PROCEEDINGS OF SCIENCE

Neutrinos from Stored Muons

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The Neutrinos from Stored Muons (nuSTORM) facility will provide $\nu_e/\bar{\nu}_\mu$ ($\bar{\nu}_e/\nu_\mu$) 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 will allow measurements of the $\nu_e(\bar{\nu}_e)N$ and $\nu_\mu(\bar{\nu}_\mu)N$ 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 further the understanding of 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.

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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 $\nu_e(\bar{\nu}_e)N$ and $\nu_\mu(\bar{\nu}_\mu)N$ interactions with per-cent-level precision; and
- Search for sterile neutrinos with exquisite sensitivity.

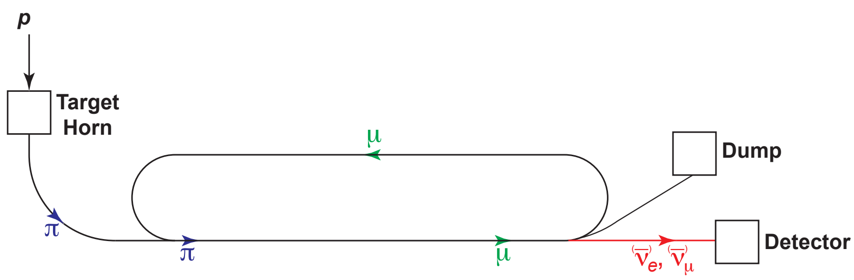

Figure 1: Schematic of the nuSTORM neutrino-beam facility.

A muon beam with an energy of 3.8 GeV, derived from an injected pion beam of energy 5 GeV, was proposed in [2] to search for sterile neutrinos using a magnetised detector placed 1.8 km from the end of the production straight. With 10^{21} protons on target, the proposed configuration was shown to be able to test the LSND and MiniBooNE anomalies with 10σ sensitivity [3]. The case for a neutrino-scattering programme was also made in [2]. This contribution to the DIS'17 workshop presents the case for nuSTORM as a facility at which a definitive neutrino-nucleus-scattering programme can be carried out that will be ground-breaking in precision.

2. Neutrino-nucleus scattering

Impact on searches for leptonic CP-invariance violation

The search for CP-invariance violation (CPiV) in present and planned long-baseline neutrino-oscillation experiments relies on the measurement of the rate of $\nu_e(\bar{\nu}_e)$ appearance in $\nu_\mu(\bar{\nu}_\mu)$ beams.

The phenomenological description of the effect relies on the assumption of three neutrino-mass eigenstates that mix to produce the three neutrino flavours [4, 5, 6, 7]. 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 [8] and the proposed Hyper-K experiment [9, 10, 11], 800 km for NOνA [12] and 1300 km for the DUNE experiment [13, 14, 15, 16]. The "CP asymmetry", $A_{\rm CP}$, given by:

$$A_{\rm CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \, ; \tag{2.1}$$

where $P(\nu_\alpha \rightarrow \nu_\beta)$ is the probability for the transition $\nu_\alpha \rightarrow \nu_\beta$, may be used to study the size the CPiV effect. The matter-induced CP asymmetry grows from $\sim 10\%$ at 295 km to $\sim 40\%$ at 1300 km. The "true" CPiV effect is maximised when $\delta = \pm\frac{\pi}{2}$. For maximal CPiV, the true CP asymmetry is $\sim 38\%$ at 295 km, $\sim 35\%$ at 800 km and $\sim 30\%$ at 1300 km. For a long-baseline experiment to be capable of excluding CP-invariance conservation at the 3σ confidence level for 75% of all possible values of δ requires that the total uncertainty on $A_{\rm CP}$ be $< 5\%$ ($\lesssim 5\%$ for a baseline of 295 km, $\lesssim 4.5\%$ for a baseline of 800 km and $\lesssim 4\%$ for a baseline of 1300 km).

The projected sensitivity to CPiV of the DUNE experiment is shown as a function of exposure [14] in figure 2. 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 detector 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.

The projected sensitivity of the Hyper-K experiment, updated from [9], is also shown in figure 2 [17]. 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 is dominated by the combined "flux and near-detector" and the "cross-section model" uncertainties.

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 $\nu_e(\bar{\nu}_e)$ and $\nu_\mu(\bar{\nu}_\mu)$ cross sections are known with percent-level precision and that systematic uncertainties, and possibly biases, associated with the cross-section models are also under control at the percent level.

Potential for impact on understanding of the structure of the nucleus

Theoretical understanding of the structure of the nucleon is detailed and precise and can be used to predict cross sections for a wide variety of processes over a wide kinematic range. However, a number of measurements, such as the spin structure of the nucleon, challenge the present understanding [18]. The theoretical description of the structure of the nucleus is similarly accurate yet requires development, for example to describe correlations among the nucleons that make up the nucleus [19]. Phenomenological models of lepton-nucleus scattering are based on the present

