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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 ("neutrino mass ordering" - NMO). 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 NMO, 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.

In this note a long-baseline neutrino experiment is proposed 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) comprizes the measurement of the CP violation phase (δ_{CP}) and the NMO. Thanks to the long baseline (2595 km) and the 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.

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). With a 9 m vertical step between the DOMs and a 20 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 range between 2 GeV and 30 GeV with the primary goal to determine the NMO. 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. 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 [1]. 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 NMO is expected after three years of data taking [1]. ORCA will also provide

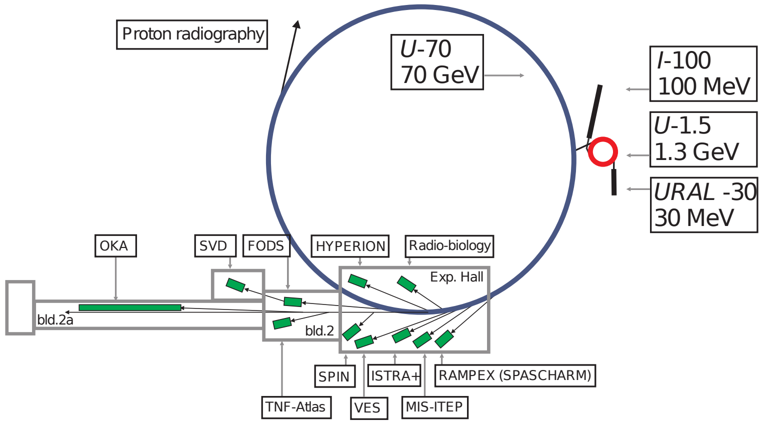

Figure 1: Schematic view of the Protvino accelerator complex.

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. 1) 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 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 NMO 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 ≈ 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, at an inclination angle of 11.8° (206 mrad) below the horizontal. A baseline design of the neutrino beamline, shown in Fig. 2, 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 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 finds 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. In the antineutrino mode, a 94% pure muon antineutrino beam can be obtained [7].

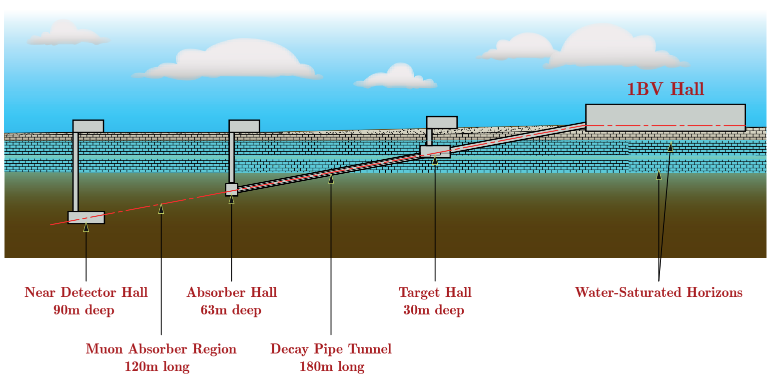

Figure 2: Elevation view of the proposed neutrino beamline (the baseline design).

5 Neutrino mass ordering (NMO)

Sending a neutrino beam from Protvino to ORCA with a baseline of 2595 km yields the first $\nu_\mu \to \nu_e$ oscillation maximum 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, thus facilitating high-precision measurements of neutrino flavor conversions.

The effects of the NMO and δ_{CP} are most pronounced in the ν_e appearance channel. The large instrumented volume of ORCA will allow to detect thousands of neutrino events per year, even with a relatively modest accelerator beam power and despite the very long baseline.

