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Status of the European Spallation Source neutrino Super Beam

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The measured relatively high value of θ_{13} in 2012 privileges the 2nd neutrino oscillation maximum for the discovery of CP violation in the leptonic sector instead of the usually used 1st oscillation maximum. At the 2nd oscillation maximum the importance of systematic errors is significantly less while the sensitivity to CP violation is about three times higher than for the 1st oscillation maximum. Compared to the 1st oscillation maximum, for the same neutrino energy, the far detector has to be placed in a distance about three times longer than for the 1st oscillation maximum. For this a very intense neutrino beam is necessary. The European Spallation Source under construction, will have a proton linac of 5 MW power and 2 GeV energy. This linac, on top of neutron production, has the potential to also produce the world's most intense neutrino beam with very high potential to discover a neutrino CP violation. Here, the physics performance of this neutrino Super Beam has been evaluated considering a megaton underground Water Cherenkov detector installed at a distance of about 500 km from ESS. The choice of the detector will extent the physics program to proton decay, atmospheric neutrinos and astrophysics studies. The ESS proton linac upgrades, the accumulator ring needed for proton pulse compression, the target station optimization and the physics potential are described. This facility will also produce at the same time a copious number of muons which could be used after by a Neutrino Factory or a muon collider. The ESS neutron facility will be fully ready by 2025 at which moment the upgrades for the neutrino facility could start.

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1. Introduction

Up to now only CP violation in the hadronic sector has been observed. This CP violation is not enough to explain the matter-antimatter asymmetry in the Univers [1]. It is now necessary to investigate onto other sources of CP violation as in the leptonic sector using neutrinos. According to the already measured neutrino oscillation parameters, such a discovery, under some assumptions, could explain the matter-antimatter asymmetry.

The last measured neutrino mixing parameter θ_{13} has been found to be relatively high compared to expectations, showing that "classical" high intensity neutrino beams (Super Beams) were well placed to discover neutrino CP violation at relatively low cost compared to the Neutrino Factory. For the current θ_{13} value the sensitivity to a CP violation observation and measurement of the violating parameter δ_{CP} is enhanced at the second oscillation maximum compared to observations at the first one [2, 3, 4]. Moreover, by placing the far detector at the second oscillation maximum, the experiment is significantly less affected by systematic uncertainties. This is an important point since improvement of the present systematic errors is known to be very hard (see discussion in [5] and given references). It is also known that the final systematic errors will only be known after the future long baseline experiments will start taking data. Operating the facility at the 2nd oscillation maximum decreases the probability to be dominated by irreducible systematic errors and thus increases the discovery potential of the project.

The drawback of placing the far detector at the 2nd oscillation maximum comes from the fact that very high intensity neutrino beams are needed to compensate for the longer baseline. The European Spallation Source (ESS) facility under construction in Lund, Sweden, to produce neutrons, will have a 5 MW, 2 GeV proton linac operated at a rate of 14 Hz (4% duty cycle). This linac could also be used to produce an intense neutrino beam, which, combined with a megaton Water Cherenkov detector placed at a distance of about 500 km, could observe for the first time a CP violation by being operated at the second neutrino oscillation maximum. This project, called ESS neutrino Super Beam (ESSνSB) [6], has been proposed after measuring the last mixing angle θ_{13} and it is under optimisation for an exclusive operation on the 2nd oscillation maximum.

2. The Neutrino Facility

The ESS proton linac will have a duty cycle of 4%, leaving the linac inactive for 96% of its time. While the average proton power is very high (5 MW) compared to existing facilities, it is possible to double the linac frequency of 14 Hz to 28 Hz and thus having one pulse for neutron and one pulse for neutrino production.

To produce a neutrino beam, the ESS proton linac needs some modifications on top of the cooling power upgrades. Due to limitations at the level of the hadron collector of the neutrino facility, the proton bunches have to be compressed from 2.86 ms used for neutron production to few μs for the neutrino beam. This compression can be obtained by adding an accumulation ring after the linac and before the neutrino target station. The presence of an accumulator obliges to use H^- ions instead of protons to avoid space charge effects during the injection in the accumulator.

An evaluation of all required upgrades of the linac can be found in a CERN note [7]. An important message from this note is that no showstoppers have been identified or incompatibilities with the present design of the ESS neutron facility. In this report is also recommended to increase the proton energy from 2 GeV to 2.5 GeV (initial design) in order to reduce space charge effects. This proton energy is now considered as the baseline of the ESSνSB project.

