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 enable 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. Such an experiment, nicknamed P2O (Protvino-to-ORCA), would yield an unparalleled sensitivity to matter effects in the Earth, allowing to determine the neutrino mass ordering with a high level of certainty due to its baseline of 2595 km after only few years of running time at a modest beam intensity up to 100 kW. A second phase of the experiment, comprizing a further intensity upgrade of the accelerator complex and a significant densification of the ORCA detector would allow for a competitive and complementary measurement of the leptonic CP-violating Dirac phase with a Mton detector but avoiding underground excavation costs. 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 conducted.

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, as well as 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 (the CP-violating Dirac phase in the neutrino mixing matrix) and the relative ordering of the three neutrino mass eigenstates ("mass ordering"). These 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), the NOνA experiment in the USA (810 km baseline), and the DUNE experiment (1300 km baseline), also in the USA. A typical setup 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 δ_{CP}, the mass ordering, and (the octant of) the θ_{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 in the Mediterranean sea as a far detector. The scientific potential of this experiment (Protvino-to-ORCA, P2O) is presented with an emphasis on the sensitivity to CP violation (δ_{CP}) and neutrino mass ordering. We argue that, thanks to the long baseline (2595 km) and huge sensitive volume of the far detector (8 Mt), P2O would be complementary and competitive to other existing and future long-baseline experiments (T2K, T2HK, NOνA 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 Protvino accelerator complex and its potential to run at a higher beam intensity are presented in Section 3. Sections 4 and 5 discuss the neutrino beamline and the near detector, respectively. Sections 6 and 7 present the scientific case for the P2O long-baseline experiment and the proposed short-baseline research program. Section 8 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 [1]. 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 structures (detection units, DUs) (see Fig. 1). With a 9 m vertical step between the DOMs and a 23 m horizontal step between the DUs, the total instrumented water volume will approach 8 megatons. ORCA is optimized for the study of atmospheric neutrino oscillations in the energy

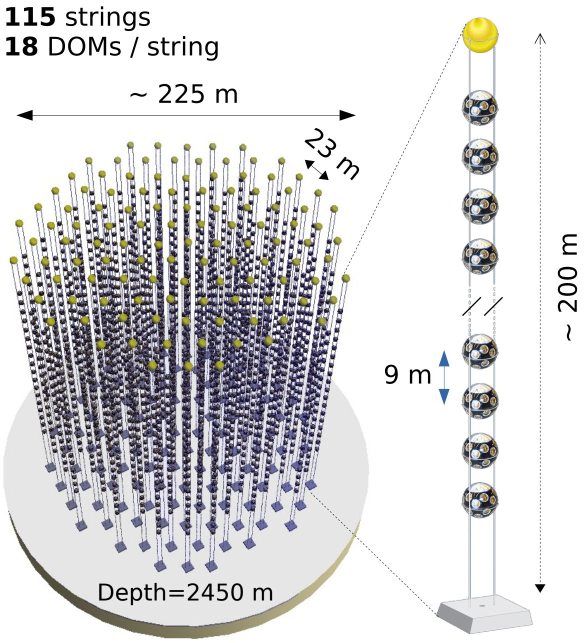

Figure 1: Schematic view of the KM3NeT/ORCA detector

range between 2 GeV and 30 GeV with the primary goal to determine the neutrino mass ordering. The majority of neutrino events observed by ORCA will be due to electron and muon neutrino and antineutrino charge-current (CC) interactions, with tau neutrinos and neutral current (NC) interactions representing minor backgrounds. 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 $\approx 7°$ (at $E_\nu = 5$ GeV). A result with a 3 σ statistical significance on the mass ordering is expected after three years of data taking [1]. ORCA will also provide improved measurements of the atmospheric neutrino oscillation parameters (Δm^2_{23}, θ_{23}) and will probe the unitary of 3-neutrino mixing by measuring the ν_τ 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 yr.

