The CERN to Frejus project: from neutrino beams to MEMPHYS

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Abstract. MEMPHYS is a proposed 0.5 Mton Water Cherenkov underground experiment to be located under the Fréjus mountain in the Alps. The project is part of the LAGUNA-LBNO european design study which aims at defining future large multipurpose experiments for grand unification, neutrino astrophysics and longbaseline neutrino oscillation studies. The recent measurement of a large theta13 angle is directly impacting the physics reach of those future projects. Now the priorities can be given to the measurement of the CP violating phase and the mass hierarchy in a large θ_{13} scenario. To address efficiently those issues, the MEMPHYS detector is looking at neutrinos from a Super-Beam or a Beta-Beam produced at CERN, at a distance of 130 km. The physics reach and performances of this detector setup with the various neutrino beam options are summarized in this paper.

Keywords: neutrino physics, neutrino oscillation, water cherenkov detector, Superbeam, Betabeam
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INTRODUCTION

For the last two decades, neutrino physics has been producing major discoveries including neutrino oscillations. The recent measurements of large θ_{13} angle [1] clarify the possible next steps in the exploration of the PMNS neutrino flavour oscillation matrix. It will allow a clear determination of the neutrino mass hierarchy and opens the exciting possibility to measure the CP violation phase. These studies will require accelerator-based intense neutrino beams. Several approaches with various beam and detector technologies are considered in the world through specific design study programs. One of those studies is the CERN to Fréjus project in which a huge water Cherenkov detector called MEMPHYS (MEgaton MAss PHYSics) located in an undergound laboratory under the Fréjus moutain in the Alps is able to study low energy neutrinos from two types of beams (Superbeam and Betabeam) produced at CERN, with a baseline of 130 km. In addition to oscillation physics and the study of neutrino properties the MEMPHYS detector will also address astrophysics with solar, atmospheric and supernova neutrino detections and will be able to push limits on nucleon decay search by more than one order of magnitude if not observed. This paper reviews the part concerning the CERN neutrino beam project and the physics performance of the detector based on the latest beam configurations and improved simulations. The potential of the project with the beams was first investigated in [4]. Several changes occurred (detector geometry, oscillation physics knowledge) which require new studies to be performed.

THE CERN NEUTRINO BEAM OPTIONS

Superbeam

The CERN Super Beam is a low-energy high-intensity conventional muon neutrino beam (Super-Beam) based on a High Power Super Conducting Linac (HP-SPL) providing a proton beam power of 4 MW with an energy of 4.5 GeV at a repetition rate of 50 Hz.

The neutrino produced by the decays of mesons after the magnetic horn collector have an average energy of 300 MeV after optimisation. This energy allows to be on the first maximum of the atmospheric oscillation at 130 km distance providing an excellent reach for leptonic CP violation with a large water Cherenkov detector.

Beams of neutrinos or anti-neutrinos can be obtained by inverting the horn polarity from positive to negative. This defines the two main oscillation channels which will be studied for the CP phase: $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$. Figure 1 shows the energy distributions of the various neutrino (left) and antineutrino species produced in the Superbeam using the design optimised in [2].

The current design for the CERN to Frejus neutrino beam based on the SPL has been studied in the framework of the EUROnu design study,

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[1] on behalf of the MEMPHYS collaboration

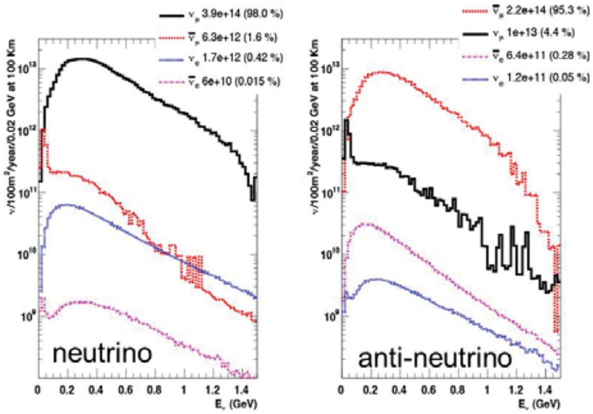

FIGURE 1. Neutrino fluxes obtained with the optimized horn and decay tunnel in positive (left) and negative (right) focusing mode.