In order to produce the neutrino beam a dedicated target station is needed. This station has to be placed just downstream of the accumulation ring. The adopted design is the one proposed by the EU Design Study EUROν [8] and consists of four targets and magnetic horns, the hadron decay tunnel and the beam dump. The four targets/horns are hit alternatively by the proton pulses. The four target/horn scheme has been adopted in order to mitigate the effect of the 5 MW proton beam.

The EUROν study found that the water Cherenkov far detector MEMPHYS [9] was ideally suited for neutrinos of around 300 MeV as studied in ESSnuSB. Compared to this performance evaluated few years ago, the MEMPHYS detection capability could now be significantly improved for the same cost, by increasing the number of photomultipliers with furthermore higher Quantum Efficiency, profiting from recent developments on this subject [10]. This will significantly improve the electron neutrino detection efficiency and thus increase the physics performance of the facility. Thanks to the large volume of this detector, the project will also have a rich astroparticle physics program and could perform studies on proton decay.

The neutrino beam is directed towards the north of Sweden in the direction of the Garpenberg mine, 540 km away, which could host the far detector. Another alternative is to use the Zinkgruvan mine at 360 km from Lund, which by chance is also located in the same direction as the Garpenberg mine. One option which is now under investigation is to locate half of the MEMPHYS detector in Zinkgruvan mine and the other half in Garpenberg mine in order to increase the performance to discover CP violation but also to measure with high precision the CP violation parameter δ_{CP}. It is also proposed to use a near detector to monitor the unoscillated neutrino beam and thus further reduce the systematic uncertainties.

3. Physics Performance

To evaluate the physics performance of the facility, the target station as defined by EUROν has been adopted. The decay tunnel has been adapted to the ESS proton energy and is of the order of 25 m. Fig. 1 presents the unoscillated neutrino energy distribution which could be obtained by the proposed facility at an arbitrary on-axis distance of 100 km from the neutrino target. This distribution corresponds to one year neutrino run (200 days). An almost pure muon neutrino beam is produced with a main contamination of about 0.5% of electron neutrinos. Studying the $\nu_\mu \to \nu_e$ oscillation, this contribution polluting the primary muon neutrino beam, could be used to measure the electron neutrino cross-section using a perfomand near detector.

Fig. 2 presents the $\nu_\mu \to \nu_e$ oscillation probability at a distance of 540 km for several values of δ_{CP} and for normal and inverted neutrino mass hierarchies. The overlapping grey distribution is the ν_e energy distribution coming from the ν_μ oscillation. It is well seen that the 2nd oscillation maximum is fully covered. From this figure it is also seen that the CP violation discovery potentiality is not affected by the unknown neutrino mass hierarchy. It has to be mentioned that this project is exclusively devoted to CP violation discovery and not to the masse hierarchy determination which is believed to be solved by then by experiments supposed to start taking data during the next decade.

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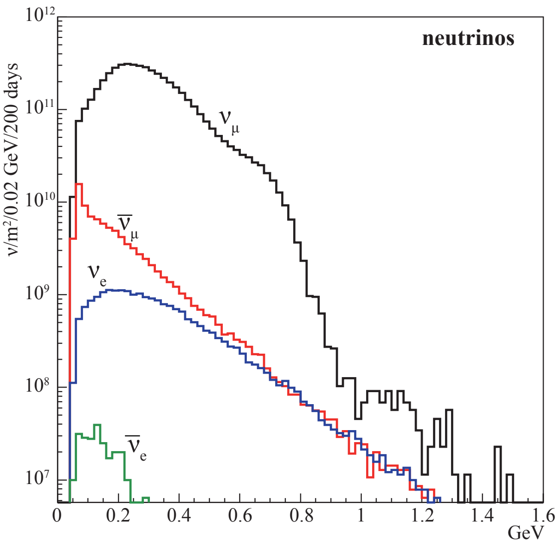

Figure 1: Neutrino energy distribution for neutrino (left) and anti-neutrino (right) runs at an arbitrary distance of 100 km from the target station, for 2.5 GeV protons.