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 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 from 50 GeV to 70 GeV, with a proton intensity of up to 1.5×10^{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

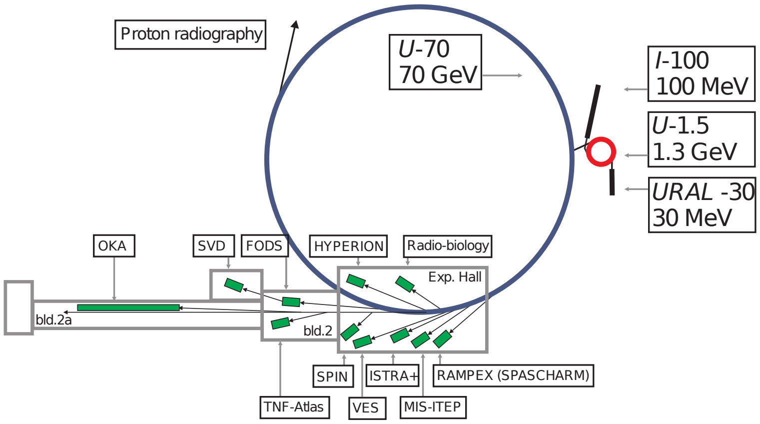

Figure 2: Schematic view of the Protvino accelerator complex.

beam spill. A dedicated neutrino beamline supplied a neutrino beam to the SKAT bubble chamber (1974–1992) [2], the ITEP-IHEP spark chamber spectrometer [3], the IHEP-JINR neutrino detector (1989–1995, upgraded 2002–2006) [4], and other experiments. The results from these experiments include neutrino-nucleon cross section measurements and constraints on the $\nu_\mu \to \nu_e$ 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 currently not 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 makes 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 1990s, a new injection scheme was considered at IHEP, which makes it possible to increase the intensity of the beam to 5×10^{13} protons per cycle [5]. Together with the shortening of the cycle to 7 s, this gives a beam power of 75 kW. 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). Such a beam power is perfectly suited for the ultimate measurement of the neutrino mass ordering at the KM3NeT/ORCA detector. An upgrade up to 450 kW could be made possible by a new chain of injection accelerators [6]. Note that the design of the main U-70 synchrotron potentially allows for operation at a beam power up to $\approx$ 450 kW. Such a beam power would be adequate for an unequalled measurement δ_{CP} aiming at a significantly densified version of the ORCA detector.

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 will need to be aligned towards the ORCA site (see Fig. 3), at an inclination angle of 11.8° (206 mrad) below the horizontal. 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; beam target (graphite); secondary beam focusing system (magnetic horns); decay pipe, where neutrinos are produced from pion and kaon decays; and beam absorber (beam dump). The longest

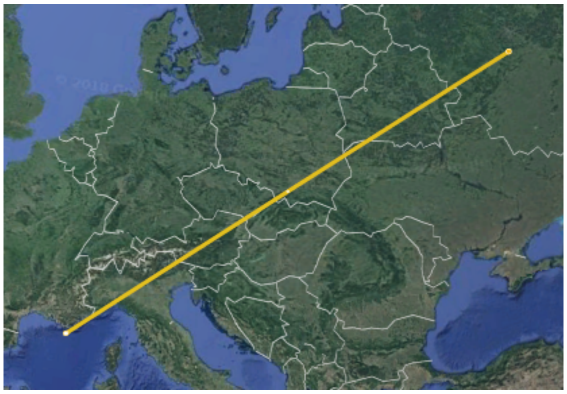

Figure 3: Path to be traveled by the neutrino beam (from top right to bottom left). The deepest point along the beam path is 135 km below sea level (in the upper mantle).

section of the beamline is the decay pipe. In the baseline design, the target hall is located at a depth of ≈ 30 m under ground level, the decay pipe is ≈ 180 m long (subject to optimization), the absorber hall is ≈ 63 m below ground level, and the near detector hall is ≈ 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 modes.

