COHERENT LOI 4: Inelastic Neutrino-Nucleus Interaction Measurements with COHERENT

COHERENT Collaboration

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NF Topical Groups:

☐ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
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Abstract: We describe here the current and future capabilities for measurement of inelastic neutrino-nucleus cross-sections in the neutrino energy regime up to ∼50 MeV by several detectors in COHERENT's suite. These measurements have relevance for supernova neutrino physics, nuclear physics and beyond-the-standard-model searches.

1 Introduction

Although the primary goal of COHERENT [1–4] is the measurement of coherent elastic neutrino-nucleus scattering (CEvNS) [1, 2], for which the experimental signature is very low-energy nuclear recoils (few to tens of keVnr), COHERENT's detectors are also capable of measuring inelastic charged-current (CC) and neutral-current (NC) interactions of neutrinos with nuclei. Although the interaction cross sections for these processes lack the N^2 enhancement associated with CEvNS and therefore tend to be at least one order of magnitude smaller than for CEvNS processes, the observable final-state particles of these interactions have typical energies on the same order as the neutrino energies. Therefore inelastic interactions occupy a different, and typically easier-to-access, experimental regime.

For the Spallation Neutron Source (SNS) stopped-pion flux, CC interactions of ν_e on nuclei result in an electron with energy approximately equal to $E_\nu - Q$, where E_ν is the neutrino energy and Q is the Q value of the interaction. The interactions may also result in final-nuclear-state deexcitation products (gamma rays or ejected nucleons). NC interactions of all the available neutrino flavor components (ν_e, ν_μ, $\bar{\nu}_\mu$) may also result in observable nuclear deexcitation products.

Neutrino-nucleus cross sections in this $\mathcal{O}(10)$-MeV regime are quite poorly understood. There are very few existing measurements, and none at better than the 10% uncertainty level [5]. With the exception of cross sections on simple targets, such as neutrino-electron elastic scattering and inverse beta decay of $\bar{\nu}_e$ on free protons, theoretical understanding of these processes is also relatively poor, due to strong dependence of the interaction rates on the specific initial- and final-state nuclear wavefunctions. Uncertainties can be up to a factor of a few, on both total cross sections and on differential cross sections describing distributions of observable interaction products.

The $\mathcal{O}(10)$-MeV neutrino energy regime is of direct relevance for supernova neutrino detection, as well as processes in a supernova involving neutrinos. The burst of neutrinos from a core-collapse supernova includes neutrinos of all flavors, with average energies of about 10-15 MeV and ranging up to several tens of MeV. Other neutrino sources of astrophysical interest in this regime include solar neutrinos, the diffuse supernova neutrino flux, and the low-energy end of the atmospheric neutrino flux. The low-energy atmospheric flux is of relevance for the CEvNS "neutrino floor" for direct dark-matter detection. To interpret experiments probing these neutrino fluxes, understanding of the neutrino-nucleus cross sections is required. Such understanding is also required for better understanding of supernova explosion processes, including nucleosynthesis of heavy elements in supernovae and merger events.

Measurement of neutrino-nucleus cross sections is also of intrinsic interest for their insight into the weak couplings themselves. For example, there is potentially information about nuclear axial structure to be gained using interactions of neutrinos on nuclei with non-zero spin.

The well-understood stopped-pion neutrino spectrum provided by the SNS is a near-ideal neutrino source for improved measurements of neutrino-nucleus cross sections in this energy regime. Several of COHERENT's current and planned future targets will have sufficient mass to enable statistically meaningful measurements.

2 Inelastic Neutrino Interactions on Argon

The detection of the burst of $\mathcal{O}(10)$-MeV neutrinos from a nearby core-collapse supernova is one of the primary goals of the Deep Underground Neutrino Experiment (DUNE) [6]. A wealth of physics and astrophysics will be learned from this burst [7, 8]. Solar neutrinos, which range up to about 15 MeV, are another interesting possibility in DUNE [9]. The primary interaction observed is expected to be ${}^{40}\mathrm{Ar}(\nu_e, e^-){}^{40}\mathrm{K}$, which will give DUNE unique sensitivity to the *electron neutrino* flavor component of the supernova burst.

