Neutrinos from Stored Muons

K. Long[*]

Imperial College London and STFC

E-mail: K.Long@Imperial.AC.UK

The nuSTORM facility will provide ν_e ($\bar{\nu}_e$) and ν_μ ($\bar{\nu}_\mu$) beams from the decay of low energy muons confined within a storage ring. The instrumentation of the ring, combined with the excellent knowledge of muon decay, will make it possible to determine the neutrino flux at the %-level or better. The neutrino and anti-neutrino event rates are such that the nuSTORM facility, serving a suite of near detectors, will allow measurements of the $\nu_e A$ ($\bar{\nu}_e A$) and $\nu_\mu A$ ($\bar{\nu}_\mu A$) cross sections to be made with the precision required to enhance the sensitivity of the next generation of long-baseline neutrino-oscillation experiments thereby enhancing their discovery potential. By delivering precise cross section measurements with a pure weak probe nuSTORM has the potential to make measurements important to understanding the physics of nuclei. The precise knowledge of the initial neutrino flux also makes it possible to deliver uniquely sensitive light sterile-neutrino searches. The concept for the nuSTORM facility will be presented together with an evaluation of its performance. The status of the planned consideration of nuSTORM at CERN in the context of the Physics Beyond Colliders Study Group will be summarised.

[*]Speaker.

1. Introduction

nuSTORM ("Neutrinos from Stored Muons") is a facility based on a low-energy muon decay ring (see figure 1) [1, 2]. Pions, produced in the bombardment of a target, are captured in a magnetic channel. The magnetic channel is designed to deliver a pion beam with central energy E_π and energy spread $\sim \pm 20\% E_\pi$ to the muon decay ring. The pion beam is injected into the production straight of the decay ring. Roughly half of the pions decay as the beam passes through the production straight. At the end of the straight, the return arc selects a muon beam of central energy $E_\mu < E_\pi$ and energy spread $\sim \pm 10\% E_\mu$ that then circulates. Undecayed pions are directed to a beam dump. A detector placed on the axis of the production straight will receive a bright flash of muon neutrinos from pion decay followed by a series of pulses of muon and electron neutrinos from subsequent turns of the muon beam. Appropriate instrumentation in the decay ring and production straight will be capable of determining the integrated neutrino flux with a precision of $\lesssim 1\%$ [2]. The flavour composition of the neutrino beam from muon decay is known and the neutrino-energy spectrum can be calculated precisely using the Michel parameters and the optics of the muon decay ring. The pion and muon energies (E_π and E_μ) can be optimised to:

- Measure $\nu_e A$ ($\bar{\nu}_e A$) and $\nu_\mu A$ ($\bar{\nu}_\mu A$) interactions with per-cent-level precision; and

- Search for sterile neutrinos with exquisite sensitivity.
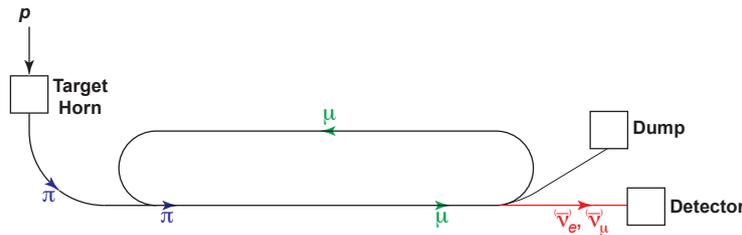
Figure 1: Schematic of the nuSTORM neutrino-beam facility.

2. Neutrino-nucleus scattering

The search for CP-invariance violation (CPiV) in present and planned long-baseline neutrino-oscillation experiments relies on the measurement of the rate of ν_e ($\bar{\nu}_e$) appearance in ν_μ ($\bar{\nu}_\mu$) beams. The phenomenological description of the effect relies on the assumption of three neutrino-mass eigenstates that mix to produce the three neutrino flavours [3, 4, 5, 6]. CPiV arises in this framework if the value of a phase parameter, δ, is such that $\sin\delta \neq 0$.

The oscillation probability is a function of the source-detector distance (the baseline) and the neutrino energy. Typical baselines range from 295 km for T2K [7] and the proposed Hyper-K experiment [8, 9, 10, 11], 800 km for NOνA [12] and 1300 km for the DUNE experiment [13, 14, 15, 16]. Neutrino interactions that occur as the neutrino beam passes through the earth introduce a "matter effect" that causes the oscillation probability of neutrinos to differ from that of anti-neutrinos. This introduces an "apparent" CPiV effect that depends on the neutrino mass hierarchy.

The discovery of CPiV in neutrino oscillations requires that the "true" CPiV that depends on δ be distinguished from the apparent CPiV that arises from neutrino interactions with the earth.

