Letter of Interest for a Neutrino Beam from Protvino to KM3NeT/ORCA

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Abstract

The Protvino accelerator facility located in the Moscow region, Russia, is in a good position to offer a rich experimental research program in the field of neutrino physics. Of particular interest is the possibility to direct a neutrino beam from Protvino towards the KM3NeT/ORCA detector, which is currently under construction in the Mediterranean Sea 40 km offshore Toulon, France. This proposal is known as P2O. Thanks to its baseline of 2595 km, such an experiment would yield an unparalleled sensitivity to matter effects in the Earth, allowing for the determination of the neutrino mass ordering with a high level of certainty after only a few years of running at a modest beam intensity of $\approx 90$ kW. At the same time, a mild sensitivity to the leptonic CP-violating Dirac phase can be achieved. A second phase of the experiment, comprising a further intensity upgrade of the accelerator complex and a significant densification of the ORCA detector, would allow for a high precision measurement of the CP phase, competitive and complementary to other planned experiments. The initial composition and energy spectrum of the neutrino beam would need to be monitored by a near detector, to be constructed several hundred meters downstream from the proton beam target. The same neutrino beam and near detector set-up would also allow for neutrino-nuclei cross section measurements to be performed. A short-baseline sterile neutrino search experiment would also be possible.

1 Introduction

Neutrino physics is one of the most actively developing branches of particle physics, with many fundamental parameters still awaiting to be experimentally determined, and indicates great promise for new insights into physics beyond the Standard Model. Some of the key open questions are the presence of charge-parity (CP) violation in the lepton sector, e.g. by the

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CP-violating Dirac phase in the neutrino mixing matrix, and the relative ordering of the three neutrino mass eigenstates ("mass ordering"). Both questions can be answered by studying flavour oscillations of GeV neutrinos over a long baseline ($\gg$ 100 km). Particle accelerators provide a well-controlled environment suited for conducting high precision measurements of that type. Several long-baseline accelerator neutrino experiments are currently running and/or under construction, in particular the T2K/T2HK experiment in Japan (295 km baseline) [1, 2], the NO$\nu$A experiment in the USA (810 km baseline) [3], and the DUNE experiment (1300 km baseline), also in the USA [4]. A typical set-up includes a near detector, to measure the initial energy spectrum and composition of the neutrino beam, and a far detector, to measure the neutrino beam properties after oscillations. Several experiments with different baselines will likely be necessary to cleanly disentangle effects from various poorly constrained parameters, such as the CP-violating phase $\delta_{CP}$, the mass ordering, and (the octant of) the $\theta_{23}$ mixing angle. Furthermore, any new significant experimental finding will need to be independently verified, ideally with an experiment which does not share the same systematic measurement uncertainties. In this regard, the construction of multiple experiments with different baselines is generally well motivated.

This letter expresses interest in a long-baseline neutrino experiment using the accelerator complex in Protvino (Moscow Oblast, Russia) for generating a neutrino beam and the KM3NeT/ORCA detector [5] in the Mediterranean Sea as a far detector. The scientific potential of the Protvino-ORCA (P2O) experiment is presented with an emphasis on the sensitivity to the CP-violating Dirac phase $\delta_{CP}$ and neutrino mass ordering. We argue that, thanks to the long baseline (2595 km) and 8 Mt sensitive volume of the far detector, P2O would be complementary and competitive to experiments such as T2K, NO$\nu$A and DUNE. A vision of the long-term future of P2O is proposed, including upgrades of the Protvino accelerator complex and the ORCA detector. Additionally, a short-baseline neutrino research program is proposed which includes studies of neutrino-nuclei interactions as well as searches for phenomena beyond the Standard Model.

This document is organized as follows: the ORCA neutrino detector is introduced in Section 2. The current status and proposed upgrades of the Protvino accelerator complex are presented in Section 3. The neutrino beamline and the near detector are discussed in Sections 4 and 5, respectively. Sections 6 and 7 present the scientific potential of the P2O long-baseline experiment and the proposed short-baseline research program, respectively. Section 8 refers to a possible future upgrade of ORCA. Section 9 gives a summary.