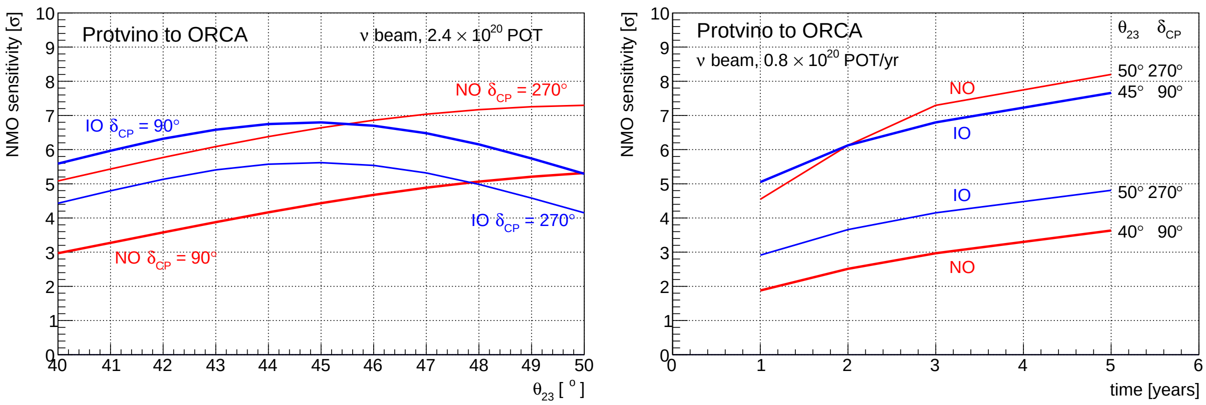

Figure 3: Sensitivity of P2O to the NMO. Left: as a function of the θ_{23} mixing angle after 3 yr of running with a 90 kW beam. Right: as a function of the accumulated exposure time with the 90 kW beam. The θ_{23} and δ_{CP} values are chosen so as to show both the most and the least favorable scenarios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

The NMO would be determined with a 4–8σ statistical significance after one year of running with a 450 kW beam or after five years with a 90 kW beam (using positive beam polarity) [8]. Three years of running with a 90 kW beam would already be sufficient to reach a $\geq$3σ sensitivity, for any value of θ_{23} between 40° and 50° and any value of $\delta_{\rm CP}$ (see Fig. 3 taken from [8]). This would provide a solid confirmation of the $\approx$ 3–5σ result expected to be achieved in the coming years by ORCA using atmospheric neutrinos [1], NOνA [9] using accelerator neutrinos, and JUNO [10] using reactor neutrinos. At the same time, a $\approx 2\sigma$ sensitivity for CP-violation can been reached.

6 Super-ORCA and CP violation

A more densely-instrumented version of the ORCA detector, called Super-ORCA, is under discussion as a possible next step after ORCA. The Super-ORCA detector would provide a lower energy threshold for neutrino detection, better neutrino flavour identification capability and better energy resolution compared to ORCA. Such an upgrade would substantially enhance the scientific potential of the experiment, in particular the accuracy of the CP phase measurement.

For Super-ORCA, a 10 times denser detector geometry compared to ORCA is assumed along with a 4 Mt fiducial volume. This detector geometry has originally been studied for measuring the CP phase using $\sim$ GeV atmospheric neutrinos [11, 12], and has not been optimised for a neutrino beam from Protvino.

The $\delta_{\rm CP}$ measurement with a neutrino beam from Protvino to Super-ORCA profits from running in neutrino as well as in antineutrino beam mode in order to resolve the $\delta_{\rm CP} - \theta_{13} - \theta_{23}$ degeneracy [13]. It is assumed that 50% of the total exposure comes in neutrino beam mode and 50% in antineutrino beam mode. An equal share between neutrino and antineutrino data was found to be close to optimal. A beam power of 450 kW and normal NMO is assumed for all presented $\delta_{\rm CP}$ sensitivity figures.

