European Spallation Source: a future for Coherent Neutrino Nucleus Scattering

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The European Spallation Source (ESS), currently finishing its construction, will soon provide the most intense neutron beams for multi-disciplinary science. At the same time, it will also produce a high-intensity neutrino flux with an energy suitable for precision measurements of Coherent Elastic Neutrino-Nucleus Scattering. We describe some physics prospects, within and beyond the Standard Model, of employing innovative detector technologies to take the most out of this large flux. We show that, compared to current measurements, the ESS will provide a much more precise understanding of neutrino and nuclear properties.

1 Introduction

In the Standard Model (SM), neutrinos only interact through the weak interactions. This makes their properties sensitive to tentative Beyond the Standard Model (BSM) effects with sub-weak strength. At the same time, they are a very clean probe to explore weak-interaction properties of different systems. Further pursuing this research program requires precision measurements of neutrino-matter interactions.

In the SM, such interactions can take place between neutrinos and atomic nuclei through the weak neutral current, by exchanging a Z boson. Interestingly, if the momentum transfer $q$ remains smaller than the inverse nuclear size (which, for medium-sized nuclei, requires $|q| \lesssim 50$ MeV), the process can take place coherently with the whole nucleus. This dramatically enhances the interaction cross-section, that in the fully coherent regime is proportional to the square of the number of neutrons in the target nuclei.

Despite the large cross-sections that would open the way for large-statistics measurements of neutrino interactions, Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) is very challenging to detect. The main reason is that the only observable final state is a recoiling nucleus with a kinetic energy in the few keV to sub-keV range. Indeed, CEνNS was only detected in 2017 by the COHERENT collaboration $^1$, more than 40 years after its first theoretical description $^2$. This first detection, however, has opened up many research prospects, both within and beyond the SM $^{3,4,5,6}$. As present results are mostly limited by statistical uncertainties, high-statistics CEνNS measurements would undoubtedly broaden these prospects.
Figure 1 – Neutron production from existing and planned spallation sources, compared to the ESS. The COHERENT experiment is placed at the Oak Ridge Spallation Neutron Source, labelled as SNS in the figure.

Figure 2 – Expected integrated CEνNS rate above nuclear recoil threshold, 20 m away from the ESS target, for different detectors. The vertical lines show the thresholds considered in Ref. 7, and for illustration we also show in blue the threshold of the COHERENT CsI detector. See Ref. 7 for more details.

2 CEνNS at the European Spallation Source

There are two main strategies that would allow for high-statistics CEνNS measurements. On the one hand, using a more intense low-energy neutrino flux would increase the number of events while keeping the interaction coherent. A unique opportunity in this direction is brought by the European Spallation Source (ESS), whose user programme begins in 2023. It is a neutron spallation source, that produces a well-understood neutrino flux through pion decay at rest. This same operating principle generates the neutrinos used at COHERENT, but at the ESS the neutrino flux should be larger by about one order of magnitude7 (see Fig. 1).

On the other hand, the CEνNS cross-section strongly increases for small nuclear recoil energies. Thus, employing state of the art, low-threshold detectors would also enhance the statistical power of CEνNS measurements. This is illustrated in Fig. 2, that shows the expected number of events at the ESS as a function of the detector energy threshold for different materials. As the ESS is still under construction, suitable space can be allocated for such detectors7.

3 Physics prospects

As an example of the physics reach of the strategies discussed above, we consider two scenarios characteristic of BSM and SM physics that can be probed with CEνNS: non-standard neutrino interactions (NSI) and neutron radii of nuclei. Further scenarios are explored in Refs. 7,8.

From a model-independent approach, a useful parametrization of BSM effects is through the addition of higher-dimensional operators to the SM Lagrangian. At dimension 6, the allowed
set of operators includes four-fermion operators affecting neutrino production, propagation and detection. They include the so-called neutral current vector NSI

\[ 2\sqrt{2}G_F\varepsilon_{\alpha\beta}(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta)(f\gamma^\mu f), \]

where \( G_F \) is the Fermi constant, \( \alpha \) and \( \beta \) are neutrino flavors, \( f \) is a SM fermion, and \( P_L \) is a left-handed projection operator. These operators are very challenging to constrain, due to the uncertainties in computing high-energy neutrino-nucleus interactions and the experimental difficulties in measuring neutral current cross sections precisely. Furthermore, they can significantly impact the interpretation of neutrino oscillation data \cite{9,10,11}.

These same operators, however, also affect CE\( \nu \)NS. Thus, this process can provide competitive constraints on NSI, completely independently from neutrino oscillation bounds. Figure 3 shows the 90% confidence level bounds that could be obtained after 3 years of data taking at the ESS with different detector materials. These would significantly tighten present constraints.

An example of physics within the SM that can be probed with CE\( \nu \)NS is the neutron radius of nuclei, a quantity for which almost no model-independent measurements exist. CE\( \nu \)NS is a process that takes place essentially with the neutrons in the target nucleus, and it is therefore sensitive to their distribution inside it. This is precious information to complement proton densities accessible with elastic electron scattering, and its understanding impacts the limits of existence \cite{12} and size \cite{13} of atomic nuclei, as well as being an important test of first-principles nuclear calculations \cite{14}. Beyond the structure of nuclei, neutron distributions can be linked to the properties of neutron-rich matter, which determines the size and structure of neutron stars \cite{15,16}.

Figure 4 shows the sensitivity that the ESS can achieve on the neutron radius of various nuclei, compared to the present COHERENT sensitivity and to different theoretical nuclear physics model predictions. As the results show, high-statistics measurements at the ESS would have an experimental sensitivity of the order of the spread among the theoretical models.

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Figure 4 – Present determination and future sensitivity of the neutron skin thickness from CEνNS experiments for different nuclei. See Ref. 17 for more details.

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