The projected sensitivity to CPiV of the DUNE experiment is plotted as a function of exposure in figure 2 [14]. An exposure of 288 kt MW years will be achieved after seven years of running, with the planned staging to reach a total detector mass of 40 kt and a proton beam-power of 1.2 MW [17]. Equal exposures in neutrino and antineutrino mode have been assumed. The DUNE collaboration presents the sensitivity as a function of the assumed normalisation uncertainties on the ν_e and $\bar{\nu}_e$ appearance signals. Reducing the $\bar{\nu}_e$ normalisation uncertainty from 3% to 1% brings the exposure required to exclude CP invariance at the 3σ confidence level over 75% of all possible values of δ down from ~ 1200 kt MW years to ~ 600 kt MW years.
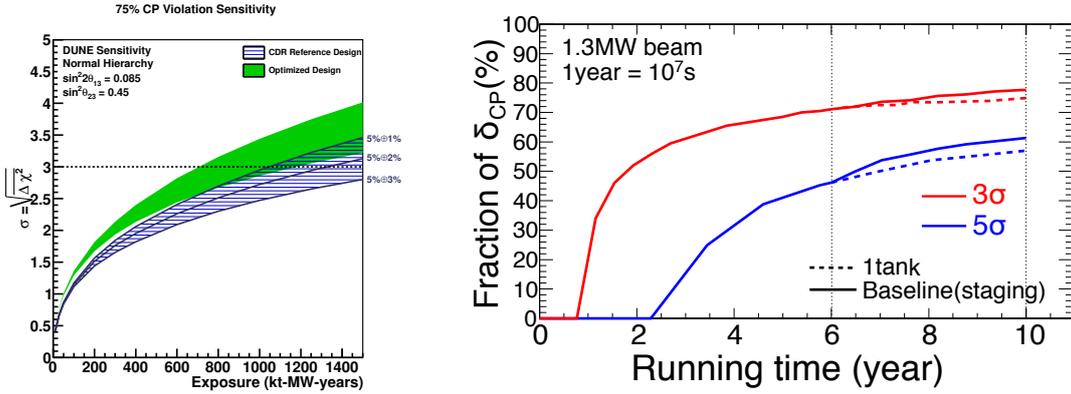
Figure 2: Left panel: Expected sensitivity of the DUNE experiment to CP-invariance violation plotted as a function of exposure in kt·MW·years assuming equal running in neutrino and antineutrino mode, for a range of values for the ν_e and $\bar{\nu}_e$ signal-normalisation uncertainties (from 5% to 1%) added in quadrature to an uncertainty of 5% on the normalisation of the background. The sensitivities shown are for the exclusion of CP-invariance conservation over 75% of the available range of values of δ assuming the normal hierarchy. The two bands represent a range of potential beam designs: the blue hashed band is for the CDR Reference Design and the solid green band is for the optimised design. The figure is taken from [14]. Right panel: fraction of all values of the CPiV phase, δ ($= \delta_{CP}$), for which $\delta = \delta_{CP} = 0, \pi$ can be excluded at 3σ (red) or 5σ (blue) plotted as a function of running time. An exposure of $13\,\text{MW} \times 10^7$ s is expected to be achieved after 10 years of operation. Figure updated from [9].

The projected sensitivity of the Hyper-K experiment, updated from [9], is also shown in figure 2. An exposure of $13\,\text{MW} \times 10^7$ s will be achieved after ten years assuming a 1:3 ratio between neutrino and anti-neutrino running. The planned staged implementation of two 187 kt detectors is indicated, a proton beam-power of 1.3 MW at 30 GeV has been assumed. The systematic uncertainties assumed by the Hyper-K collaboration in their estimation of the CPiV sensitivity of their experiment dominated by the combined "flux and near-detector" and the "cross-section model" uncertainties [9].

In addition to systematic uncertainties, a lack of knowledge of $\nu_{e,\mu}A$ ($\bar{\nu}_{e,\mu}A$) cross sections or inaccuracies in the simulation of the hadronic final state can lead to biases in the parameters extracted from the data. Such biases may arise, for example, from mis-classification of events [18] or mis-reconstruction of the energy of the incident neutrino [19, 20, 21, 22]. A discussion of

possible sources of bias is presented in [23]. When searching for CPiV, any effect that differs in $\nu_e A$ and $\bar{\nu}_e A$ scattering and is not quantitatively understood is particularly pernicious since such a difference may be mis-interpreted as a signal for CPiV.

The next generation of long-baseline neutrino-oscillation experiments, DUNE and Hyper-K have the potential to observe CPiV violation. To maximise the scientific impact of the large, exquisitely-precise data sets that they will collect requires that the ν_e ($\bar{\nu}_e$) and ν_μ ($\bar{\nu}_\mu$) cross sections be known with percent-level precision and that uncertainties associated with cross-section models are also under control at the percent level.

3. nuSTORM and the CERN Physics Beyond Colliders study

A detailed study of nuSTORM that includes consideration of the implementation of the facility at FNAL may be found in [2, 24, 25]. A preliminary investigation of possible options for siting the facility at CERN may be found in [26, 27]. In these studies the facility was optimised for the search for a light sterile neutrino. A short description of the principal considerations that will inform the re-optimisation of the facility for the study of neutrino-nucleus scattering will be given here.