2 KM3NeT/ORCA

ORCA (Oscillation Research with Cosmics in the Abyss) is one of the two neutrino detectors under construction by the KM3NeT Collaboration [5]. It is located at 42°48’N 06°02’E, about 40 km off the coast of Toulon, France, at a depth between 2450 m (the seabed depth) and 2250 m. When completed, ORCA will consist of 2070 digital optical modules (DOMs) installed on 115 vertical strings (detection units, DUs) (see Fig. 1). With a 9 m vertical spacing between the DOMs and a $\approx$ 20 m horizontal spacing between the DUs, the detector instruments in total 8 Mton of sea water. ORCA is optimized for the study of atmospheric neutrino oscillations in the energy range between 2 GeV and 30 GeV with the primary 

3
115 strings
18 DOMs / string
~ 225 m
23 m
9 m

Figure 1: Schematic view of the KM3NeT/ORCA detector.

The goal to determine the neutrino mass ordering. The majority of neutrino events observed by ORCA will be from electron and muon neutrino and antineutrino charge-current (CC) interactions, while tau neutrinos and neutral current (NC) interactions constitute minor backgrounds (7% and 11% of the total neutrino rate, respectively, for $\nu_\tau$ CC and all-flavour NC). Studies performed by the KM3NeT Collaboration suggest that at $E_\nu = 5$ GeV the majority (> 50%) of muon neutrino CC events detected by ORCA can be correctly identified as muon neutrinos, while less than 15% of electron neutrino CC events are misidentified as muon neutrinos. ORCA will provide a neutrino energy resolution of $\approx 30\%$ and a zenith angle resolution of $\approx 7$ degrees at $E_\nu = 5$ GeV. A result with a 3 $\sigma$ statistical significance on the mass ordering is expected after three years of data taking [5]. ORCA will also provide improved measurements of the atmospheric neutrino oscillation parameters $\Delta m^2_{23}$, $\theta_{23}$ and will probe the unitary of 3-neutrino mixing by measuring the $\nu_\tau$ flux normalisation. Non-standard neutrino interactions, as well as astrophysical neutrino sources, dark matter, and other physics phenomena will also be studied. The detector construction has recently started and is expected to be completed within 4 years.

3 The Protvino Accelerator Complex, Current Status and Proposed Upgrades

The Protvino accelerator complex (see Fig. 2) is located at 54° 52’ N 37° 11’ E, approximately 100 km South of Moscow, Russia. Its core component is the U-70 synchrotron of 1.5 km in circumference which accelerates protons up to 70 GeV. U-70 was originally built in the 1960s and has been in regular operation since then. The proton injection chain includes an
ion source, a 30 MeV linear accelerator, and a 1.5 GeV booster synchrotron. The accelerator chain is normally operated at a beam energy of 50 GeV to 70 GeV, with a proton intensity of up to $1.5 \times 10^{13}$ protons per cycle. The beam cycle is 10 s, with a beam spill duration of up to 3.5 s; or 8 s, with a 5 µs beam spill. A dedicated neutrino beamline supplied a neutrino beam to the SKAT bubble chamber (1974–1992) [6], the ITEP-IHEP spark chamber spectrometer [7], the IHEP-JINR neutrino detector (1989–1995, upgraded 2002–2006) [8], and other experiments. The results from these experiments include neutrino-nucleon cross section measurements and constraints on the $\nu_\mu \rightarrow \nu_e$ oscillation parameters. The beamline was able to provide a high-purity muon neutrino beam, thanks to the steel muon absorbers preventing muon decay in flight, and a tunable beam spectrum, thanks to active lenses. The beamline is not currently operational and its active components will require refurbishing if they are to be used again. Meanwhile, the rest of the U-70 accelerator complex is in good operational condition. The complex is operated by the Institute for High Energy Physics (IHEP), which is part of the “Kurchatov Institute” National Research Center.

