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To cite this article: Małgorzata Harańczyk 2016 *J. Phys.: Conf. Ser.* **689** 012019

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Simulations of the Long Baseline Neutrino Experiment for the Sieroszowice Underground Laboratory (SUNLAB)

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Abstract. The Sieroszowice Underground Laboratory in Poland, SUNLAB, had been studied in the years 2008-2011 within the framework of the FP7 LAGUNA design study as an option for the realization of a next generation large volume neutrino observatory in Europe. However, in order to fully understand its physics capabilities, the feasibility studies of the SUNLAB laboratory have continued after 2011, including sensitivity calculations focused on the delta CP measurement for a large LArTPC detector at a distance of 950 km from CERN in a long baseline neutrino experiment. For this purpose the neutrino beam based on the SPS proton accelerator at CERN was simulated and the LAr data used to simulate the detector response.

1. Introduction

Neutrino studies have entered a very exciting era. The discovery of neutrino mixing and oscillations over almost the two past decades has provided solid evidence for new physics beyond the Standard Model. Recently, θ_{13} has been determined to be moderately large ($\sin^2 2\theta_{13} = 0.084^{+/-} 0.005$ [1]). This discovery has opened up exciting prospects for current and future long baseline neutrino oscillation experiments towards the answers to the remaining fundamental questions, in particular the type of the neutrino mass hierarchy and the value of CP-violating phase. There is no doubt that a demonstration of CP violation in neutrino oscillations will give an important clue for models of leptonic CP violation and leptogenesis. The combined analysis from the currently running and foreseen for the near future experiments will very probably lead to the determination of the neutrino mass hierarchy. However, the measurement of CP phase is even more challenging and requires higher event statistics, i.e. high intensity neutrino and antineutrino beams and a large, sensitive detector. Several worldwide projects concerning long baseline neutrino experiments aiming at CP violation discovery have been recently discussed. The LBNF project located in the USA with the baseline of 1300 km distance, coupling the Fermilab - neutrino beam with the DUNE - far detector (Liquid Argon TPC) in the Homestake historical mine, is the most advanced one with granted financial support. Other projects, such as Hyper-Kamiokande with a 295 km baseline situated in Japan and the LAGUNA-LBNO project with the longest 2300km baseline from CERN to Pyhasalmi mine in Finland, are being or have been discussed.

The physics-oriented studies of the Sieroszowice Underground Laboratory (SUNLAB) as a long baseline neutrino experiment assume a 950 km long baseline and a neutrino beam from CERN -SPS to



a far detector located in the Polkowice-Sierszowice mine. The chosen technology for the far detector is the Liquid Argon Time Projection Chamber (LAr-TPC), known for its ability to provide excellent tracking and calorimetry performance.

2. Neutrino oscillations

Neutrino oscillation is a quantum mechanical phenomenon in which a neutrino changes its flavour as it travels. This phenomenon takes place if neutrinos have non-degenerate masses and if mixing occurs. For three neutrino flavours, ν_e , ν_μ , ν_τ , and three mass eigenstates, ν_1 , ν_2 , ν_3 , the mixing matrix is defined by six independent parameters. There are two independent mass-squared differences among the three neutrino masses: $\Delta m_{21}^2 = m_2^2 - m_1^2$, responsible for solar neutrino oscillations, and $\Delta m_{31}^2 = m_3^2 - m_1^2$, responsible for atmospheric neutrino oscillations; three mixing angles: θ_{12} - solar mixing angle, θ_{23} - atmospheric mixing angle, θ_{13} - a mixing angle which connects the solar sector with the atmospheric one; and one Dirac-type CP phase δ_{CP} .

The neutrino oscillations are studied in two ways: in the appearance experiments, where the probability that a neutrino of flavour α from the source will arrive at the far detector as a neutrino of flavour β is determined (e.g. $P(\nu_\mu \rightarrow \nu_e)$), or in the disappearance experiments, where the probability of a neutrino surviving with the same flavour is measured (e.g. $P(\nu_\mu \rightarrow \nu_\mu)$). Depending on which oscillation parameter is to be investigated, the oscillation channel should be chosen so as to maximally emphasize the visible measurable effect.