The sensitivity to discover CP violation is shown in Fig. 4 (left) for 3 and 10 years of operation with an equal share between neutrino and antineutrino beam from Protvino. For comparison,

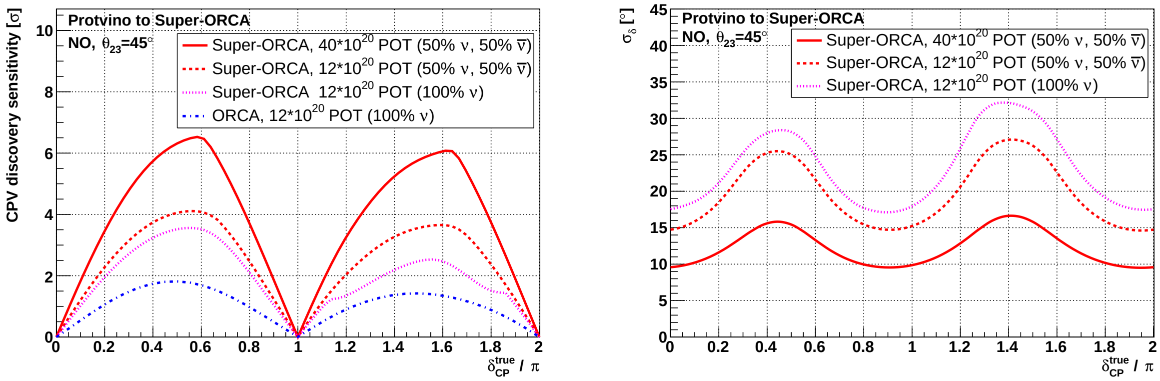

Figure 4: Left: Sensitivity to detect CP violation by operating ORCA 3 years (100% ν beam, shown by dash-dotted line), Super-ORCA 3 years (dotted line for 100% ν beam and dashed line for 50% ν/50% $\bar{\nu}$ beam) and Super-ORCA 10 years (solid line for 50% ν/50% $\bar{\nu}$ beam) in a 450 kW beam from Protvino. Right: Resolution on $\delta_{\rm CP}$ as function of the true $\delta_{\rm CP}$ value for Super-ORCA with the 450 kW beam operating for 3 years with 100% ν beam (dotted line) and 50% ν/50% $\bar{\nu}$ beam (dashed line) and 10 years with 50% ν/50% $\bar{\nu}$ beam (solid line).

also the sensitivity for running only in neutrino mode without antineutrino mode is shown. The expected $\delta_{\rm CP}$ resolution reached after 3 and 10 years of running is shown in Fig. 4 (right). The best measurement precision is achieved for $\delta_{\rm CP} = 0°$ and $\delta_{\rm CP} = 180°$ with a resolution of $\sigma_{\delta_{\rm CP}} \approx 10°$ after 10 years, while for $\delta_{\rm CP} = 90°$ and $\delta_{\rm CP} = 270°$ a resolution of $\sigma_{\delta_{\rm CP}} \approx 16°$ is achieved. The systematics limiting the $\delta_{\rm CP}$ resolution are the uncertainty on θ_{13} (mainly for $\delta_{\rm CP} = 0°$ and $\delta_{\rm CP} = 180°$), the e/μ energy scale skew (mainly for $\delta_{\rm CP} = 90°$ and $\delta_{\rm CP} = 270°$) and the true value of θ_{23} (full $\delta_{\rm CP}$ range). Both figures have been taken from [8].

While the shown measurement precision for $\delta_{\rm CP}$ is competitive to other future long baseline projects and reachable on similar time scales, P2O has the unique possibility to improve these results substantially beyond the shown performance. Contrary to other projects, which aim for multi-MW neutrino sources, P2O will be able to operate at significantly lower beam power thanks to its large detector mass. This opens the possibility to equip the beam pipe with active detector elements to detect and measure each neutrino at its creation ("neutrino tagging") from the related meson decay and to associate it with the neutrino detected in ORCA. This will allow to drastically improve the energy resolution while reducing the related systematic uncertainties. With such a new-generation experiment a radical improvement of the measurement precicion of $\delta_{\rm CP}$ becomes feasible. A detailed study of this option is currently carried out within an approved ANR.

7 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 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. The unique possibility to implement a "neutrino tagging" scheme will further substantially enhance the δ_{CP} measurement precision.

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