The U-70 synchrotron routinely operates at a time-averaged beam power of up to 15 kW. In the 1990’s, a new injection scheme was considered at IHEP, which would allow for an increase of the beam intensity to $5 \times 10^{13}$ protons per cycle [9]. Together with the shortening of the cycle to 7 s, this would provide a beam power of 75 kW. After some further incremental improvements, a beam power of 90 kW could be reached. Hence, in the following, we will use the value of 90 kW as the achievable goal of such an upgrade. Assuming that the accelerator works for the neutrino program with a 60% efficiency for 6 months a year, one year of the 90 kW beam corresponds to $\approx 0.8 \times 10^{20}$ protons on target (POT). Note that the design of the main U-70 synchrotron potentially allows for operation at a beam power up to $\approx 450$ kW. An upgrade up to 450 kW could be made possible by a new chain of injection accelerators [10]. Such a beam power would be adequate for high-precision studies of CP violation (see Sect. 8).
Figure 3: Path to be traveled by the neutrino beam from Protvino (in the top right) to ORCA (in the bottom left). The path length is $\approx 2595$ km and the deepest point is $135$ km below sea level, in the upper mantle.

4 Neutrino Beamline

A new neutrino beamline will need to be constructed at Protvino to enable the proposed research program. In order to serve the P2O long-baseline experiment, the beamline should be aligned towards the ORCA site (see Fig. 3), at an inclination angle of $11.8^\circ$ (206 mrad) below the horizon. A baseline design of the neutrino beamline, shown in Fig. 4, includes the following main components: beam extraction station, which could be installed on an accelerator section located in the main experimental hall; straight section, which delivers the beam from the extraction point to the target; graphite beam target; secondary beam focusing system using magnetic horns; decay pipe, where neutrinos are produced from pion and kaon decays; and beam absorber. The longest section of the beamline is the decay pipe. In the baseline design, the target hall is located at a depth of $\approx 30$ m under ground level, the decay pipe is $\approx 180$ m long (subject to optimization), the absorber hall is $\approx 63$ m below ground level, and the near detector hall is $\approx 90$ m below ground. The magnetic horns will allow for reversal of the electric current polarity in order to choose between the neutrino and antineutrino mode.

A simulation study of the proposed beamline suggests that a muon neutrino beam with 98% purity can be obtained using the 70 GeV proton beam, with a plateau in the neutrino energy distribution between 2 GeV and 7 GeV (see Fig. 5). In the antineutrino mode, an antineutrino beam with 94% purity may be obtained [11]. Compared to the old neutrino beamline previously operated at Protvino, the new beamline design presents the following new challenges: 1) need for a higher beam intensity; 2) beamline to be constructed in an inclined tunnel. These challenges are to be addressed in a dedicated R&D study.
Figure 4: Top view and elevation view of the proposed neutrino beamline (the baseline design).
5 Near Detector

Following the classic paradigm of long-baseline neutrino experiments, the primary purpose of the near detector is to monitor the energy spectrum, composition and direction of the neutrino beam close to the source, before the composition is modified by oscillations. This is important for controlling the measurement uncertainties and thus achieving the targeted performance and sensitivity of the experiment. The near detector can also be used for studies of neutrino-nuclei interactions, searches for short-baseline oscillations, and other studies. The P2O near detector would be located ~120 m downstream from the beam dump (~320 m from the proton target). The detector should be large enough to fully contain hadronic cascades created by 5–10 GeV neutrinos. Muon tracks exiting the main detector volume could be measured by additional muon detectors. For a reference, a 5 GeV muon travels ≈22 m in water before stopping.

The choice of technology and materials for the near detector is a complex subject. It is generally preferable to use the same material and detector technology for the near and far detector in order to reduce systematic uncertainties related to extrapolations from one target material to another and from one detector technology to another. However, additional considerations and constraints may call for other design choices. For instance, the use of a higher granularity detector at the near site may be preferable, as it would allow for a more refined measurement of the neutrino interaction products, thus enabling more detailed studies of neutrino cross sections and related nuclear physics. Constraints on the maximal dimensions of the near detector hall may call for use of heavy materials to reduce...
the detector dimensions. The final design of the near detector needs to balance all requirements and constraints. Several design options for the P2O near detector are currently under consideration. They can be subdivided into two main groups:

1) A high granularity detector containing water in one or several of its subsystems. This design option is inspired in part by the T2K’s ND280 \cite{12} and NOνA near detector \cite{3} designs.

2) A large water tank instrumented with PMTs. This is similar to the TITUS and NuPRISM designs proposed for T2HK \cite{13}. This design could incorporate KM3NeT PMTs as light sensors, thus closely mimicking conditions of the far detector (ORCA).