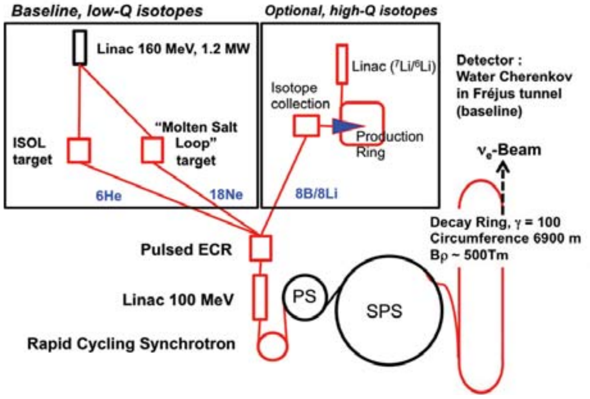

FIGURE 2. Layout of the CERN Beta Beam, where the PS and the SPS are existing machines. The baseline scenario is to use 6He/18Ne (low-Q) with neutrinos to Fréjus

Betabeam

The Betabeam concept has been introduced in 2002 [3]. The idea is to produce collimated pure electron neutrinos and anti-neutrinos by accelerating to high energies radioactive isotopes which subsequently decay in a storage ring. The neutrino energy depends on the Q-value of the beta decay and of the relativistic γ boost of the stored isotopes. The CERN Beta Beam facility is based on CERN infrastructure and machines (PS and SPS) and on existing technologies. Two isotope pairs have been selected and studied for $\overline{\nu}_e \nu_e$ production: one with a low-Q at around 3.3 MeV with ^{6}He and ^{18}Ne and the other one with high-Q at around 13 MeV with ^{8}Li and ^{8}B. The low-Q option with ^{6}He and ^{18}Ne isotopes is well adapted for neutrino energy (300 MeV) and baseline (130 km) required for the CERN-Fréjus Betabeam. The SPS allows a maximum gamma of 150 for ^{6}He or 250 for ^{18}Ne. A relativistic γ of 100 has been chosen for both ions after physics optimisation. The estimations have been done assuming rates of 2.9×10^{18} anti-neutrinos/year from ^{6}He and 1.1×10^{18} neutrinos/year from ^{18}Ne and 5 years run per isotope.

The main parts of the facilities needed for the Betabeam at CERN are shown in Figure 2. The main characteristics of the decay ring are a magnetic field of the main magnet in the ring of 6 T, a circumference of 6900 m and two straight sections with length equals to 2500 m.

The neutrino oscillation appearance channels accessible with the Betabeam are $\nu_e \to \nu_\mu$ and $\overline{\nu}_e \to \overline{\nu}_\mu$. The combination of the Super Beam appearance channels with the Beta-Beam ones allow to perform tests of both CP and T symmetries.

In addition the unoscillated neutrinos of one facility can be used to study well the efficiencies of the other one since the neutrino energy distributions of both machines match well.

THE MEMPHYS DETECTOR

MEMPHYS is a proposed 0.5 Mton Water Cherenkov underground experiment to be located under the Fréjus mountain in the Alps, in the tunnel connecting France to Italy near the existing Modane underground laboratory (LSM) in France. The rock overburden amounts to about 4800 m.w.e. The potential for neutrino physics with specific Super- Beams and Beta-Beams was initially investigated in detail in [4]. The authors assumed the same performance as the Super-Kamiokande (SK) detector [5] in terms of detection efficiency, particle identification capabilities and background rejection. The detector setup was based on 3 cylindrical modules of 65 m in diameter and 60 m in height. However, at the Fréjus site, the quality and the characterictics of the rock allow for a larger excavation in the vertical direction up to 103 m. The new reference design presently envisaged consists of 2 modules of 103 m height and 6 5m diameter. Taking into account a 1.5 m thick veto volume surrounding the main tank and a cut at 2 m from the inner tank wall for the definition of the fiducial volume, as done in Super-Kamiokande to allow for Cherenkov cone development, the total fiducial mass should correspond to 500 kilotons. Each module is equipped with $\sim$120 000 8" or 10" photomultipliers (PMTs) providing 30% optical coverage (equivalent, in terms of number of collected photoelectrons, to the 40% coverage with 20" PMTs of SK). A schematic view of the detector and of a possible layout for installation at the Fréjus site are shown in Figure 3.