The interesting contribution to the oscillation effect from CP violating part, proportional to $\sin(\delta_{CP})$ and $\sin(\theta_{13})$, can be probed in a neutrino oscillation experiment by measuring the appearance probability of an electron flavour. For the disappearance experiments ($\alpha=\beta$) the imaginary CP-violating term of the transition probability equation becomes zero.

During propagation through matter, the weak interaction couples the neutrinos to matter. The ordinary matter, here the Earth's mantle, consists of electrons, protons and neutrons but it does not contain any muons, tau-leptons or antiparticles, such as positrons. The neutrinos of all three flavours (ν_e , ν_μ and ν_τ) interact with the electrons, protons and neutrons of matter through flavour independent neutral current interaction mediated by Z bosons. Moreover, the electron neutrinos have an additional contribution because of their charged current interactions with the electrons which are mediated by the W^\pm exchange. This matter contribution creates an additional difference between the neutrino and anti-neutrino oscillation probabilities, which is the larger the longer baseline is assumed. As a result, besides the CP asymmetry caused by the CP phase δ_{CP} , we have also a “fake” asymmetry induced by matter, which causes difficulties in extracting the information on δ_{CP} . However, this “fake” asymmetry is related to the yet unknown neutrino mass hierarchy.

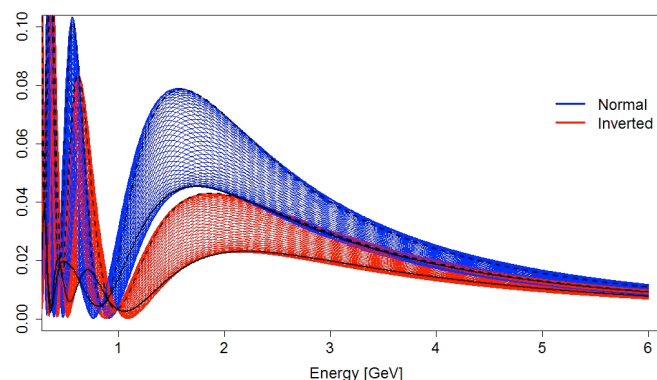


Figure 1 ν_e appearance probability as a function of neutrino energy for 950 km and δ_{CP} ($-\pi, \pi$); Normal mass hierarchy - blue, Inverted mass hierarchy - red.

The sign of Δm_{31}^2 is unknown, hence two patterns of neutrino masses are possible: $m_3 > m_2 > m_1$, called the Normal Hierarchy, where Δm_{31}^2 is positive, and $m_2 > m_1 > m_3$, called the Inverted Hierarchy, where Δm_{31}^2 is negative.

The global fit [2] of all the available neutrino oscillation data in three-flavour analysis gives as the best fit for mass differences: $\Delta m_{21}^2 = 7.5 \times 10^{-5} \text{ eV}^2$ and $|\Delta m_{31}^2| = 2.4 \times 10^{-3} \text{ eV}^2$ with the relative 1σ precision of 2.4% and 2.8%, respectively; for mixing angles: $\sin^2\theta_{12} = 0.3$ (1σ precision is 4%), $\sin^2\theta_{13} = 0.023$ (1σ precision is 10%), $\sin^2\theta_{23} = 0.41$ (1σ precision is 12%); CP phase δ_{CP} is unknown. These values were used in the neutrino oscillation simulations presented below. Figure 1 shows the calculated probability of the electron neutrino appearance after travelling a distance of 950 km through Earth for two mass hierarchies: Normal and Inverted, for δ_{CP} values from the range $(-\pi, \pi)$ - each thin line represents different δ_{CP} value. For a better illustration, the maximal effect from CP phase $\delta_{CP} = \pi/2$ (black solid line) and $\delta_{CP} = -\pi/2$ (black dashed line) is depicted.

3. The SUNLAB laboratory

The idea of SUNLAB was developed in 2007, when seven sites in Europe were considered as candidate hosts of the next generation large volume neutrino observatory within the LAGUNA FP7 design study. The location in the Polkowice-Sieroszowice mine in Poland was discussed among them and the study on excavation of large detector caverns was performed [3]. Independently, a project of a small low background underground laboratory was considered and included in the Polish Roadmap of Research Infrastructures in 2015. The SUNLAB small laboratory will be placed 950 meters below the surface in a salt-rock characterized by an extremely low level of natural radioactivity. The results of the measurements of natural radioactivity in the Sieroszowice salt-rock strata can be found in [4], while more recent measurements performed using the Germanium gamma spectrometers in the underground salt caverns are given in [5].