The use of a water-based liquid scintillator is under consideration as a possible alternative to pure water for both design options. A part of the detector could be filled with heavy water, which would be useful for studies of nuclear effects and determination of cross sections on free protons and neutrons. The option to use several different detectors with different measurement techniques can be considered as well.

6 Science with the Neutrino Beam from Protvino to ORCA

Sending a neutrino beam from Protvino to ORCA provides a baseline of 2595 km, larger than any accelerator neutrino experiment currently operating or planned elsewhere. The first $\nu_\mu \rightarrow \nu_e$ oscillation maximum is then at $E_\nu \approx 5$ GeV, within the energy range readily available from the U-70 synchrotron and within the ORCA’s nominal energy range. In this energy regime, the neutrino interaction cross section is dominated by deep inelastic scattering, which is relatively well described theoretically (compared to resonant interactions which dominate at $\approx 2–3$ GeV), thus facilitating high-precision measurements of neutrino flavor oscillations. For a reference, a recent study by the MINERνA Collaboration reported a 10% uncertainty for the total neutrino cross section at 2.5 GeV and a 5% uncertainty at 5 GeV \cite{14}. The 2595 km baseline is well suited for probing the CP-violating Dirac phase $\delta_{CP}$, as well as for measuring the matter resonance effect ($E_{res} = 4$ GeV for the Earth crust) \cite{15, 16}. The effects of the mass ordering and $\delta_{CP}$ are most pronounced in the $\nu_e$ appearance channel (see Figs. 6 and 7). The large instrumented volume of ORCA, 8 million cubic meters, will allow one to detect thousands of neutrino events per year, even with a relatively modest accelerator beam power and despite the very long baseline.

A preliminary study of the scientific potential of the P2O experiment \cite{17, 18} suggests that the neutrino mass ordering could be determined with a 4–8 $\sigma$ statistical significance after one year of running with a 450 kW beam or after five years with a 90 kW beam (see Figs. 8 and 9). This would provide a solid confirmation of the $\approx 3–5$ $\sigma$ result expected to be achieved in the coming years by ORCA using atmospheric neutrinos, NOνA using accelerator neutrinos, and JUNO \cite{19} using reactor neutrinos. After 3 years of operation with the 450 kW beam, the P2O experiment could also provide up to a 3 $\sigma$ sensitivity to discover CP violation. Depending on the true $\delta_{CP}$ value, the 1 $\sigma$ accuracy on the value of $\delta_{CP}$ is of 20°–40° (see Fig. 10). The sensitivity estimates quoted here were obtained using a preliminary data analysis pipeline developed for atmospheric neutrino studies \cite{5} and do not include
Figure 6: Oscillation probabilities for $\nu_\mu \rightarrow \nu_e$ (electron neutrino appearance) for baseline of 2595 km for normal (red) and inverted (blue) mass ordering.

Figure 7: The effect of the CP phase on the expected number of neutrino events that would be detected by ORCA after 3 years of running with a 90 kW beam from Protvino. Normal neutrino mass ordering with $\theta_{23} = 45^\circ$ is assumed. The x-axis shows the true neutrino energy.
Figure 8: Sensitivity of P2O to the neutrino mass ordering (NMO) as a function of the $\theta_{23}$ mixing angle after 3 years of running with a 90 kW beam. The $\theta_{23}$ and $\delta_{CP}$ values chosen provide the most and the least favorable scenarios for both normal and inverted ordering. One year of running with the 90 kW beam corresponds to $\approx 0.8 \times 10^{20}$ protons on target (POT).

