PROCEEDINGS OF SCIENCE

CEvNS and COHERENT

PoS(NOW2022)066

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The first experimental discovery of CEvNS (Coherent Elastic Neutrino-Nucleus Scattering) was made by the COHERENT Collaboration using a cesium iodide detector in 2017. Later in 2021, COHERENT also observed CEvNS on an argon target. On its own, the experimental detection of CEvNS was important because it confirmed the theoretical prediction that preceded it by more than 40 years. Now, a more detailed study of CEvNS can be used as a probe to accurately test the Standard Model. This work will discuss a brief overview of CEvNS, a review of previous experiments, the state of current detectors, and provide an outlook on planned subsystems.

Neutrino Oscillation Workshop-NOW2022
4-11 September, 2022
Rosa Marina (Ostuni, Italy)

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1. Introduction

This publication comprises a status update on the COHERENT Collaboration. COHERENT has been publishing experimental results since 2017, initially with the observation of CEvNS (described next section) [1]. After that first experimental detection, the collaboration progressed on searching for CEvNS on different nuclear targets utilizing different detector technologies, in addition to using CEvNS as a means to study new physics – not only strictly neutrino physics. This article discusses the results from past detectors, the present status on current detectors that are still collecting data, and the outlook on future detectors. Namely, the following detectors will be covered: CsI (cesium iodide detector), CENNS-10 (liquid argon detector), 1-ton liquid argon detector, D_2O (heavy-water detector) NaIvE/NaIvETe (sodium iodide detectors), Ge-mini (Germanium detector), and Nubes (short for neutrino cubes).

2. What is CEvNS

CEvNS, short for “Coherent Elastic Neutrino Nucleus Scattering”, is a neutral current process where a neutrino collides with an atomic nucleus coherently and elastically. A coherent interaction means the neutrino “sees” the many nucleons as a whole entity as opposed to the neutrino interacting with an individual nucleon. Elastic scattering occurs when the products of an interaction are the same particles in the initial state. In this case, there is only a transfer of energy between the neutrino and the nucleus [2, 3].

The CEvNS differential cross section, for a nucleus with N neutrons and Z protons, is

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin\theta_W)Z)^2}{4} F^2(Q^2)$$

where k is the neutrino energy, Q is the momentum transfer, and θ_W is the weak mixing angle. The CEvNS cross section is approximately proportional to the square of the number of neutrons in the nucleus (given that the Z contribution almost vanishes), multiplied by the nuclear form factor. This N^2 dependency is also being probed by the COHERENT experiments. The nuclear form factor is close to unity for lower neutrino momentum transfer Q and smaller nuclear sizes. Comparatively, the CEvNS cross section with argon is dominant (compared to argon charged current cross section) up to around 100 MeV, and is less than half for 200 MeV. This can be seen in Figure 1.

While studying CEvNS is already important on its own because it confirms well established Standard Model predictions, CEvNS is also a potential probe to investigate other fields of physics (e.g. supernovae), searches for physics beyond the Standard Model, such as new interactions, new neutrino properties, dark matter, and more [1]. The Standard Model provides a very direct prediction of the CEvNS cross section, and any possible deviation would immediately represent indications of new physics. Both neutrino magnetic moment and neutrino charge radius affect the CEvNS cross section. CEvNS can also be used to search for sterile neutrinos via oscillations, since it is a neutral-current process [4].

Daniel Freedman, the theoretical physicist who first predicted the coherent elastic neutrino-nucleus scattering effect in 1974, pointed out that proposing such an experiment “may be considered an act of hubris” given the tremendous experimental challenges to be overcome in order to successfully detect this interaction. Such challenges include the interaction rate, resolution, and