A simulation study of the proposed beamline suggests that a 98% pure muon neutrino beam 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, a 94% pure muon antineutrino beam can be obtained [7]. Compared to the old neutrino beamline previously operated at Protvino, the new beamline design presents the following new challenges: 1) higher beam intensity; 2) beamline to be constructed in an inclined tunnel. These challenges are to be addressed in a dedicated R&D study.

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 ultimate experiment performance and sensitivity. 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 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 in water for ≈ 22 m 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 facilitate the measurement of neutrino flavour conversions and 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 allows for a more refined measurement of the neutrino interaction products, thus enabling more detailed studies

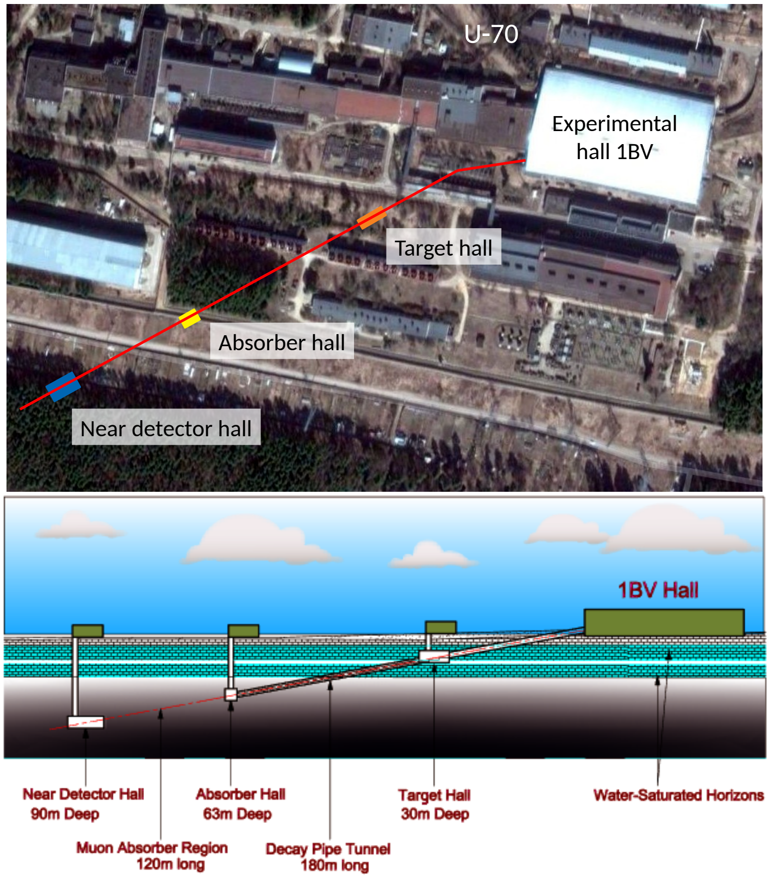

Figure 4: Top view and elevation view of the proposed neutrino beamline (the baseline design).

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 considerations. 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 [8] and NOνA near detector design [9].

2) A large water tank instrumented with PMTs. This is similar to the TITUS and NuPRISM designs proposed for T2K [10]. This design could incorporate KM3NeT DOMs as light sensors, thus closely mimicking conditions of the far detector (ORCA). The use of a liquid water-based scintillator is under consideration as a possible alternative to pure water for both design options.

