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nuSTORM physics reach: cross sections and exotics

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The intense beam of muon and electron neutrinos with precisely known energy distributions provided by the stored-muon facility (nuSTORM) shall allow for a rich physics program with considerable impact in our understanding of fundamental properties of neutrinos and their interactions. The physics case for such a facility is presented, with emphasis on neutrino cross section measurements and the search for exotic processes in scattering and short-baseline flavor transitions.

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In a nutshell, the concept of a nuSTORM facility consists of using the decays of muons stored in a ring to produce a precisely understood neutrino beam with energy distribution and flavor composition set by muon decay ($\mu^+ \to e^+\,\nu_e\,\bar{\nu}_\mu$ or $\mu^- \to e^-\,\bar{\nu}_e\,\nu_\mu$) and a normalization that can be determined with less than a 1% uncertainty [1]. The feasibility of implementing nuSTORM at CERN has been studied as part of the CERN Physics Beyond Colliders study [2]. The SPS would provide the primary beam of pions directed towards a decay ring capable of storing muon beams with a central momentum from 1 GeV$/c$ to 6 GeV$/c$. Such a beam, complemented with the corresponding detector complex will allow to perform a physics program focused on (i) precise (few-percent level) and detailed neutrino cross section measurements, including exotic, beyond standard model (BSM) reaction mechanisms and (ii) short-baseline flavor transitions and sterile neutrino searches.

A nuSTORM facility would allow to perform unprecedentedly precise studies of both elementary processes and neutrino-nucleus scattering. These prospects are not only interesting by themselves as a source of information about the axial structure of nucleons and nuclei, but also crucial to achieve the high-precision goals of neutrino oscillation experiments [3, 4]. Indeed, near detectors help reducing systematic uncertainties but do not turn oscillation analysis to a mere rescaling because near and far detectors are not identical, have different efficiencies and are illuminated by different neutrino fluxes. In addition, oscillation probabilities depend on the neutrino energy which is not known on an event-by-event basis but has to be reconstructed. To minimize any bias in neutrino-energy reconstruction a realistic simulation of the interaction process is necessary.

Elementary processes. In this context, by elementary processes one understands neutrino-nucleon interactions, whose relevance is often underestimated. The available information about them is scarce and comes mostly from old bubble chamber experiments. These cross sections could be measured directly using hydrogen or deuterium targets or indirectly with the help of hydrogen-enriched target and subtraction techniques. Examples of these are the *solid hydrogen* concept [5], where the (anti)neutrino proton interactions are obtained from the subtraction of events in plastic (CH_2) and graphite (C) targets and a high pressure TPC with hydrogen-rich gases (like CH_4), where the cross section on hydrogen would be extracted using transverse kinematic imbalance [6]. nuSTORM is the ideal place for such an experiment because of the precision that can be achieved. The input for event generators would be highly valuable. Furthermore, the availability of both muon and electron flavors of neutrinos under similar experimental conditions would allow to investigate flavor-dependent features such as radiactive corrections and non-standard (BSM) interactions.

The simplest one among the elementary processes is charged-current quasielastic scattering ($\nu_l\, n \to l^-\, p$ and $\bar{\nu}_l\, p \to l^+\, n$. Even for such a basic process which could serve as a *standard candle* to constrain neutrino fluxes, the dependence of the axial form factor (F_A) on the four-momentum transferred to the nucleon squared (Q^2) is not precisely measured. Moreover, it has been recently noticed that lattice-QCD determinations of $F_A(Q^2)$ are in fairly good agreement among themselves but tension with the empirical determinations [7]. These lattice-QCD results would imply a 20% increase of the quasielastic cross section.

Neutrinos also scatter inelastically on nucleons, predominantly leading to single pion (πN) but also to γN, $\pi\pi N$, ηN, ρN, KN, $\pi\Sigma$, $\bar{K}N$, KY, ... final states. For inelastic processes, the cross section arises from the interplay of resonant and non-resonant amplitudes, which becomes highly non-trivial at higher invariant masses of the hadronic final state, with several overlapping resonances and coupled channels. This is the shallow inelastic scattering region, where a large fraction of events at DUNE will be found. This dynamics has been investigated in detail in partial wave analyses of large data sets available for photon, electron and pion-nucleon interactions. This information is valuable to constrain weak inelastic processes and has been used in their modeling. However, the properties of the axial current at finite Q^2 remain experimentally unconstrained. The transition from the resonant to the deep-inelastic scattering regime is also highly uncertain. Quark-hadron duality on one hand and QCD (high-twist and target mass) corrections on the other are valuable tools to describe it (see Ref. [8] for a recent review), but progress in their development is hindered by the lack of experimental nuclear-effect-free information from elementary targets. With muon momenta in the range $1 \leq p_\mu \leq 6$ GeV$/c$, the resulting neutrino spectrum goes up to ~ 4 GeV (see Fig. 11 of Ref. [2]) and would make the detailed study of this region possible.