The Polkowice-Sieroszowice mine belongs to the KGHM Polska Miedź S.A. holding of copper mines (with additions of other metals and salt layers as well) and is located in Kaźmierzów, Polkowice district, Lower Silesia province in south-western Poland. Geologically, it is located in the so called Zechstein formation, a unit of sedimentary rock layers.

4. Neutrino beam simulation

A conventional neutrino beam is produced from a decay of secondary mesons (mainly pions and kaons), which are created by high energy primary protons hitting a thick target. The direction of the neutrino beam is defined by the decay tunnel towards the far detector site. The magnetic horns mounted just behind the target make it possible to choose positively (or negatively for an antineutrino beam) charged mesons of a desired energy and direct them into the decay tunnel. In our simulations, using the Geant4 package [6,7], the SPS at CERN is assumed as the source of 400 GeV protons. It is assumed to deliver 1.5×10^{20} protons on target per year. The graphite target is 1 m long and two magnetic horns are placed in the so called NuMI design (horn and reflector). This kind of a setup can be operated in two modes by switching the direction of the circulating current inside the horns: positive horn focusing (PHF) mode for neutrino beam and negative horn focusing (NHF) mode for antineutrino beam. By changing the size and position of the elements of the beamline setup, one can optimise the expected neutrino flux. In our case, the first oscillation maximum for the 950 km baseline is expected at neutrino energies around 1.95 GeV (Figure 1) and the simulated setup has been optimised accordingly. An example of the optimisation process is shown in Figure 2 for the expected neutrino and antineutrino flux for three target positions. By moving the graphite target inside the horn (downstream - green line) the mesons of lower energy are chosen, and by placing the target more upstream (blue line) we get a wider spectrum and with higher energy neutrinos. In our studies, the most optimal position for the target was found just at the entrance of the horn, in the so called zero position (yellow line).

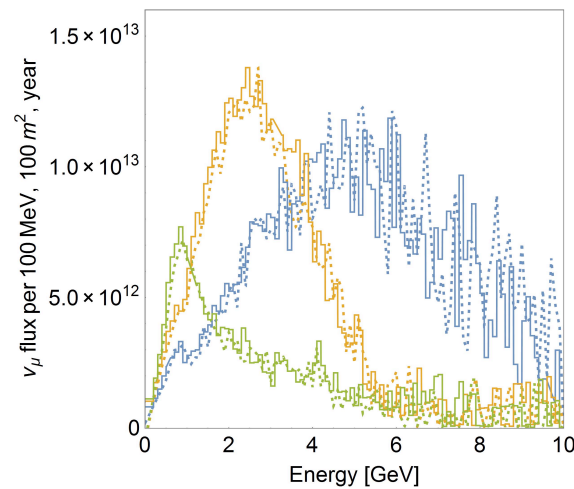


Figure 2 The muon neutrino (solid) and antineutrino (dashed) flux in the case of three different target vs horn positions

The conventional muon neutrino beam from mesons decays contains contaminations by other neutrino flavours. Pions and kaons decay into muons and muon neutrinos, while the muon itself produces a muon antineutrino, electron neutrino and positron while decaying. Also kaons may decay into an electron, electron neutrino and pion. These additional neutrino flavours are the main source of background for the experiments studying the electron-neutrino appearance in the muon neutrino beam. By carefully choosing the length of the decay tunnel one can minimise the number of muon decay processes. In our simulation the length of the decay tunnel is 100 m. The final simulated neutrino flux with all neutrino flavours for both PHF and NHF modes is presented in Figure 3.