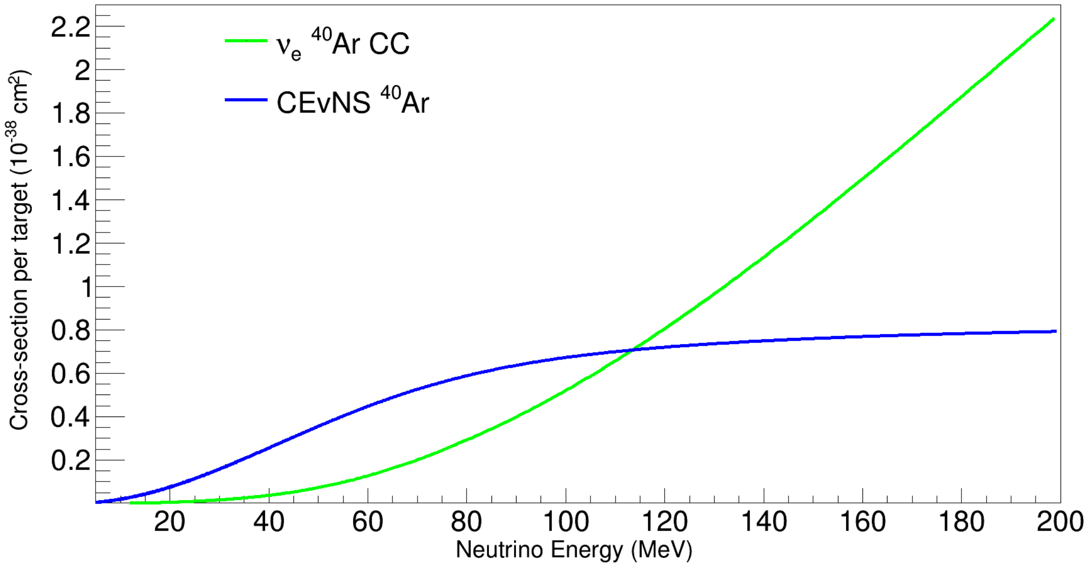

Figure 1: Comparison between CEvNS and CC cross sections for argon.

background [2], which ultimately demand a very high flux of neutrinos and a detector with high resolution placed in a well shielded laboratory, to mitigate any possible background.

3. Experiment location

The COHERENT Collaboration detectors are located in the Neutrino Alley, a corridor housed in the basement of the Spallation Neutron Source (SNS) target building at the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, U.S.A. The SNS delivers 10^{20} protons on target per day, at an energy of 1 GeV with short ~350 ns pulses, with about 9% of the protons yielding 3 neutrinos each. This is the ideal venue to study CEvNS, due to the 1.4 MW of beam power, being the most powerful pulsed neutrino source in the world. The vast majority of those neutrinos, as a result of pion and muon decay at rest, are produced in our region of interest, up to 50 MeV.

The choice of this location was the result of extensive background studies. Detectors in the Neutrino Alley are located 20 ~ 30 m from the target. The concrete, gravel, and steel filling that spans this distance provides shielding from SNS neutrons. The concrete overburden eliminates the hadronic component of cosmic rays and attenuates muon flux by a factor of 3. Present detectors at Neutrino Alley are: NaI185 (“NaIvE”), D_2O, Ge-mini, NuThor, NaIvETe, CENNS-10.

4. CsI detector and first observation of CEvNS

Using the CsI detector, nearly 43 years after the theoretical predictions by Daniel Freedman in 1974, the COHERENT Collaboration was the first to experimentally observe CEvNS (published August of 2017) [1, 2]. The CsI detector was the result of years of studies and simulations comprising a collective effort by numerous people. All labor ultimately culminated in the CsI detector’s final installation that took less than 24 hours at the experimental site after test assembly at the University of Chicago. Weighing less than 15kg with dimensions comparative to that of a kitchen microwave, the CsI detector itself was the first ever working handheld neutrino detector.

Updated results with more years of data taking on the CsI detector have just been published [5]. This detector has already been decommissioned to make room for other experiments. Current limitations on interpretation of results for this detector are due to systematic uncertainty (10%) caused by the unmeasured neutrino flux. The present neutrino flux at the SNS has only been calculated by simulation [6].

5. CENNS-10: observation of CEvNS in argon

The CENNS-10 detector, originally built at Fermilab by the team led by Jonghee Yoo [7], was recomissioned at Indiana University and moved to the SNS in July of 2017, when it started taking data. This detector contains 24kg of liquid argon, with two photo-multiplier tubes (one PMT on top and one at the bottom). In 2021 the detector successfully observed CEvNS in argon, wherein the cross sections (calculated by two completely independent analysis teams) matched the theoretical cross section within error bars [8]. Detecting CEvNS in both CsI and Ar was important since some possibilities of new physics may only arise by comparing nuclei with different number of neutrons.

This detector will be upgraded to a 1-ton scale liquid argon detector, occupying the same space it currently does at Neutrino Alley. Acquiring the necessary amount of underground argon (free from Ar^{39}) will be essential to achieve low background and therefore a more accurate study of CEvNS. Once this step is completed, we expect to observe 3000 CEvNS events/year, in addition to charged-current events.

6. Tackling neutrino flux uncertainty with a heavy water detector

The current largest source of uncertainty for studying neutrinos at the SNS resides in the knowledge of neutrino flux production, limited at about 10% based on theoretical models. A heavy water detector provides an experimentally-based method to calibrate neutrino flux at the SNS using the well-known theoretical neutrino-deuteron charged current interaction cross section. After a few years of data taking, that uncertainty could be lowered to as little as 2% [4].

This detector uses Cherenkov light as a means of detection, has 12 PMTs on top, reflective lining on the inside for maximum photon collection, and an acrylic vessel separating the internal heavy water from the external light water (for full energy reconstruction). Currently performing engineering runs, it is fully filled with light water only. At present, with the required amount of heavy water being already available, we project that the acrylic vessel should be ready in early 2023. Figure 2 shows both virtual and real images of the detector, Figure 3 shows relevant cross sections, and Figure 4 shows the amount of expected deuterium and oxygen events to be observed. The number of events involving electron-neutrino scattering, or neutrino scattering on carbon (among others) are minimal due to the combination of their cross sections and the amount of those particles in the detector.

