Experimental Status of Coherent Neutrino Scattering and the NUCLEUS Experiment

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Abstract

Neutrino nucleus coherent elastic scattering is a process involving the neutral current scattering of a neutrino with an entire nucleus. We introduce the experimental discovery of this process next to a neutron spallation facility and describe the prospect for detecting low-energy neutrinos with the NUCLEUS cyogenic experiment that will be deployed at the Chooz nuclear power station in France.

1 Introduction

Low energy neutrino detection (of less than 50 MeV) usually requires large detectors if the source is not in very close proximity. However, the Standard Model of Particle Physics predicts that a particular interaction of neutrinos with atomic nuclei, called coherent elastic scattering (CENS), occurs with a relatively high probability, and could be used to significantly reduce the size of neutrino detectors. This reduction in detector size is possible because the probability of neutrinos interacting via this process is increased by a factor that varies as the number of neutrons in the target nuclei squared, which is considerable in the case of a high atomic number target such as tungsten, for instance. The probability of interaction can thus exceed by more than two orders of magnitude that of standard neutrino detection methods, such as inverse beta decay (IBD), which is by far the most widely used method for measuring reactor neutrinos to date. However, despite the increased probability of interaction, the experimental signature, i.e. nuclear recoil, is at the same time attenuated in proportion to the mass of the target nucleus. This ambivalence imposes strict optimizations of the detection systems, and call for the usage of cryogenic detectors for detecting reactor neutrinos.

In 2017, the COHERENT collaboration [1] made the first observation of coherent neutrino scattering using a sodium-doped cesium-iodine scintillator exposed to neutrinos from a spallation neutron facility at the U.S. National Laboratory in Oak Ridge. This is a significant breakthrough in fundamental physics since the coherent elastic scattering of neutrinos has been undetected for four decades! This delay was due to the difficulty of detecting the low energy (below keV) nuclear recoil produced as a unique result of the interaction while reducing background noise.

Since the first experimental detection of coherent scattering in 2017, fundamental research in this field has become more popular internationally. Indeed, this new detection channel may allow major advances in the understanding of neutrinos, and has the potential to discover new physics beyond the standard model. The scientific community involved is therefore growing and a wide range of experimental projects using various techniques is being developed.

2 Coherent Neutrino Scattering on Nuclei (CEvNS)

CEvNS is a neutral current interaction, so all neutrino flavors will participate with the same cross section. Since its original proposal in 1974 [2], the Coherent Neutrino Scattering on Nuclei (CEvNS) has attracted increasing attention in the field of particle physics.

The coherence condition is generally met for neutrinos with an energy below 100 MeV. In this energy range, coherent neutrino scattering on neutrino nuclei has a large effective cross-section on neutron-rich targets compared to other common detection channels such as inverse beta decay (IBD) and electron scattering of neutrinos. After the interaction, it is not possible to see the neutrino, but it is possible to detect the small nucleus recoil. Considering neutrinos from spallation neutron facility the relevant recoils are in the sub-keV range. But for reactor neutrinos these recoils drop to the few tens of electron-volt.

The physical implications are vast. This technique could allow to study non-standard neutrino interactions, to search for sterile neutrinos, to constrain the nucleon structure, and to better understand the ultimate backgrounds of direct dark matter experiments (called the <eutrino floor).

3 Experimental Discovery in 2017

In 2017, using 15 months of data collection time, the COHERENT experiment [1] observed for the first time the process of coherent elastic scattering of neutrinos at a confidence level of 6.7σ using a 14.6 kg CsI scintillator doped with sodium and exposed to neutrinos from a spallation neutron facility located at the U.S. National Laboratory in Oak Ridge.