any potential analysis improvements thanks to the known arrival direction and timing of the neutrino beam. The treatment of systematic uncertainties includes a 5% normalization uncertainty for the combined $\nu_\mu$ and $\nu_e$ event rate, a 10% normalization uncertainty for $\nu_\tau$, a 5% normalization uncertainty on the NC event rate, and a 10% uncertainty on the neutrino flavour identification performance of ORCA. The neutrino oscillation parameters $\theta_{13}$, $\theta_{23}$, $\Delta m^2_{23}$ and $\delta_{CP}$ were allowed to vary during the minimization procedure, with $\theta_{13} = 8.42^\circ \pm 0.15^\circ$ constrained with a Gaussian prior for both the NMO and CP-phase determination. For the latter also $\theta_{23}$ and $\Delta m^2_{23}$ are constrained by Gaussian priors as $\theta_{23} = 45.0^\circ \pm 2.0^\circ$ and $\Delta m^2_{23} = (2.50 \pm 0.05) \times 10^{-3}$ eV$^2$. Another study, conducted independently and reported in [20], finds similar results. Minor differences with respect to our work can be explained by differences in the treatment of systematic uncertainties, the choice of priors on the oscillation parameters, and the assumed beam spectra.

The estimated sensitivity of P2O to mass ordering and CP violation is compared to the sensitivity of some proposed and presently operating long-baseline experiments in Table [1]. It is worth mentioning that both T2K and NO$\nu$A have published experimental constraints on the mass ordering and CP violation [21, 22] which are within statistical error bars from the sensitivity figures given in Table [1]. It can be noted that the mass ordering sensitivity of P2O exceeds that of NO$\nu$A and is competitive with the sensitivity of DUNE. Note also that T2K has a marginal sensitivity to mass ordering due to an insufficiently long baseline. The CP violation sensitivity of P2O is competitive with T2K and NO$\nu$A and, to a lesser extent, with the future DUNE and T2HK experiments. Both T2K and NO$\nu$A alternate between using positive and negative beam polarity ($\nu$ and $\bar{\nu}$ modes), both polarities providing sensitivity to $\delta_{CP}$. At the P2O baseline of 2595 km, most of the sensitivity to $\delta_{CP}$ comes from one beam
Figure 9: Sensitivity of P2O to neutrino mass ordering as a function of the accumulated exposure time with the 90 kW beam. For both normal and inverted ordering, the most and the least favorable scenarios are shown.

Figure 10: Sensitivity to measure the CP phase $\delta_{CP}$ in the P2O experiment after 3 years of running with a 450 kW beam for 4 example true values of the CP phase ($0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$). Each curve represents an average $\sqrt{\Delta \chi^2}$ plot that would be obtained if the true $\delta_{CP}$ value equals the test value indicated by the corresponding label. $\sqrt{\Delta \chi^2} = 1$ corresponds to the 1 $\sigma$ uncertainty.
| Experiment | T2K | T2HK | NOνA | DUNE | P2O |
|------------|-----|------|------|------|-----|
| Location   | Japan | Japan | USA  | USA  | Russia/Europe |
| Status     | operating | proposed | operating | construction | proposed |
| Accelerator facility | J-PARC | J-PARC | Fermilab | Fermilab | Protvino |
| Baseline   | 295 km | 295 km | 810 km | 1300 km | 2595 km |
| Off-axis angle | 2.5° | 2.5° | 0.8° | 0° | 0° |
| 1-st max $\nu_\mu \rightarrow \nu_e$ | 0.6 GeV | 0.6 GeV | 1.6 GeV | 2.4 GeV | 4 GeV |
| Detector   | SuperK | HyperK | NOνA | DUNE | ORCA | Super-ORCA |
| Target material | pure water | pure water | LS | liquid Ar | sea water |
| Detector technology | Cherenkov | Cherenkov | LS | TPC | Cherenkov |
| Fiducial mass | 22 kt | 186 kt | 14 kt | 40 kt | 8000 kt | 4000 kt |
| Beam power | 500 kW | 1300 kW | 700 kW | 2400 kW | 450 kW | 450 kW |
| $\nu_e$ events per year (NO) | $\approx 20$ | 230 | $\approx 20$ | 230 | 3500 | 3400 |
| $\bar{\nu}_e$ events per year (IO) | $\approx 6$ | 165 | $\approx 7$ | 60 | 1200 | 1100 |
| NMO sensitivity ($\delta_{CP} = \pi/2$) | - | - | 4 $\sigma$ | 1 $\sigma$ | 7 $\sigma$ | $>7 \sigma$ | $\gg 7 \sigma$ |
| CPV sensitivity ($\delta_{CP} = \pi/2$) | 1.5 $\sigma$ | 3 $\sigma$ | 8 $\sigma$ | 2 $\sigma$ | 7 $\sigma$ | 3 $\sigma$ | 9 $\sigma$ |
| 1$\sigma$ error on $\delta_{CP}$ ($\delta_{CP} = \pi/2$) | 22° | 11° | 30° | 8° | 4° | 15° | 10° |
| 1$\sigma$ error on $\delta_{CP}$ ($\delta_{CP} = 0$) | 7° | 6° | 15° | 10° | 4° | 15° | 10° |
| Year / data taking years | 2018 | 2026 | 10 yr | 2024 | 10 yr | 6 yr | 10 yr |
| Refs. | [21] | [23] | [2, 24] | [3, 25] | [4, 26] | [17, 18] | [38, 41] |