However, the physics to be learned from a DUNE supernova burst detection will be limited by the lack of knowledge of the interaction cross section. The cross-section calculations vary by at least tens of percent. A measurement of the cross section and distribution of interaction products will be critical for eventual interpretation of DUNE's low-energy physics.

The tonne-scale liquid argon (LAr) detector is expected to see ∼340 ν_eCC events per year, as well as ∼100 inelastic NC events. Another major unknown is the contribution of NC interactions to the supernova burst yield in DUNE. An inclusive measurement in COHERENT's tonne-scale LAr detector could be made to ∼5% percent precision in three years.

3 Inelastic Neutrino Interactions on ^{127}I

Originally envisioned as a means of astrophysical neutrino detection [10], interest in the $^{127}\text{I}(\nu_e, e^-)^{127}\text{Xe}^*$ reaction has motivated cross-section calculations [11, 12] as well as measurements of the Gamow-Teller strength [13]. There is one previous measurement of the cross section $^{127}\text{I}(\nu_e, e^-)^{127}\text{Xe}$ to bound states of ^{127}Xe [14] at the 30% level. Improved measurement of the reaction will serve as a benchmark for calculations and as a probe for g_A-quenching effects. The issue of g_A quenching is a matter of critical importance for future neutrinoless double-beta decay experiments (e.g., [15]). In particular, recent nuclear models predict a dependence of g_A quenching on momentum transfer (e.g., [16]) that could be tested with a stopped-pion neutrino source. COHERENT will make an improved measurement of the energy-dependent, inclusive, ^{127}I CC ν_e cross section. COHERENT's currently-deployed 185-kg NaIVE detector will make the first measurement, and the soon-to-be-deployed 3.3-tonne detector will provide much greater statistics.

4 Inelastic Neutrino Interactions on ^{16}O

A supernova burst will also create charged- and neutral-current interactions in water detectors like Super-K and Hyper-K [17–21]. While in these detectors the dominant supernova neutrino channel is inverse beta decay, resulting in a primary sensitivity to $\bar{\nu}_e$, water offers subdominant interaction channels on ^{16}O. The CC channel, $\nu_e + ^{16}\text{O} \rightarrow e^- + ^{16}\text{F}^{(*)}$, has a threshold of 15.4 MeV. These interaction cross sections have never been measured in this energy range. About 120 events per SNS year per tonne of water are expected. COHERENT's planned heavy-water flux-normalization detector will have sufficient energy resolution to disentangle the contributions from the CC interactions on the deuteron given the significant differences in the electron recoil distributions. Furthermore, some inelastic NC neutrino-induced excitations of oxygen are expected [20], although the deexcitations will produce relatively small amounts of visible Cherenkov light in the water.

5 Neutrino-Induced Neutron Interactions (NINs)

Neutrino-induced neutrons (NINs) result from interactions of neutrinos in lead, iron, or other shielding materials that emit neutrons from the final-state nucleus. Such neutrons are relevant especially for supernova neutrino detection. COHERENT will perform measurements of the CC and NC cross sections Pb(ν_e,n) and Fe(ν_e,n) which result in NINs. The measurement of this cross section on lead has implications for supernova neutrino detection in the ongoing HALO supernova neutrino detection experiment [22, 23]. The spallation of neutrons from heavy elements is also expected to influence the nucleosynthesis of heavy elements in supernovae [24, 25]. The NIN inelastic signal is also a background for CEvNS, which is another motivation for measurement of these cross sections. COHERENT has two detectors deployed for the measurement of NINs; these are the so-called "neutrino cubes" or "nubes," one making use of lead and another using iron.

6 Summary

COHERENT's current and future plans include inelastic CC and NC neutrino-nucleus measurements on several targets. However, there are other future possibilities, including deployments at the SNS Second Target Station [26]. Improved measurements can be accomplished with larger detectors and improved detector technologies for more fine-grained final-state particle measurements.

7 References

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