The behaviour of a larger scale detector will, however, be different because of the larger distance travelled

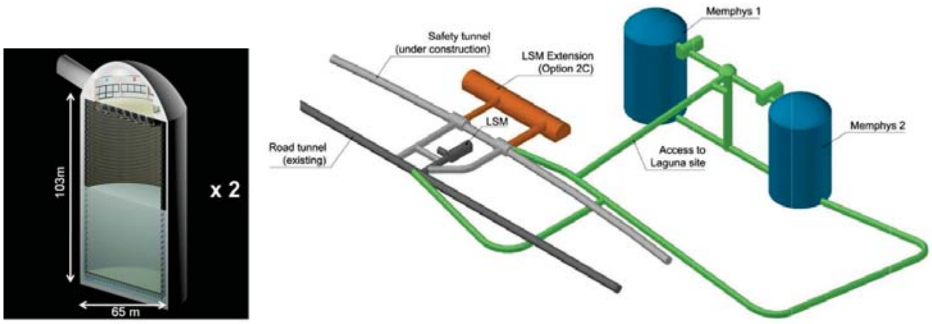

FIGURE 3. Schematic view of one MEMPHYS module (left) and design for installation and infrastructure at a possible extension of the LSM undeground laboratory at the Fréjus site (right, courtesy of Lombardi). Each tank is 65 m in diameter and 103 m in height.

by light to reach the photomultipliers. New studies have been recently done to reestimate the MEMPHYS detector perfomance. They use a full detailed Geant-4 simulation developed from a code originally written for the T2K-2km detector project. It allows a detailed detector description, easy to modify, and implements the new layout with two 65x103 m tanks. The neutrino interactions in water are simulated with GENIE [6].

A complete analysis chain has been built, based on what is done in Super-Kamiokande. Some of the algorithms are a simplified version of the SK ones. Their performance was also evaluated by running the full simulation with the SK parameters (size, PMT coverage etc...) to ensure that no significant degradation of efficiencies and background rejection are introduced by the algorithms. The aim of the procedure is the reconstruction of the incoming neutrino energy and the identification of its flavour to perform appearance or disappearance analyses with the different types of beams. This is only relevant for Charged Current (CC) neutrino interactions. Neutral Current (NC) interactions where a final-state pion can mimic an electron or muon are considered separately. The analysis proceeds through five main steps: reconstruction of the interaction vertex from the timing of the hits in the different PMTs; determination of the outgoing lepton direction from the pattern of the Cherenkov ring; lepton identification (μ vs e), from the "fuzziness" of the Cherenkov ring; rejection of NC interaction with a π^o in the final state from ring counting and reconstruction of the lepton momentum from the charge collected on the PMTs. The incident neutrino energy is then deduced from the measured lepton momentum and direction. Figure 4 shows the reconstructed neutrino momentum for 360 MeV ν_μ and Figure 5 shows the electron momentum resolution as a function of momentum obtained for fully contained (FC) single ring electron produced in ν_e interactions. A detailed description of those different algorithms and results are given in Ref [7].

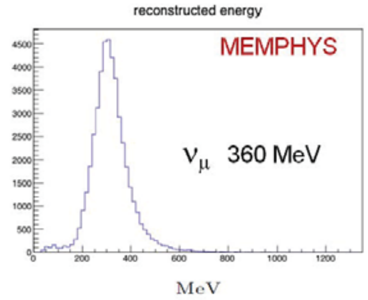

FIGURE 4. Reconstructed energy for 360 MeV muons

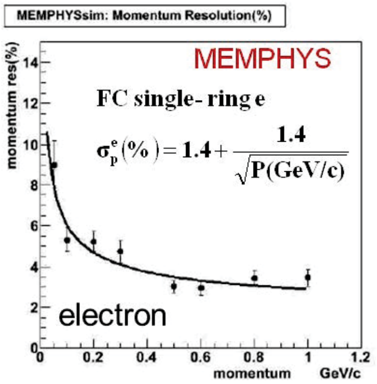

FIGURE 5. Momentum resolution for fully contained single ring electron.

In order to take into account the effects of reconstruction in the efficiency evaluation the correlations between reconstructed and true neutrino energy have to be determined. The corresponding Migration Matrices have been computed for the 6 different detection channels used in the ν_μ and ν_e selections.