Table 1: Sensitivity of present and future long-baseline accelerator neutrino experiments to neutrino mass ordering (NMO) and leptonic CP violation (CPV). All sensitivities are given for the case of normal mass ordering. Expected number of $\nu_e$ ($\bar{\nu}_e$) events per year is given for the case of normal mass ordering using positive (negative) polarity beam. LS stands for liquid scintillator.

polarity: positive for the case of normal mass ordering and negative for the case of inverted mass ordering. For that reason, the P2O sensitivity to $\delta_{CP}$ was derived assuming a fixed beam polarity chosen according to the mass ordering. It is worth mentioning that the 90 kW positive-polarity beam will produce $\approx 4000$ neutrino events in ORCA per year. In the case of normal mass ordering, $\approx 700$ of these events will be $\nu_e$ events. For comparison, the DUNE experiment, using a 1.3 MW beam in combination with a 40 kt liquid argon detector over a 1300 km baseline, will detect $\approx 230 \nu_e$ events per year.

A combined analysis of the atmospheric and accelerator neutrino data collected by ORCA will be possible, improving the systematic uncertainties and parameter degeneracies. Additional science topics with P2O may include non-standard neutrino interactions and sterile neutrino searches.
7 Science with the Near Detector

One of the main sources of systematic uncertainties in modern and future experiments for the study of fundamental properties of neutrinos is the uncertainty in the knowledge of the cross sections for neutrino and antineutrino interactions with nuclei. The cross sections due to charged and neutral currents are usually assumed to be a sum of cross sections for the reactions of (quasi)elastic (QES, ES) scattering, nucleon and baryon resonances production with their subsequent decay into a nucleon and pions (RES), production of kaons, light strange hyperons (for $\nu_\mu$), and charmed mesons, and production of multiple hadrons including strange and charmed particles in deep inelastic scattering (DIS); see Refs. [27, 28, 29, 30] and references therein. At neutrino energy range around 1 GeV, the cross sections for (Q)ES, RES, and DIS are comparable in magnitude (see Fig. 11). Current uncertainties in the theoretical calculation of the cross sections are related to difficulties in accounting for nontrivial nuclear effects (meson exchange currents, exchange of baryon resonances between nucleons in the nucleus, multinucleon correlations, etc.) and significant uncertainties in the knowledge of the elastic and transition form factors of the nucleon, especially for the axial-vector and pseudoscalar, as well as for the nonstandard scalar and tensor form factors (for the latter two, at present, there are only very rough experimental upper limits). In the absence of a generally adopted and reliable model for neutrino-nuclei interactions which would be available in a wide energy range, different authors use different phenomenological models tuned to different energy ranges and detector targets. As a result, the values of the fundamental phenomenological parameters for neutrino-nucleon interactions, extracted from the experiments, often contradict each other, strongly depend on the interaction model used in analyses and, moreover, on average energies of neutrino and antineutrino beams. This in turn leads to uncertainties in extrapolations of the cross section models from one target material to another.

High precision measurements with P2O will require an accurate knowledge of the (anti)neutrino cross sections in water. So far, the only experimental result on neutrino cross sections on a water target was obtained with T2K experiment [31] at the mean neutrino energy $\sim 1$ GeV. Additional measurements appear necessary, both to improve the neutrino-nuclei interaction models and facilitate high-precision neutrino oscillation studies with P2O. The P2O near detector could provide a measurement of the neutrino and antineutrino cross sections with nucleons on a water target at neutrino energies from $\sim 2$ to 20 GeV. The obtained cross section data would also help to enhance the precision of the ORCA measurements using atmospheric neutrinos.