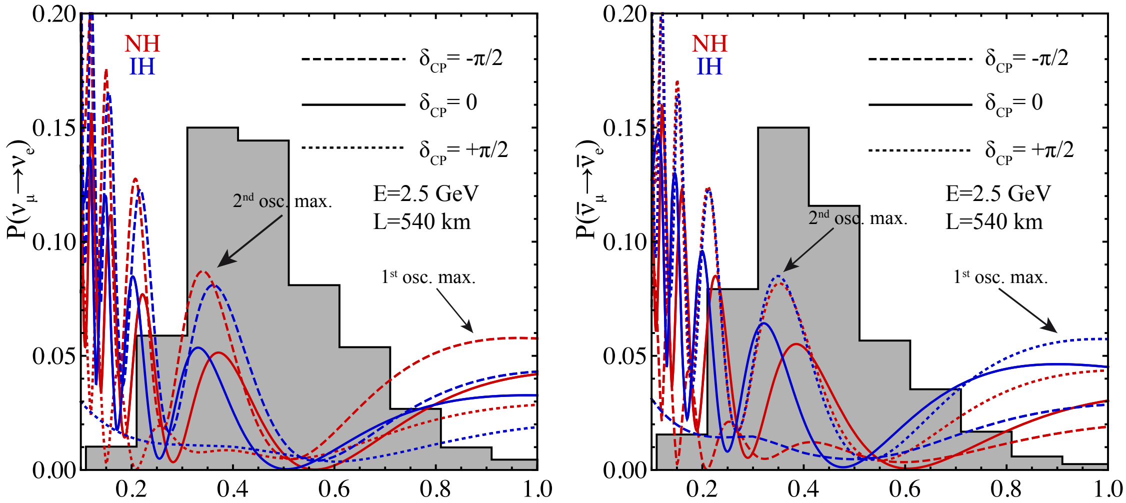

Figure 2: $\nu_\mu \to \nu_e$ oscillation probability as a function of the energy for neutrino (left) and anti-neutrino (right) runs. The red (blue) lines are for normal hierarchy (inverted). The shaded histogram is the energy distribution of ν_e produced by the ν_μ oscillation and detected by the far detector.

The physics performance of all projects strongly depends on the considered systematic uncertainties. As said before, systematic uncertainties play less role on the 2nd oscillation maximum, thanks to the interference term in the oscillation probability dominating the solar and atmospheric terms [3]. For this evaluation the systematic errors reported in publication [11] have been considered, with mainly 5% error on the signal. After 10–years operation, it is expected that about 600 electron neutrinos and antineutrinos will be detected by the far detector. Studies are under way to increase the number of detected neutrinos by further optimising mainly the magnetic horn shape and the far detector performance.

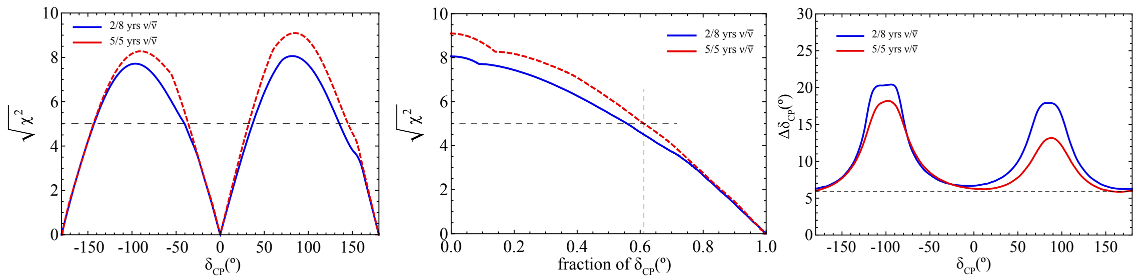

Figure 3: The significance with which CP violation can be discovered as function δ_{CP} (left) and of the fraction of the full δ_{CP} range (middle). The right plot presents the accuracy on δ_{CP} as a function of δ_{CP}.

Fig. 3 shows the CP violation discovery significance versus δ_{CP} (left) and the covered δ_{CP} fraction (middle), the right plot shows $\Delta\delta_{CP}$ versus δ_{CP}. It is seen that for a confidence level corresponding to 5 σ, more than 60% of the δ_{CP} values are covered. The achieved resolution of δ_{CP} near 0° and 180° is of the order of 6°. This example is for a facility running with 5 years in "neutrino" mode and 5 years in "antineutrino" mode. The same performance is also shown for 2/8 years $\nu/\bar{\nu}$. After 10–years of operation the results are still dominated by the statistical errors.

A very high number of muons ($> 10^{21}$/year) with a mean energy of about 0.5 GeV is also produced together with the neutrinos in the decay tunnel of the target station. These muons could be used by a Neutrino Factory or a muon collider in a later stage of the facility.

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