Neutrino-nucleus interactions. There is a considerable interest in the study of neutrino scattering on the heavy targets used in oscillation experiments. In this scenario, nuSTORM can have a high impact by characterizing the flavor differences which are particularly important at low energy and momentum transfers (in the Laboratory frame). These differences can arise from a subtle interplay between lepton kinematic factors and response functions. The search for CP-invariance violation in present and planned long-baseline neutrino-oscillation experiments is based on the measurement of the rate of ν_e appearance in ν_μ beams. nuSTORM has the potential to perform high-statistics measurements of the ν_e cross section and, in particular, the $\sigma(\nu_e)/\sigma(\nu_\mu)$ ratio, which is among the largest systematic uncertainties at DUNE. With the help of nuSTORM, the required sensitivity to CP violation can be reached with a smaller exposure.

Measurements of quasielastic-like scattering at nuSTORM can also lead to a better description of initial state nucleon-nucleon correlations and meson-exchange currents, which are known to provide a sizable contribution to the semi-inclusive electron scattering cross section and have been found important at MiniBooNE and T2K: comparisons of different theoretical results to data can be found, for example, in Figs. 8 and 9 of Ref. [9] (MiniBooNE) and in Figs. 7-9 of Ref. [10] (T2K). The comparisons of the SUSA model to these data have been recently summarized in Ref. [11]. Discrepancies with theory (or, at least with its generator implementation) have been found at the higher energy and momentum transfers probed at MINERvA and NOvA as can be appreciated in Refs. [12, 13]. nuSTORM can play an important role in understanding these differences.

The characterization of nuclear corrections to parton distribution functions will also benefit form precise measurements of the inclusive neutrino-nucleus cross section, to unravel the differences in nuclear effects observed in weak and electromagnetic process and resolve the tensions that have been observed by nCTEQ. It was indeed found that νA and $l^\pm A$ data could only be reconciled if the correlations in νA were not taken into account (see Sec. 5.6 of Ref. [8] and references therein).

With a suitable detector set, nuSTORM can also study exclusive channels in neutrino-nucleus scattering. These include one and two-nucleon knockout but also single and multiple meson production. These reactions are largely influenced by strong final state interactions between the produced particles and the nuclear environment. Pions, in particular, can scatter, change charge or be absorbed in their way out of the nucleus [14]. Accurate modeling of these interactions are crucial to reduce biases in calorimetric neutrino energy determination.

Exotic processes. If the precision of the nuSTORM concept is combined with high statistics, the study of *rare* processes with small cross sections becomes feasible. To this category one can ascribe neutrino-electron scattering, coherent meson production, weak and electromagnetic production of single photons and dileptons. Like elementary quasilastic scattering, neutrino-electron scattering or even coherent meson production could be precisely measured and used as *standard candles* for flux determination in other experiments. Furthermore, weak couplings and $\sin^2\theta_W$ can be extracted, providing a precision test of the SM. Unlike DUNE, nuSTORM has access to both $\nu_\mu-$ and $\nu_\mu-$electron scattering.

While these exotic processes are allowed in the SM, precision measurements can disclose BSM physics. This is the case of neutrino tridents in which neutrino scattering off the Coulomb field of a heavy nucleus generates a pair of charged leptons. The existence of light Z' or other particles in the dark sector can modify the trident cross section [15].

Single photon emission in neutral current interactions is another rare process that has received attention as a background in ν_e appearance measurements in Cherenkov detectors. Its cross section has never been measured and, so far, only upper limits from NOMAD, T2K and, more recently, MicroBooNE are available. Besides, some of the proposed explanations of the MiniBooNE anomaly involve the production of a heavy (1-100 MeV) neutrino via electromagnetic (γ mediator), weak (Z) or BSM (Z') interactions, leading to a signal in the single photon or e^+e^- channels (see Ref. [16] for a recent review). While recent MicroBooNE results disfavor some explanations of the MiniBooNE anomaly, the full range of possible solutions is still unexplored [17].

Short-baseline flavor transitions and sterile neutrino searches. The basic idea is to use the $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ decay to search for ν_μ appearance from $\nu_e \to \nu_\mu$ and $\bar{\nu}_\mu$ disappearance from $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations [2]. The former requires a good charge identification to detect the μ^- in a large μ^+ background. The later relies on measuring a spectral distortion of the μ^+ spectrum in the detector; this requires accurate momentum measurement. The experiment can therefore address open questions about the non-unitarity of neutrino mixing matrix, non-standard interactions, Lorentz invariance (and CPT violation) and provide the definitive test for light sterile neutrinos [2, 18].

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