The P2O near detector could be designed so as to allow for simultaneous measurements of the cross sections on two or more different nuclear targets, e.g. water and a carbonaceous scintillator. This would permit an unbiased comparison between the different materials, and, ultimately, a better understanding of the physics of neutrino scattering on nucleons bound in nuclei. The cross section measurement programme could be further enhanced by additional specialized experiments. In this context it is worth noting that a strong motivation exists for a new experiment using the simplest targets, namely hydrogen and/or deuterium, in which case the investigation of the nucleon is separated from the complications that arise due to in-medium nuclear effects.

The near detector will also enable searches for sterile neutrinos and other exotic phenom-
Figure 11: Total CC cross sections as functions of (anti)neutrino energy and normalized to energy for $\nu_\mu$ and $\bar{\nu}_\mu$ scattering off isoscalar nucleons in comparison with experimental data [32]. The curves and bands of theoretical uncertainties show the QES [33] (with contribution from light strange hyperons productions in the case of $\bar{\nu}_\mu$ reactions [34]), RES [35], and DIS [27] (see references therein) contributions and their sums. The shaded band indicates the energy range relevant for ORCA.
ena. In particular, it would allow for an independent test of the so-called LSND anomaly \[36\] and a similar anomaly reported recently by the MiniBooNE Collaboration \[37\]. Both of these anomalies have been hypothesized to be caused by transitions to sterile neutrino states and can be tested using the U-70 neutrino beam \[11\]. The beamline configuration considered in this letter will allow to search for sterile neutrinos at comparatively larger values of the squared mass difference ($\Delta m^2$).

## 8 Future Beyond ORCA

A more densely-instrumented version of the ORCA detector, called Super-ORCA, is under discussion as a possible next step after ORCA. Super-ORCA could provide a lower energy threshold for neutrino detection, better neutrino flavour identification and better energy resolution compared to ORCA \[38\]. Such an upgrade could substantially enhance the scientific potential of the P2O experiment, in particular the accuracy of the CP phase measurement. A very preliminary projection of the sensitivity of Super-ORCA using the Protvino neutrino beam is shown in Figs. 12 and 13. In these figures, a 10 times denser detector geometry compared to ORCA is assumed along with a 4 Mt fiducial volume. With such an increased instrumentation density, the energy threshold for neutrino detection is reduced to $\sim 0.5$ GeV, allowing one to reach the second oscillation maximum. The increased instrumentation density also allows one to separate $\nu_\mu/\nu_e$ via the fuzziness of the Cherenkov rings, so that 95%-pure samples of muon-like (dominated by $\nu_\mu$ CC) and electron-like events (dominated by $\nu_e$ CC) can be selected. The neutrino energy resolution is $\approx 20\%$ at $E_\nu > 1$ GeV and is dominated by fluctuations in the number of emitted photons in the hadronic shower \[39\]. Consequently, such a configuration can yield up to a 9 $\sigma$ sensitivity to discover CP violation along with a $\sim 10^5$ precision on $\delta_{CP}$ after 10 years of data taking with the 450 kW beam. The kinks in Fig. 12 (black and yellow curves) and Fig. 13 (red and blue solid curves, $\delta_{CP}/\pi \approx 1.12$ and 1.88) are caused by the $\delta_{CP} - \theta_{23}$ degeneracy. This $\delta_{CP} - \theta_{23}$ degeneracy is partly resolved when combining neutrino and antineutrino data, as can be seen in Fig. 13. The $\delta_{CP}$ resolution reachable after 3 and 10 years of running with the 450 kW beam is shown in Fig. 14. It is worth to note that the highest precision is achieved for $\delta_{CP} = [90^\circ, 270^\circ]$, complementary to DUNE \[4\], T2HK \[2\] and ESS$\nu$SB \[40\] which achieve the highest measurement precision for $\delta_{CP} = [0^\circ, 180^\circ]$. In the case of Super-ORCA, the $\delta_{CP}$ resolution for $\delta_{CP} = [0^\circ, 180^\circ]$ is limited by the $\delta_{CP} - \theta_{23}$ degeneracy, while for $\delta_{CP} = [90^\circ, 270^\circ]$ the $\delta_{CP}$ resolution profits more from the large event statistics. Super-ORCA also offers interesting prospects for neutrino oscillation tomography of the Earth and CP violation studies using atmospheric neutrinos \[38\].