6 Science with the Neutrino Beam from Protvino to ORCA

Sending a neutrino beam from Protvino to ORCA would provide a baseline of 2595 km, larger than any accelerator neutrino experiment currently operating or planned elsewhere. The first $\nu_\mu \to \nu_e$ oscillation maximum would be at $E_\nu \approx 5$ GeV, within the energy range readily available from the U-70 synchrotron and within the ORCAs 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

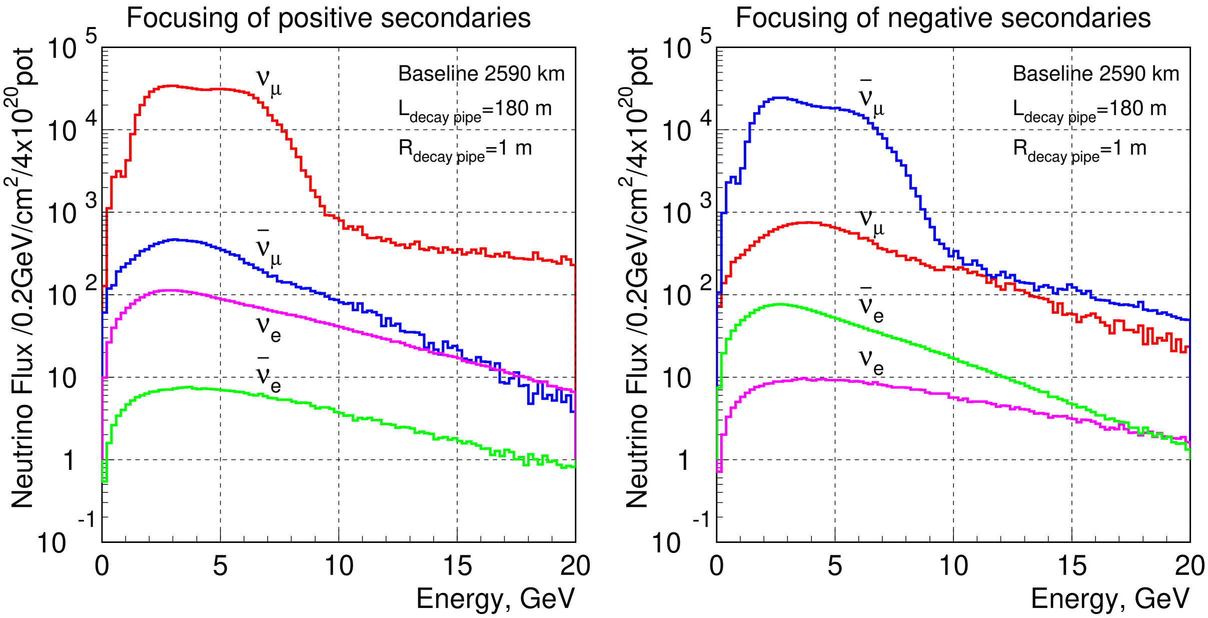

Figure 5: Simulated spectra of the P2O neutrino beam at the ORCA location in neutrino (left panel) and antineutrino (right panel) modes. The absolute normalization is given for 4×10^{20} protons on target (POT), which corresponds to 1 yr of operation at the beam power of 450 kW.

high-precision measurements of neutrino flavor conversions. 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 [11]. The 2595 km baseline is well suited for probing the CP violating Dirac phase δ_{CP}, as well as for measuring the matter resonance effect ($E_{res} = 4$ GeV for the Earth crust) [12, 13]. The effects of the mass ordering and δ_{CP} are most pronounced in the ν_e appearance channel (see Fig. 6). The large instrumented volume of ORCA, 8 million cubic meters, will allow to detect thousands of neutrino events per year, even with a relatively modest accelerator beam power and despite the very long baseline.

6.1 Neutrino mass ordering and early results on CP violation.

A preliminary study of the scientific potential of the P2O experiment [14, 15] suggests that the neutrino mass ordering could be determined with a 5–10 σ statistical significance after five years with a 90 kW beam. (see Fig. 7) based on the striking difference in the ν_e-CC event rate around the first oscillation maximum in the neutrino energy range of 3–6 GeV. This would provide a solid confirmation of the ≈ 3 σ result expected to be obtained in the coming years by ORCA (using atmospheric neutrinos) and NOνA (using accelerator neutrinos).