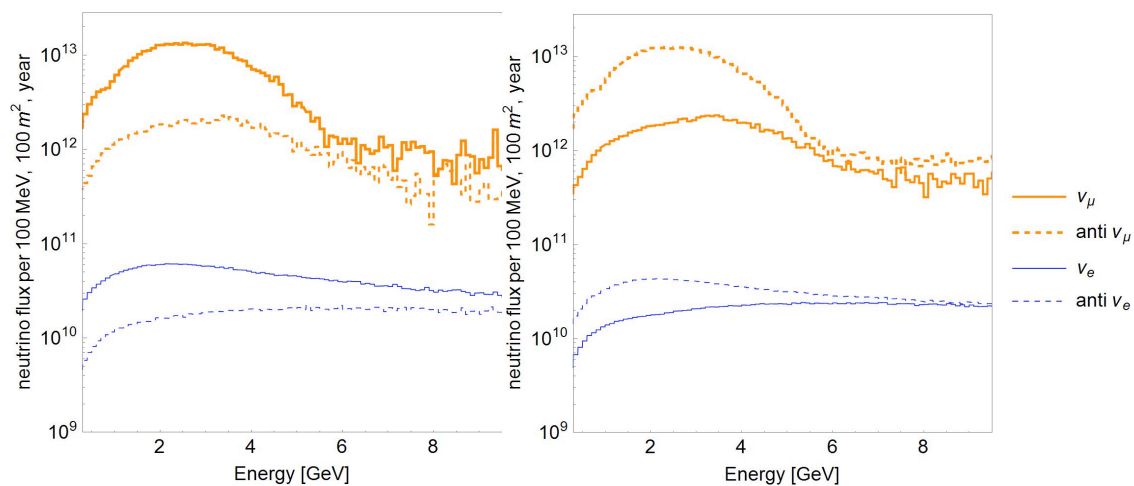


Figure 3 Neutrino beam composition produced at CERN with the SPS used for accelerating protons. The neutrino flux at a distance of 100 km per year. The PHF (left) and NHF (right) modes.

5. Far detector parameterisation

In this study the Liquid Argon Time Projection Chamber is assumed as a far detector located in SUNLAB. LAr TPC can provide excellent imaging with a good energy resolution for large active volumes. This allows us to include in the analysis the events with complicated topology. This technology was successfully tested during the operation of the ICARUS-T600 experiment in Gran Sasso [8] and currently is under vivid development. For this simulation two detector masses are

assumed, the first phase detector - 20 kton of liquid Argon, and the large final phase detector - 100 kton.

The reconstructed neutrino energy threshold is assumed to be 300 MeV. The detection efficiency for charged current electron (ν_e CC) and muon (ν_μ CC) events is 100%. The energy resolution of the detector is expected to be good and here it is assumed to be 15% of \sqrt{E}/GeV for ν_e CC events and 20% of \sqrt{E}/GeV for ν_μ CC. For the ν_e appearance signal the ν_e CC events in the far detector are searched for. The efficiency for the rejection of the background due to neutral current events is assumed to be 99.5%. An additional background source comes from muons wrongly identified as electrons - here less than 0.5%. The last assumed background comes from the intrinsic beam contamination of electron neutrinos - the most difficult to reduce, here assumed at the level of 20%.

6. Sensitivity of CP violation

The neutrino oscillations, expected event rates and sensitivity of the δ_{CP} measurement, assuming the LAr detector at SUNLAB, were calculated using the GLOBES software [9]. The Earth matter effects were included and the oscillation parameters were used as described in Section 2.

Figure 4 depicts the expected signal and background event spectra in the ν_e appearance channel as a function of the reconstructed neutrino energy, including the efficiency and the background rejection capabilities described in Section 5. A large influence of neutral current background events (green dashed line) in the low reconstructed energy region is visible. On the other hand, in the higher energy region the beam contamination by electron neutrinos (red dotted line) is dominant.