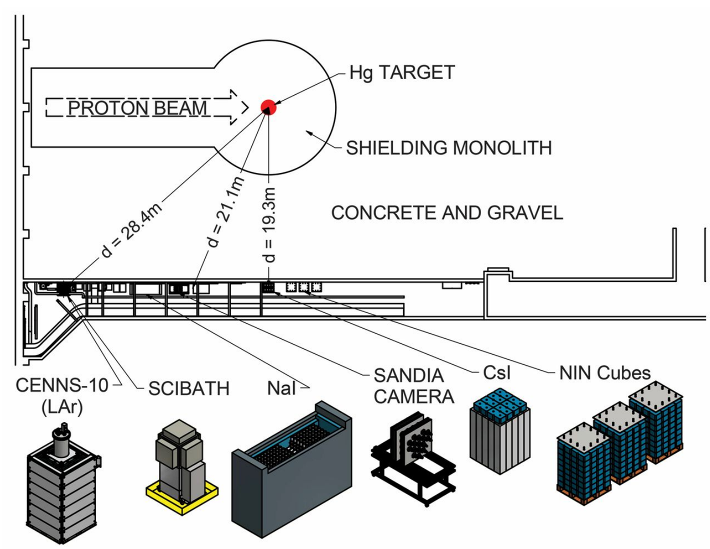

Figure 1: Detectors from the COHERENT experiment located at the Oak Ridge spallation source (US). The experimental sites, located in a basement corridor, benefit from a shielding of more than 19 m against neutrons associated to the beam, and a modest overburden of 8 m thick concrete to reduce cosmic ray induced backgrounds (adapted from [1]).

The COHERENT experiment is set up in a basement corridor benefiting from more than 19 m of shielding against neutrons associated to the proton beam and a modest vertical overburden of 8 meter water equivalent, capable of reducing the background noise induced by cosmic radiation (see figure 1).

Moreover, this spallation source is pulsed, which has been a valuable asset for this first detection.

By comparing the CsI [Na] signals occurring before the neutrino emission and those occurring immediately after, an excess is visible both in the energy spectrum and in the distribution of signal arrival times (see figure 2). The agreement with the predictions of the standard model is excellent even if the measurement uncertainties are still relatively high: 134 ± 22 observed events for 173 ± 48 expected [1].

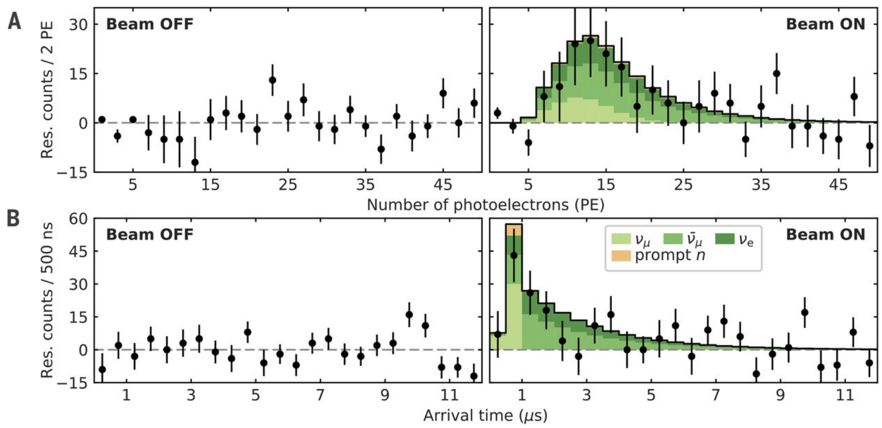

Figure 2: First observation of the coherent elastic neutrino scattering of neutrinos on nuclei. Residual differences (datapoints) between the CsI [Na] signals and the next/previous 12 µs-POT trigger events are indicated according to their energy (A) and the arrival time of the event (B). Error bars are statistical. They are shown for 153.5 actual days of SNS inactivity ("Beam OFF") and 308.1 actual days of neutrino production ("Beam ON"), during which 7.48 GWh of energy was supplied to the mercury target. About 1.17 photoelectrons per keV of nuclear energy from CsI [Na] recoil are expected. Characteristic excesses closely following the prediction of the standard model (histograms) are observed for periods of neutrino production only, with a rate correlated to the instantaneous beam power (adapted from [1]).

4 Search for Coherent Neutrino Scattering at Nuclear Reactors

The coherent neutrino scattering process was observed for the first time in 2017 at a spallation source emitting neutrinos of a few tens of million electron volts (MeV). At these energies, the recoils of the detected atomic nuclei are of the order of kilo-electron-volt (keV). Contrary to reactor neutrinos, the neutrinos produced at the spallation lead to a partial coherence of the interaction . An enhanced coherence is expected in the case of reactor neutrinos.

Nuclear reactors deliver large flux of neutrinos with typical energies of a few MeV, about ten times lower than a neutrino spallation source, leading therefore to nuclear recoil at least ten times lower and then much more difficult to detect with certainty. Thus, the first crucial step lies in the detection of reactor neutrinos by the process of coherent diffusion on atomic nuclei.

This is already a well identified short-term objective in fundamental research prospects, with for example the NUCLEUS, Ricochet Billard:2016giu, or CONUS [3] experiments that are currently being designed, built, or collecting data. It is reasonable to think that this crucial step could be achieved within the next 5 years.