With an integrated beam intensity of $12 \cdot 10^{20}$ POT, the P2O experiment could also provide an up to 3 σ sensitivity to discover CP violation, assuming a fixed beam polarity chosen to be positive (negative) for the case of normal (inverted) mass ordering. Depending on the true δ_{CP} value, the accuracy on the value of δ_{CP} is then 20°–40°. The sensitivity estimates quoted here were obtained using a preliminary data analysis pipeline developed for atmospheric neutrino studies [1] and do not include any potential analysis improvements made possible thanks to known arrival direction and timing of the neutrino beam. The treatment of systematic uncertainties included a 5% normalization uncertainty for the combined ν_μ and ν_e event rate, a 10% uncertainty for ν_τ, a

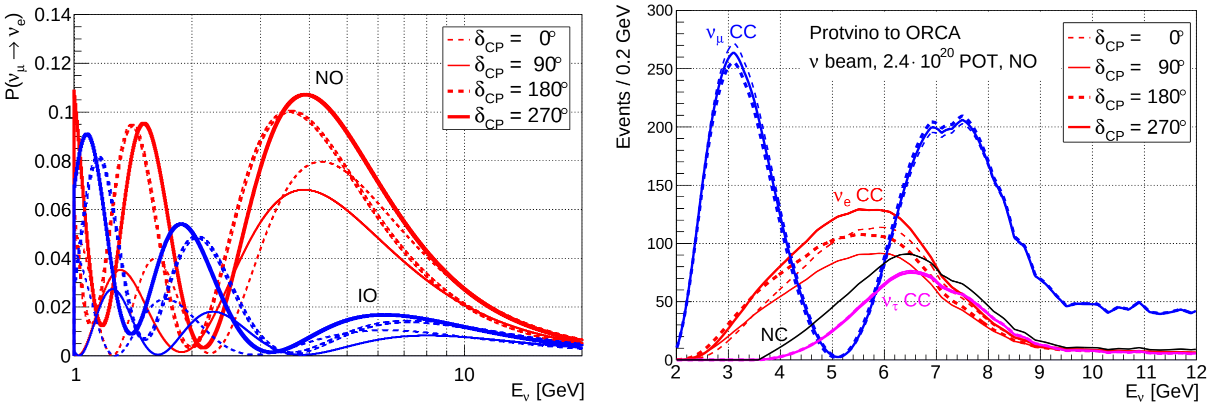

Figure 6: Left : Oscillation probabilities for $\nu_\mu \to \nu_e$ (electron neutrino appearance) for baseline L = 2595 km for normal (red) and inverted (blue) mass ordering. Right : The effect of the CP phase on the expected number of neutrino events that would be detected by ORCA for $2.4 \cdot 10^{20}$ POT. The case of normal neutrino mass ordering with $\theta_{23} = 45°$ has been assumed. The x-axis shows the true neutrino energy.