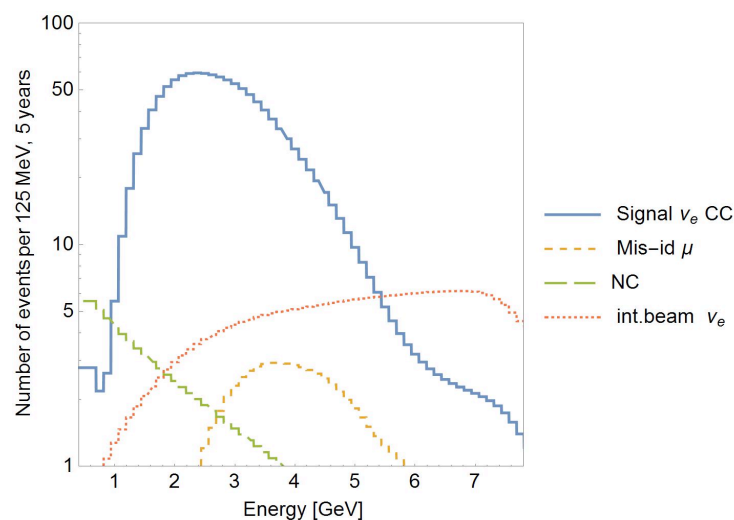


Figure 4 The expected signal (blue line) and background event rates as a function of the reconstructed neutrino energy for appearance channel. PHF mode for 5 years, 100 kton LAr TPC, Normal hierarchy, $\delta_{CP}=0$ assumed.

The expected event rate calculation can be done for all possible δ_{CP} values and mass hierarchy scenarios. Based on this calculation, one can estimate the sensitivity of the CP violation discovery. The CP violation sensitivity is defined here as the ability of the experiment to distinguish between CP violation and CP conservation at an assumed confidence level, where the CP conservation refers to $\delta_{CP}=0$ or π . The sensitivity to the CP violation (non vanishing δ_{CP}) is obtained by testing the hypothesis of the CP conservation evaluating the $\Delta\chi^2$ as a function of the value of δ_{CP} . The evaluated $\Delta\chi^2$ is plotted as a function of δ_{CP} test value assumed as an alternative hypothesis.

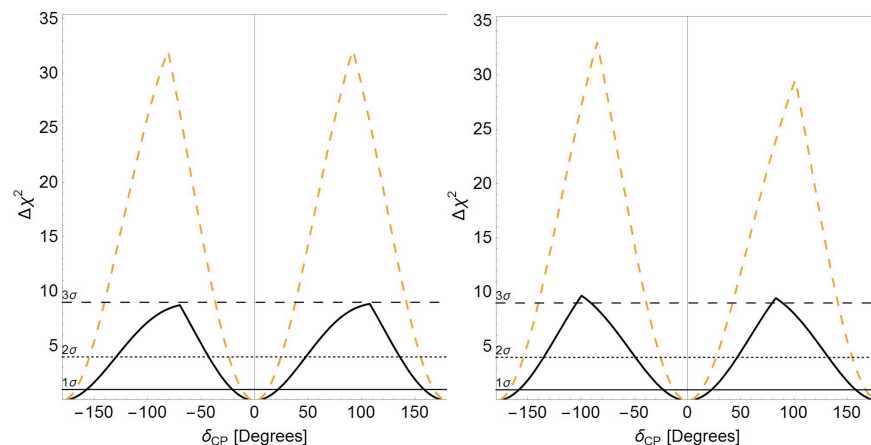


Figure 5 Sensitivity for the non-vanishing CP phase. Normal Hierarchy assumed - left, Inverted Hierarchy assumed - right.

Figure 5 shows the $\Delta\chi^2$ contours, which should be interpreted as the sensitivity to the CP violation. For this calculation the information from both neutrino and antineutrino modes were included and 5 years of data taking for each mode were assumed (10 years in total). The sensitivity was calculated separately for Normal and Inverted neutrino mass hierarchy. The black line shows the first phase scenario with the 20 kton LAr TPC detector, while the dashed orange line represents the final phase large detector of 100 kton. It is clearly visible that the SUNLAB based experiment will be most sensitive in the region of maximal CP violation ($\delta_{CP} = 90$ or -90 degrees) and in this case even the first phase detector can measure the effect on 3σ confidence level after 10 years of running. The smaller the δ_{CP} value, the more difficult the measurement, so a large 100 kton detector or a very long exposure is needed to measure the effect. These results are consistent with other neutrino long baseline projects.

7. Summary

Presented simulations show that the SUNLAB laboratory equipped with a large LAr TPC detector coupled with neutrino and antineutrino beams produced at CERN-SPS could measure the non-zero CP phase reasonably well.

The project of the small underground laboratory in the Polkowice - Sieroszowice mine will be unique in terms of an extremely low background from natural radioactivity.

Acknowledgments

We acknowledge the support from the Polish National Science Centre under the Preludium grant DEC-2011/03/N/ST2/01971.

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