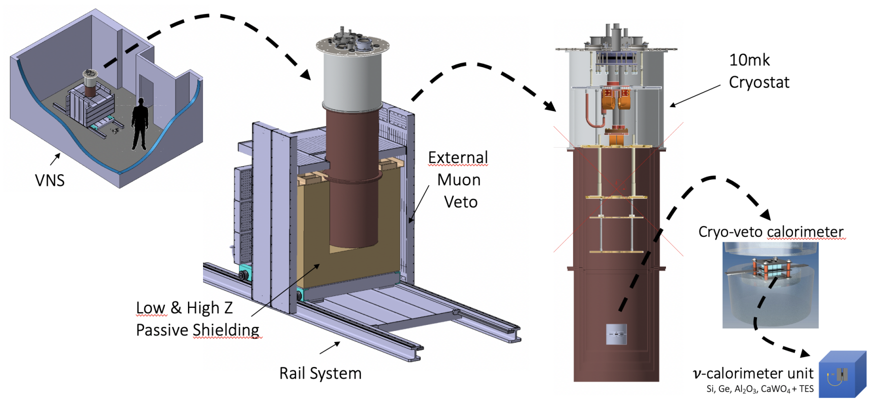

Figure 3: Sketch of the NUCLEUS cryogenic detector that will be located at the Very Near Site inside the Chooz nuclear power station (France).

5 The NUCLEUS experiment

NUCLEUS [4] is a new-generation experiment dedicated to the detection and study of the process of coherent elastic scattering of neutrinos emitted by nuclear reactors.

The Chooz nuclear power plant in France offers an ideal setting for the first detection of the CEvNS process with low energy neutrinos. The complex comprises two commercial nuclear reactors with a combined thermal power of 8.54 GW. The NUCLEUS experiment will be installed at a new experimental site, called Very-Near-Site (VNS),located right between the two 4.25 GWth reactor cores, separated by 160 meters.

This project brings together a European consortium of physicists, engineers and technicians from Austria, France, Germany, and Italy. It should be recalled here that the detection of reactor neutrinos using this process has never yet been established. With the primary objective of demonstrating the coherent scattering of reactor neutrinos, the NUCLEUS experiment will use an array of tiny cryogenic detectors that are characterized by a particularly low threshold (20 eV) for detecting nuclear recoils and a fast response time (ms), requested for operating the detector close to the surface (i.e. with an overburden of less than ten meter water equivalent).

NUCLEUS will use cryogenic calorimeter technology that measures the temperature rise following the deposition of energy in a target. The technological breakthrough envisaged is to reduce the detection threshold to less than 20 electron volts in order to further miniaturize the fiduciary volume of the experiment. The main target material will be $CaWO_4$, a scintillating bolometric crystal developed in the framework of the CRESST dark matter research experiment. The effective cross section on heavy nuclei such as tungsten, as well as the envisaged detection threshold of 20 eV, increase the signal proportion compared to the background noise that must remain sufficiently low in the target detector. The NUCLEUS target detectors are installed in a cryostat. The experimental volume is surrounded by shielding for active and passive background noise reduction. The physics reach of NUCLEUS will depend strongly on the background level reached at sub-keV energies. By using active and passive background reduction techniques, the NUCLEUS experiment aims to achieve a background count rate of $\leq$ 100 counts/(keV-kg-day). One coherent neutrino scattering interaction is expected every two days. Figure 3 shows a sketch of the NUCLEUS experiment at Chooz Very Near Site.

In the first phase of the experiment, NUCLEUS-10g, the objective is the first observation of the coherent diffusion of neutrinos on a nuclear reactor with a total target mass of only 10 g! Because of its low threshold NUCLEUS could probe, for the first time, the antineutrino spectrum of the reactor below 1.8 MeV - below the generally used inverse beta decay threshold. NUCLEUS-10g will explore this background for the first time at energies below 100 eV and at a shallow site. NUCLEUS-10g is expected to take data from 2022 onwards. A second phase, NUCLEUS-1kg will follow.

6 Conclusion and Outlook

Coherent neutrino scattering on nuclei is a new experimental process at reach. It has been detected for the first time in 2017 with neutrinos of 50 MeV by the COHERENT experiment. The NUCLEUS experiment aims to detect this process with low energy reactor neutrinos (5 MeV on average). This process will now be used by physics community to further explore non-standard interactions, to study independently the form factors of nuclear neutrons and to establish complementary limits on the Weinberg angle and sterile neutrinos. In addition, with a sufficiently low threshold, the magnetic moment of neutrinos can also be addressed. All in all, CEvNS presents interesting possibilities from a theoretical and phenomenological point of view.

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