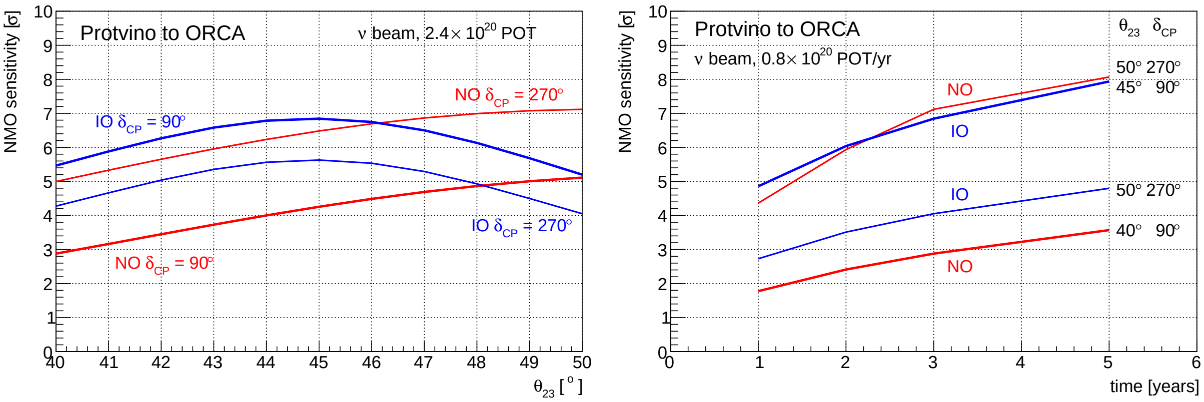

Figure 7: Sensitivity of P2O to neutrino mass ordering. Left: as a function of the θ_{23} mixing angle after 3 yr of running with a 90 kW beam. Right : as a function of the accumulated exposure time with the 90 kW beam. The θ_{23} and δ_{CP} values are chosen so as to show both the most and the least favorable scenarios for both normal and inverted ordering.

5% uncertainty on the NC event rate, and a 10% uncertainty on the neutrino flavour identification performance of ORCA. While this sensitivity on δ_{CP} is encouraging it is not sufficient in comparion with other future projects. An upgrade on the detector side is needed as well.

6.2 Future Beyond ORCA

A more densely-instrumented version of the ORCA detector, called Super-ORCA, could provide a lower energy threshold for neutrino detection, better neutrino flavour identification and better energy resolution compared to ORCA [16]. Such an upgrade could substantially enhance the scientific potential of the P2O experiment, in particular the accuracy of the CP phase measurement. A preliminary projection of the sensitivity of Super-ORCA using the Protvino neutrino beam is shown in Fig. 8. In this figure, a 10 times denser detector geometry compared to ORCA is assumed

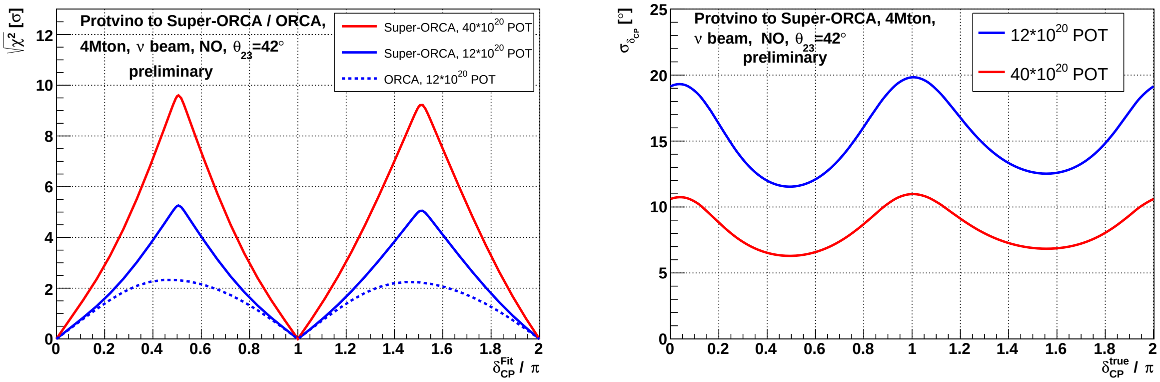

Figure 8: Left: Sensitivities to detect CP violation by operating ORCA 3 years (dashed), Super-ORCA 3 years (solid, blue) and Super-ORCA 10 years (solid-red) in a 450 kW beam from Protvino. Right : Expected 1-σ measurement precision of the CP phase for 3 years (blue) and 10 years (red) data taking with Super-ORCA. (see [16] and [17] for details).