In September 2016 CERN established the Physics Beyond Colliders (PBC) study group to consider ways in which the accelerators at CERN could be used or extended to support a diverse physics programme to complement the energy-frontier physics being pursued using the LHC [28]. The feasibility of implementing nuSTORM at CERN was included as a work package in the PBC study. Within the PBC context, the scientific objectives of nuSTORM are:

- To make detailed and precise measurements of neutrino-nucleus interactions not only as a service to the long- and short-baseline neutrino oscillation programmes but also as a means of studying the nucleus using a weak probe and seeking evidence for non-standard interactions; and

- To take forward the search for light sterile neutrinos should the results of the Short Baseline Neutrino (SBN) programme at FNAL [29] indicate that such a programme is required.

The potential for nuSTORM to establish a new technique for the study of fundamental particles and their interactions is recognised. The PBC study does not include consideration of a possible six-dimensional-cooling experiment (see for example [30]) to follow the demonstration of the reduction of normalised transverse emittance that will be provided by the international Muon Ionization Cooling Experiment (MICE) [31].

The sensitivity of all oscillation experiments depends on the precision of models of the structure of the nucleus and the details of simulations of neutrino scattering. nuSTORM will provide a beam of precisely known flavour for which the flux will be known to 1% or better. Instrumented with a detector capable of making measurements of exclusive final states and of reconstructing Q^2 and W, nuSTORM can deliver the data required for precise models of the nucleus and of neutrino-nucleus scattering to be developed if the neutrino-beam energy spans the range $1 \lesssim E_\nu \lesssim 6$ GeV. These considerations lead to the following specification for the energy of the circulating muon beam:

- Maximum stored muon energy, $E_\mu = 6$ GeV; and

- It must be possible to vary the muon-beam energy in the range $1 \lesssim E_\mu \lesssim 6\,\text{GeV}$.

Since the neutrino-energy spectrum is precisely known once the muon-beam energy is specified, the falling edge of the neutrino-energy spectrum can be used to calibrate the energy response of the neutrino detectors. Further, by combining data taken with different stored-muon energies, as described for NuPRISM in [32], cross sections may be determined in narrow neutrino-energy bands.

The accelerator study will be split into two parts: the re-optimisation of the pion-capture section and the muon-decay ring for the neutrino-scattering programme; and the study of the feasibility of implementing the facility at CERN. The re-optimisation will start from the study of the capture of $\sim 8\,\text{GeV}$ pions and their transport to the decay ring. The design of the decay ring will be revised to accommodate the maximum muon-beam energy of $6\,\text{GeV}$ and to provide the ability to store muon beams with energies in the range $1 \lesssim E_\mu \lesssim 6\,\text{GeV}$. The feasibility study will develop a preliminary proposal for siting the facility at CERN and will take into account the number of protons on target required, the extracted-beam parameters and the number of potential users. Fast extraction from the SPS and proton-beam transport to the pion-production target will be considered alongside initial engineering of the target, horn, target complex and proton-beam absorber. The siting at CERN will be considered to allow preliminary investigations of the civil engineering to be carried out. An important aspect of the feasibility study will be consideration of the radiation-protection issues raised by the target and the pion and muon fluxes.

The potential of the cross-section-measurement programme was evaluted in [2] assuming a neutrino detector with the performance of the HiResMν detector [33]. This analysis showed that nuSTORM has the potential to improve the systematic uncertainty on muon-neutrino (muon-anti-neutrino) CCQE cross section measurements by a factor of $\sim 5 - 6$. The $\nu_e A$ ($\bar{\nu}_e A$) cross-section measurements that can be made with nuSTORM will be unique.

4. Conclusions

The Neutrinos from Stored Muons (nuSTORM) facility is capable of delivering measurements of $\nu_{e,\mu} N$ ($\bar{\nu}_{e,\mu} N$) scattering for which the flux uncertainty can be reduced to 1% or better. Such measurements will reduce the systematic uncertainties and biases in future long-baseline neutrino-oscillation experiments thereby enhancing their sensitivity to leptonic CP-invariance violation and improving the precision of their measurements of the oscillation parameters. The cross-section measurement programme at nuSTORM has the potential to contribute to the understanding of nuclear physics through the use of a pure weak probe that is 100% polarised. Should the results of the FNAL Short Baseline Neutrino Program indicate that future searches for light sterile neutrinos are required, nuSTORM can support an exquisitely sensitive sterile-neutrino search programme.

The implementation of nuSTORM at CERN is being studied within the Physics Beyond Colliders Study Group. The goals of the study are to provide a preliminary proposal for siting the facility at CERN, to re-optimise the facility for the neutrino-scattering programme and to demonstrate through simulation that the normalisation of the neutrino flux can be constrained to $\lesssim 1\%$. The programme described here will establish nuSTORM as an option for CERN in time for the next update of the European Strategy for Particle Physics.

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PoS(EPS-HEP2017)120