Data from the D2O detector will impact data analysis from past, present, and future detectors because of the reduced systematic neutrino flux uncertainty. This will enable much finer constraints on the CEvNS cross section, and thus better probes of physics beyond the Standard Model.

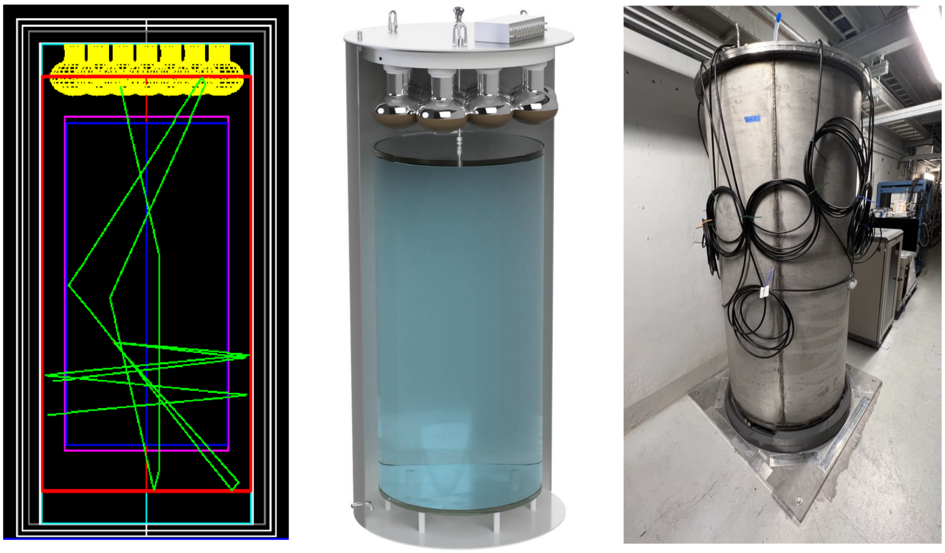

Figure 2: Heavy-water detector design timeline, left to right: initial Geant4 Simulations, computer 3D rendering, and current picture.

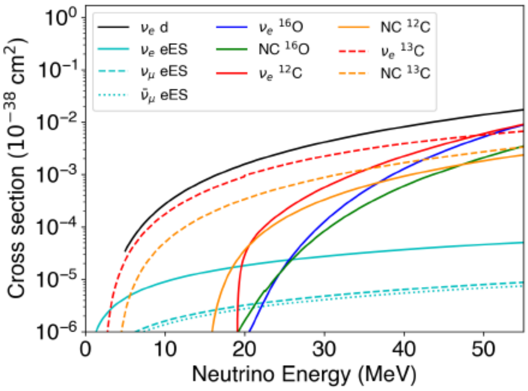

Figure 3: Cross sections among heavy-water detector materials [4].

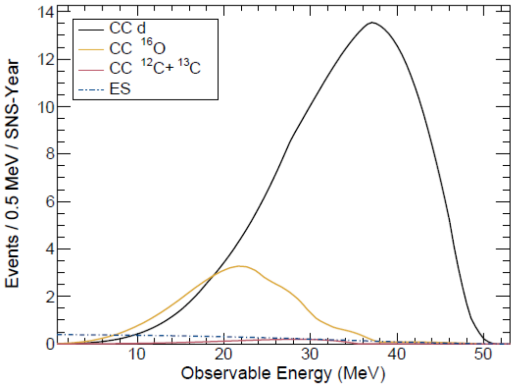

Figure 4: Simulation of expected number of events in the heavy-water detector [4].

7. Germanium detector (Ge-mini)

This future germanium array will consist of 18 kg target mass and is expected to generate 500-600 CEvNS events per year. This detector will have great energy resolution and very low threshold. The quenching factor has already been measured and is well understood.

8. Sodium iodide detectors (NaIvE/NaIvETe)

The NaI series detectors mark the transition of an 185 kg NaIvE to a 2-ton NaIvETe array of sodium iodide. The NaI-185 detector is in its final stages of data analysis. The 2-ton upgrade has potential to detect both CEvNS and CC on iodine, which will require dual-gain bases. The first of seven modules of NaIvETe is already deployed, and more modules are coming soon.

9. Nubes

The Nubes, short for "neutrino cubes", were two liquid scintillator detectors designed to observe neutrino induced neutrons (NINs). Beam-related neutrons (BRNs) were shielded by water blocks. Neutrinos from the SNS would interact with Pb and the generated neutrons were detected by liquid scintillator cells coupled with PMTs. The Nubes detectors have already been decommissioned to make room for new detectors and a publication on Pb data is forthcoming.

10. Acknowledgements

COHERENT Collaboration is composed of 20 institutions and more than 70 people, in 4 different countries. All the developments mentioned here are collective efforts of this collaboration. This work is supported by the United States Department of Energy grant: DOE DE-SC0020267.

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