along with a 4 Mt fiducial volume. With such an increased instrumentation density, the energy threshold for neutrino detection is reduced to ~ 0.5 GeV, allowing to reach the second oscillation maximum, which provides an improved δ_{CP} sensitivity. The increased instrumentation density also allows to separate ν_μ/ν_e via the fuzziness of the Cherenkov rings, so that 95%-pure samples of muon-like (dominated by ν_μ CC) and electron-like events (dominated by ν_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 [18]. Consequently, such a configuration can yield a 5(9) σ sensitivity to discover CP violation after 3(10) years of data taking along with a 7°–12° precision on δ_{CP} after 10 years, complementary to other long-baseline experiments. It is noteworthy that the highest precision is achieved for $\delta_{CP} = [90^\circ, 270^\circ]$ complementary to other project which achieve the highest measurement precision for $\delta_{CP} = [0^\circ, 180^\circ]$. This is due to the unique capability of the experiment of measuring both the first and the second oscillation maximum in the ν_e channel but also CP effects in the ν_μ channel in the energy range 2-4 GeV (see Figure 6). Super-ORCA also offers interesting prospects for neutrino oscillation tomography of the Earth and CP violation studies using atmospheric neutrinos [16].

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 on the study of fundamental properties of neutrino is the uncertainty in the knowledge of the cross sections for neutrino and antineutrino interactions with nuclei. 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 of neutrino-nucleon interactions, extracted from the experiments, often contradict each other, strongly depend on the model of interaction 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 other.

High precision measurements with P2O will require an adequate knowledge of the (anti)neutrino cross sections on water. So far, the only experimental result on neutrino cross sections on a water target was obtained with T2K experiment [19] at the mean neutrino energy ~ 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 ~ 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, for which investigation of the nucleon is separated from the nuclear aspect of the problem.

The near detector will also enable searches for sterile neutrinos and other exotic phenomena. In particular, it would allow for an independent test of the so-called LSND anomaly [20] and a similar anomaly reported recently by the MiniBooNE Collaboration [21]. Both of these anomalies have been hypothesized to be caused by $\nu_\mu \to \nu_S$ transitions and can be tested using the U-70 neutrino beam [7]. The beamline configuration considered in this letter will allow to search for sterile neutrinos at comparatively larger Δm^2 values.

8 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. The distance from Protvino to the ORCA neutrino detector in the Mediterranean sea, 2595 km, is ideal for a long-baseline neutrino experiment employing ORCA as far detector. In conjunction with a densification of the ORCA detector such an experiment promises a competitive and complementary sensitivity to the leptonic CP-violating phase δ_{CP} while the neutrino mass ordering could already be measured at an early stage of the project. 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 near detector is proposed to be constructed a few hundred meters downstream 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.

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Addendum

1 Interested Community

The projected is supported by many institutes throughout Europe. Further the following Russian institutions have declared interest:

- A.A. Logunov Institute for High Energy Physics of NRC "Kurchatov Institute", Protvino represented by S. Ivanov (director), A. Zaitsev (deputy director for science), V. I. Garkusha, F. N. Novoskoltsev, R. Sinyukov, A. A. Sokolov
- Particle Physics division of NRC "Kurchatov Institute", Moscow, represented by M. Skorokhvatov (head of division), M. Fayfman, E. Litvinovich and I. A. Sokalski
- A.I. Alikhanov Institute for Theoretical and Experimental Physics of NRC "Kurchatov Institute", Moscow represented by A. Akindinov (head of International Projects Division) and D. Zaborov
- D.V. Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow represented by A. S. Chepurnov and E. V. Shirokov
- Joint Institute for Nuclear Research, Dubna represented by V. A. Naumov and I. D. Kakorin

2 Possible time line

The following timeline depends largely on the availability of funds for the individual steps.

- 2018 Construction start of the ORCA detector (already partly financed)
- 2019-2022 P2O design study
- 2022 Completion of ORCA detector
- 2022-2026 Neutrino beam line construction and accelerator upgrade to 90kW
- 2027-2032 P2O "phase 1" data taking with ORCA
- 2027-2035 accelerator upgrade to 450kW (initially in parallel to running at 90kW)
- 2030-2035 Super-ORCA construction
- 2035 Start data taking of "P2O phase 2" with Super-ORCA

Interested people in alphabetical order

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