changes in background suppression.

We also investigated the effect of the energy resolution on the results shown in Figures 1 and 2, but no notable impact was found.

To provide a meaningful comparison, we calculated the expected sensitivities for the T2HK experiment assuming a single 187 kton WC detector. We use the simulation files provided on the GLoBES website [23] (see also Refs. [20, 61, 62]). The beam power, detector mass and running times are updated to match the current state of the T2HK proposal, featuring 1.3 MW beam power, 187 kton WC detector and 2.5 + 7.5 years of running time. When the beam from J-PARC is simulated together with a 187 kton WC detector, as in the case in the T2HK proposal, our results show 3 $\sigma$ C.L. or higher significance for CPV discovery at 75.6% of $\delta_{\text{CP}}$ values as well as 4.7 $\sigma$ C.L. for CPV discovery at $\delta_{\text{CP}} = 270^\circ$. If the WC detector were to be replaced with an opaque detector equivalent to 187 kton fiducial mass, the corresponding CPV coverage and significance would be 74.3% and 4.9 $\sigma$ C.L. with 50% efficiency for $e$-like events, respectively. Increasing the efficiency to 70% would raise the sensitivities to 77.1% and 5.3 $\sigma$ C.L. Replacing the water with an equivalent mass of opaque scintillator could therefore improve the prospects for CP violation discovery in T2HK, though the gain would be modest.

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$^3$ Muon decay based beams experiments do also have access to $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_e \to \bar{\nu}_e$ channels, but the electron appearance channels $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ still remain a notable source to the CP violation discovery.
One would therefore have to consider larger fiducial masses for the opaque detector to significantly improve the sensitivity to CP violation.

We conclude this subsection with a brief remark on the probable size of an opaque detector. As one can see from Figures 1 and 2, the suitable detector size to study CP violation depends on both the detection efficiency for electron-like events and the estimated signal-to-background ratio. In order to reach 3 $\sigma$ C.L. sensitivity to at least 75% of $\delta_{CP}$ values, the fiducial mass of the opaque detector needs to be about 120 kton and 135 kton for pion and muon beams, when the optimistic value of 70% efficiency is assumed for electron-like events. For a more conservative assumption of 50% efficiency, the required detector masses would be about 170 kton and 200 kton, respectively. The desirable detector mass is therefore about 120–200 kton, which may be feasible for an opaque detector.

### B. Sensitivity to active-sterile neutrino mixing

In the so-called short-baseline anomaly [28–30], a significant departure from the standard three-neutrino oscillation picture has been observed. The reported excess of electron-like events reported in the experiments can be explained with the oscillations of three active neutrinos and one sterile neutrino corresponding to the mass-squared difference $\Delta m_{41}^2 \simeq 1$ eV$^2$. Similar anomalies have also been noted in Galium [63, 64] and reactor anomalies [65]. Although the results have been revisited in numerous accounts (see Refs. [31–33] for reviews), none has been able to confirm or refute the sterile neutrino hypothesis. It is left to the future neutrino oscillation experiments to check whether the observed excess indeed arises from active-sterile neutrino oscillations of this range.

In this subsection, we examine the sensitivity to the 3+1–neutrino model in muon- and pion-beam experiments, while assuming a 187 kton opaque detector as the far detector. To optimize the experimental setup to look for active-sterile neutrino oscillations of $\Delta m_{41}^2 \simeq 1$ eV$^2$, a near detector of 1 kton mass is assumed. In our simulation, the near detectors are placed at 750 m and 250 m distances from the J-PARC and MOMENT facilities, respectively. These baseline lengths correspond approximately to the conditions where the first oscillation maximum occurs for $\Delta m_{41}^2 = 1$ eV$^2$.