## 9 Summary

The Protvino accelerator facility is well suited for conducting experiments with GeV neutrino beams and has a strong potential to make important contributions to modern neutrino physics, competing with facilities such as Fermilab and J-PARC. The distance from Protvino to the ORCA neutrino detector in the Mediterranean Sea is 2595 km, which is ideal for a
Figure 12: Sensitivity to measure the CP phase, assuming 3 years of operating Super-ORCA with a 450 kW beam from Protvino (solid lines). The corresponding sensitivity using atmospheric neutrinos is shown by dashed lines (see [38, 41] for details).

Figure 13: Sensitivity to detect CP violation by operating ORCA 3 years (dashed), Super-ORCA 3 years (solid blue) and Super-ORCA 10 years (solid red and purple) in a 450 kW beam from Protvino. The sensitivity is shown as a function of the true $\delta_{CP}$ value ($\delta_{CP} = 0$ and $\delta_{CP} = \pi$ correspond to CP conservation).
long-baseline neutrino experiment employing ORCA as a far detector. Such an experiment promises an outstanding sensitivity to neutrino mass ordering, easily reaching a 5 $\sigma$ significance level even with a relatively low intensity beam (90 kW). With a sufficiently long beam exposure ($\approx 6$ yr $\times$ 450 kW), a 3 $\sigma$ sensitivity to leptonic CP violation ($\delta_{CP}$) can also be reached, which is competitive with the projected sensitivity of the T2K and NOvA experiments. Unique characteristic features of P2O include 1) the longest baseline; 2) the highest energy of the oscillation maximum; and 3) the highest neutrino event statistics due to the large far detector installed in the open sea.

A new neutrino beamline will need to be constructed at Protvino in order to produce a neutrino beam focused in the direction of ORCA. Achieving a competitive sensitivity to CP violation will require an increase of the accelerator beam power from 15 kW (current value) up to at least 90 kW. Such an upgrade appears technically feasible. With a 90 kW beam, ORCA will detect $\sim 4000$ beam neutrino events per year, of which $\sim 700 \nu_e$'s (for the case of normal mass ordering, positive beam polarity). A near detector is proposed to be constructed a few hundred meters downstream from the proton target, in order to monitor the initial parameters of the P2O neutrino beam, study neutrino interactions with matter, and perform other measurements with the neutrino beam, including sterile neutrino searches.

The sensitivity of P2O to $\delta_{CP}$ could be further enhanced by means of an upgrade of the ORCA detector. Preliminary studies suggest that a 7$^\circ$–12$^\circ$ resolution on $\delta_{CP}$ could be reached using a 10 times denser version of ORCA with a fiducial volume of 4 Mt after 10 years of operation with a 450 kW beam. This is competitive with the projected sensitivity of the future experiments DUNE and T2HK. Thanks to the access to both the first and second oscillation maxima, the best accuracy on $\delta_{CP}$ would be achieved for $\delta_{CP} = 90^\circ$ and $270^\circ$, complementary to DUNE and T2HK which are most accurate for $\delta_{CP} = 0^\circ$ and $180^\circ$.

This letter of interest emphasizes the synergistic potential of the existing accelerator and detector infrastructure: the U-70 proton synchrotron at Protvino and the KM3NeT/ORCA

Figure 14: Resolution on $\delta_{CP}$ as function of the true $\delta_{CP}$ value after 3 and 10 years of operating Super-ORCA with the 450 kW beam.
detector in the Mediterranean Sea. Thanks to the large instrumented volume of ORCA (8 Mt), the beam intensity required for the P2O experiment is relatively small compared to that required for 50 kt scale experiments such as T2K and DUNE. This allows to re-use most of the existing accelerator infrastructure at Protvino. In this regard, the construction of such a neutrino beamline at Protvino appears as a good cost-efficient strategy to maximize the scientific output of the Protvino accelerator complex as well as that of ORCA.

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