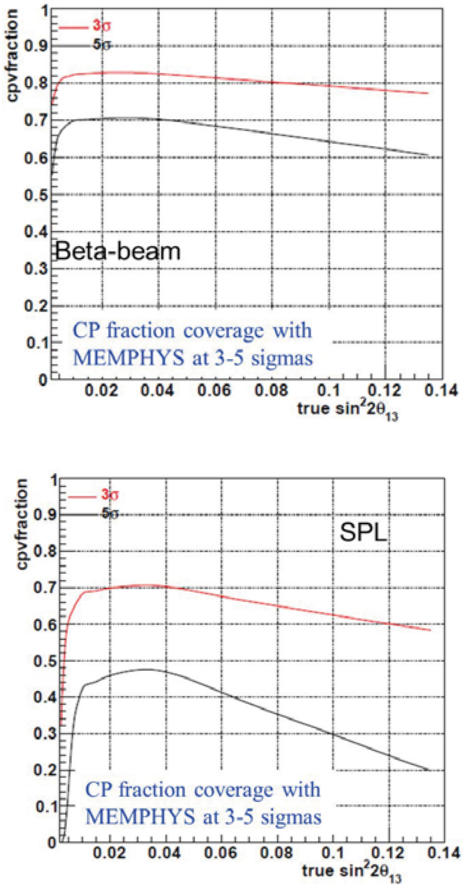

FIGURE 6. 3 and 5σ sensitivity of the MEMPHYS experiment to the CP phase, assuming normal mass hierarchy with the Betabeam (top) and the Superbeam based on SPL (bottom).

PHYSICS PERFORMANCE

Applying those migration matrices on the selected and reconstructed neutrinos in MEMPHYS, the study of the sensitivity to the leptonic CP violation has been done.

However the systematic uncertainty knowledge is essential in the large θ_{13} scenario where they play an important role in the sensitivity assessment. The systematics assumption made in this study are: 2% on the energy scale calibration (cosmics and π^o), an addional 10 MeV is accounted for the Superbeam due to the wide band spectrum; 5% on neutrino flux and residual background applying a far/near detector ratio. For ν_e appearance, a 5% for each background contribution (π^o 1ring, intrinsic ν_e, misid. muon) is taken into account. Figure 6 shows the sensitivity to the leptonic CP violation phase, δCP , using the GLOBES package [8] at 3 and 5σ, as a function of θ_{13} for each beam option. For the Beta-Beam, a running time of 5 years with neutrinos and 5 years with antineutrinos is considered, with a systematic uncertainty of 2% on both signal and background. For the Super-Beam, a running time of 2 years with neutrinos and 8 years with antineutrinos is considered, with a systematic uncertainty of 5% on signal and 10% on background. Normal mass hierarchy is assumed.

CONCLUSIONS

The new value of θ_{13} motivated to reexamine carefully physics performance for the future neutrino beam projects tuned at first atmospheric oscillation maximum. A detailed study of the performance of the MEMPHYS large scale water Cherenkov detector with a Superbeam and a Betabeam from CERN using a full simulation and realistic analysis algorithms has been recently developped. First potential results using new migration matrices confirm previous expectations. The sensitivity to the the CP violation obtained with the Superbeam to Frejus alone reaches 60% of the CP phases at 3σ. When adding the Betabeam, the phase coverage increases to 80%. When adding to these neutrino beam results the potential for detailed neutrino astrophysics and nucleon decay not covered in this paper, the MEMPHYS detector offers an outstanding research program.

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REFERENCES

1. T2K collaboration, K. Abe et al., *Phys. Rev. Lett.* **107** (2011) 041801,
   Double Chooz collaboration, Y. Abe et al., *Phys. Rev. Lett.* **108** (2012) 131801,
   Daya Bay collaboration, F.P. An et al., *Phys. Rev. Lett.* **108** (2012) 171803,
   RENO collaboration,J.K. Ahn et al., *Phys. Rev. Lett.* **108** (2012) 191802.
2. A. Longhin, *Eur. Phys. J.* **C71** (2011) 1745.
3. P. Zuchelli, *Phys. Lett.* **B532** (2002) 166.
4. J.E. Campagne et al., *JHEP* **0704** (2007) 003.
5. Super-Kamiokande Collaboration, S. Fukuda, *Nucl. Instrum. Meth.* **A501** (2003) 418.
6. C. Andreopoulos et al., *Nucl. Instrum. Meth.* **A614** (2010) 87.
7. L. Agostino et al., arXiv:1206.6665v2 [hep-ex] (2012).
8. P. Huber, M. Lindner, and W. Winter, *Comput. Phys. Commun.* **167** (2005) 195.