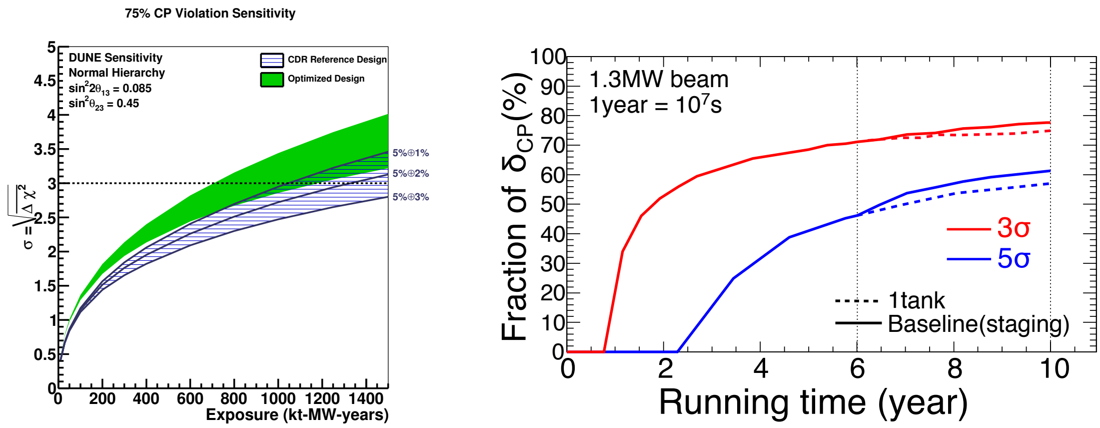

Figure 2: Left panel: Expected sensitivity of the DUNE experiment to CP-invariance violation plotted as a function of exposure in kt·MW·year assuming equal running in neutrino and antineutrino mode, for a range of values for the ν_e and $\bar{\nu}_e$ signal-normalisation uncertainties (from 5% to 1%) 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, for which $\delta = 0, \pi$ can be excluded at 3σ (red) or 5σ (blue) plotted as a function of running time. An exposure of $13\,\mathrm{MW} \times 10^7$ s is expected to be achieved after 10 years of operation. Figure updated from [9].

understanding of nuclear physics and exploit a wealth of data to determine a number of phenomenological parameters. Such models have been shown to give a good description of some of the present neutrino-nucleus scattering data but may fail when used to extrapolate beyond the range of energies, nuclei, or types of process on which they have been "tuned" [20]. A review of the challenges that must be overcome to deliver a good description of the hadronic final states is presented in [21].

A vibrant experimental programme is underway to extend and improve the scattering database on which the theoretical and phenomenological description of the nucleus relies. The neutrino offers a probe that is 100% polarised and is sensitive to flavour and isospin. It is conceivable that neutrino-nucleus scattering has a role to play in unravelling issues such as the orbital contribution to the spin of the nucleon and the nature of nucleon-nucleon correlations. A facility that is able to deliver a precisely calibration flux is required if neutrino-nucleus scattering measurements are to contribute to the development of the present understanding of nuclear structure.

3. nuSTORM and the CERN Physics Beyond Colliders study

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 [22]. 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:

- 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 [23] indicate that such a programme is required.

The potential for nuSTORM to be a means to establish a new technique for the study of fundamental particles and their interactions is recognised.

To evaluate the total cross section it is broken down into phenomenologically-convenient components. Deep inelastic scattering (DIS) dominates for neutrino energies $\gtrsim 6-8$ GeV (DIS overtakes resonance production at around ~ 6 GeV for νN scattering while for $\bar{\nu} N$ scattering it overtakes at ~ 8 GeV). Below ~ 1 GeV, the charged-current quasi-elastic (CCQE) process dominates. The resonance-production process makes a significant contribution in the range $1 \lesssim E_\nu \lesssim 6-8$ GeV. The partition between the various classes (DIS, resonance production and CCQE) is determined by fitting phenomenological model parameters to the available data. Uncertainties in the resulting contributions to the total cross section contribute to the uncertainties and biases discussed in section 2. Precise measurements of $\nu_{e,\mu}(\bar{\nu}_{e,\mu})N$ scattering are required to refine the models and to determine with provision their relative contribution. nuSTORM must provide the capability to measure $\nu_{e,\mu}(\bar{\nu}_{e,\mu})N$ scattering over 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 $1 \lesssim E_\mu \lesssim 6$ 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 [24], 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 ~ 8 GeV pions and their transport to the decay ring. The optimisation of the injection into the decay ring for the higher pion-beam energy will be considered. The design of the decay ring will be revised to accommodate the maximum muon-beam energy of 6 GeV and to provide the ability to store muon beams with energies in the range $1 \lesssim E_\mu \lesssim 6$ GeV. The feasibility study will develop a "credible" 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 on 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.

PoS(DIS2017)089

The study of nuSTORM within the PBC Study Group will not include the neutrino detectors. Rather, examples of detectors that are under development to serve as near detectors for DUNE or Hyper-K will be considered as options. A physics study group has been set up to work in parallel with the accelerator study. The aim is that a publication describing the neutrino-scattering physics will be brought forward in the summer of 2018. The PBC study group mandate is to produce a final report by the end of 2018 [25].

4. Conclusions

Muon accelerators have the potential to serve as uniquely precise sources of electron and muon neutrino beams and to provide a route to multi-TeV lepton-anti-lepton collisions. The Neutrinos from Stored Muons (nuSTORM) facility is capable of delivering measurements of $\nu_{e,\mu}(\bar{\nu}_{e,\mu})N$ 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.

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 “credible” 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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