Figure 3 presents the exclusion limits on $\Delta m_{41}^2$ and $\sin^2 2\theta_{14}$ as well as for $\sin^2 2\theta_{14}$ and $\sin^2 \theta_{24}$. The $\chi^2$ fitting has been done by marginalizing the $\chi^2$ function over all parameters except for the ones shown in the axis labels. In the left panel of the figure, the parameter values to the right of the contours are excluded for $\Delta m_{41}^2$ and $\sin^2 2\theta_{14}$ by 90% C.L. if the MOMENT and J-PARC beams are used together with opaque detectors. The lower part of the curve is due to the 187 kton far detector, while the upper part arises from the presence of the 1 kton near detector. We also plotted the corresponding limits obtained from the Daya Bay and Bugey-3 experiments [66]. The excluded region is indicated with the yellow colour. In the right panel of Figure 3, we show the exclusion contours at 90% C.L. for $\sin^2 2\theta_{14}$ and $\sin^2 \theta_{24}$, while $\Delta m_{41}^2 \sim 1$ eV$^2$. In this region sensitivity is acquired almost entirely from the near detector. We note that in both the $\Delta m_{41}^2 - \sin^2 2\theta_{14}$ and $\sin^2 2\theta_{14} - \sin^2 \theta_{24}$ panels the MOMENT beam proves to be more sensitive to the sterile neutrino parameters than the beam simulated for J-PARC. This behaviour is in contrast to the results we obtained for the CP violation discovery, where J-PARC is superior.

The upper limits on $\sin^2 2\theta_{14}$ and $\sin^2 \theta_{24}$ have recently been analysed using data from the Daya Bay, Bugey-3, MINOS and MINOS+ experiments [66]. The Daya Bay data used in the analysis is collected from 1230 days of data taking. The report sets the current bounds to $\sin^2 2\theta_{14} \lesssim 5 \times 10^{-2}$ and $\sin^2 \theta_{24} \lesssim 6 \times 10^{-3}$ for $\Delta m_{41}^2 \simeq 1$ eV$^2$ at 90% CL, placing the most stringent limits on the active-sterile neutrino parameters. Our results in Figure 3 show that a similar sensitivity can be reached using a 1 kton opaque detector in the J-PARC setup as a near detector, whereas MOMENT could provide higher sensitivities. We can therefore conclude that a near detector of at least 1 kton fiducial mass could improve the present bound on $\sin^2 2\theta_{14}$, whereas the current bound on $\sin^2 \theta_{24}$ is beyond reach.

We also studied the effect of changing the signal-to-background ratio and energy resolution in the results presented in Figure 3. We conclude that these parameters have negligible effect on the exclusion limits in the studied configuration.

The presence of the light sterile neutrino can undermine accelerator neutrino experiments in their mission to discover CP violation in the leptonic sector. It has been shown that the inclusion of a light sterile neutrino can significantly hinder the discovery potential to CP violation. In the following, we study its effect on the experimental configurations considered in this work.

We investigated whether the light sterile neutrino of $\Delta m_{41}^2 \sim O(1 \text{ eV}^2)$ can induce significant loss in the sensitivity to CP violation discovery, and if opaque detectors could help to recover the sensitivity. To do this, we calculated the
Fig. 4. The CP violation discovery potential in presence of a sterile neutrino. Both muon and pion decay based neutrino beams used with a 187 kton far detector based on Water Cherenkov (W.C.) and Opaque Detector (O.D.) techniques. The sensitivities are provided both in the 3+0 and 3+1–neutrino models. The Opaque Detector is considered for 50% and 70% efficiencies for e-like events. The sterile neutrino corresponds to the true values $\theta_{14}=7^\circ$, $\theta_{24}=9^\circ$ and $\Delta m^2_{41}=1$ eV$^2$

CP violation discovery potential as a function of $\delta_{CP}$ values both in the three-neutrino paradigm and in the 3+1 scenario, where a sterile neutrino corresponding to $\theta_{14}=7^\circ$, $\theta_{24}=9^\circ$, $\theta_{34}=0^\circ$ and $\Delta m^2_{41}=1$ eV$^2$ is included in the model. The $\chi^2$ fitting is done by marginalizing over all parameters except for $\delta_{CP}$, $\theta_{34}$, $\theta_{24}$ and $\theta_{14}$. The results are presented in Figure 4, where the sensitivities to the CP violation are shown for both Water Cherenkov and opaque detector setups.

As can be seen in Figure 4, the presence of the active-sterile oscillation parameters $\theta_{14}$, $\theta_{24}$ and $\Delta m^2_{41}$ causes a remarkable drop in the CP violation discovery potential. When a 187 kton far detector based on Water Cherenkov technique is assumed without a near detector, the sensitivity at $\delta_{CP}=270^\circ$ drops from 4.9 $\sigma$ to 4.3 $\sigma$ confidence level for J-PARC and from 4.8 $\sigma$ to 4.5 $\sigma$ for MOMENT, respectively. Replacing the Water Cherenkov vessel with an opaque detector of 70% efficiency and equivalent mass improves the sensitivity at $\delta_{CP}=270^\circ$ to 5.0 $\sigma$ and 5.4 $\sigma$ C.L. in the 3+1 model, restoring the lost sensitivity and even improving it beyond the 3+0 model limits in both J-PARC and MOMENT setups.

VI. CONCLUSIONS

We investigated the prospects of using an opaque detector in accelerator neutrino experiments, outlining its potential in neutrino beams produced via the pion decay and the muon decay. Using the future J-PARC and MOMENT beam facilities as an example of both production techniques, we studied the physics reach of neutrino detectors based on the recently proposed LiquidO technique. We consider the sensitivities to CP violation discovery and constraining the active-sterile neutrino parameters $\theta_{14}$, $\theta_{24}$ and $\Delta m^2_{41}$ in the 3+1 scenario while assuming a far detector of $\mathcal{O}(100$ kton) fiducial mass. In the sterile neutrino case we also assume a near detector of 1 kton fiducial mass.

When the CP violation discovery is studied, we find opaque detectors to be able to provide improved sensitivities through detection efficiencies and background suppression. We studied the correlation between the CP violation sensitivity and detector mass, energy resolution and signal-to-background ratio. We also studied the sensitivities while assuming the efficiency for e-like events to be between 50% and 70%, which we regard as the conservative and optimistic choices for these parameters, respectively. We remark that a 120 kton opaque detector with 70% efficiency for electron-like events and the J-PARC facility is sufficient to yield a similar CP violation coverage to that of T2HK experiment, which we estimate to be about 75.6% of the $\delta_{CP}$ values at 3 $\sigma$ confidence level with a single 187 kton Water Cherenkov tank. For the true value of $\delta_{CP}=270^\circ$, we find that CP violation can be established at 5 $\sigma$ C.L. with the same detector parameters. For efficiencies lower than 70% the mass of the opaque detector has to be increased.

We also studied the constraining power on the active-sterile mixing parameters $\theta_{14}$ and $\theta_{24}$ in the 3+1 neutrino case when $\Delta m^2_{41} \sim 1$ eV$^2$. We report exclusion limits of about 0.1 and 0.06 on $\sin^2 2\theta_{14}$ and $\sin^2 \theta_{24}$ respectively at 90% confidence level, when a system of 187 kton far detector and 1 kton near detector based on the opaque detector technique and a beam from J-PARC is used. We also note that these limits are pushed to 0.05 and 0.01 when a neutrino beam from MOMENT is used instead. Using an opaque detector can also improve the sensitivity to CP violation in presence of the sterile neutrino, improving the sensitivity from 4.3 $\sigma$ to 5.0 $\sigma$ confidence level for J-PARC and from 4.5 $\sigma$ to 5.4 $\sigma$ for MOMENT, respectively, when $\delta_{CP}=270^\circ$ and the 3+1 model are assumed.

Altogether, we find the opaque detectors an attractive detector candidate for accelerator-based neutrino experiments. Although neutrino energies above 100 MeV and below 1 GeV are a very challenging regime to the LiquidO technique, opaque detectors could offer a way to reach CP violation sensitivities much higher than those of Water Cherenkov detectors, if an adequate interplay of detector mass, efficiency and signal-to-background ratio is achieved.

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