

Coherent elastic neutrino-nucleus scattering

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Abstract. Since its prediction in 1974, the measurement of the coherent elastic neutrino-nucleus scattering (CE ν NS) has been a great challenge for many experimentalists. One of the main factors is the small recoil energies of the nucleus produced by this interaction, which is dominant for energies $\lesssim 50$ MeV, for medium target masses. The detection was finally achieved by the COHERENT experiment in 2017 and several other experiments are currently close to performing this measurement for different neutrino energies and sources, thanks to the development of very low threshold and background detectors. Measuring CE ν NS opens up new possibilities to test the Standard Model and to look for new physics beyond it. The purpose of this contribution is to provide a brief overview of the state-of-the-art on this subject, with a focus on some of the latest experimental results and future perspectives.

1. Introduction

The interest in the coherent elastic neutrino-nucleus scattering (CE ν NS) has been rising in recent years, due to the development of low threshold detectors and the many independent experimental efforts seeking to detect this interaction. CE ν NS was predicted in 1974 by Freedman [1] but has only been detected in 2017 by the COHERENT collaboration [2]. This interaction happens when a low energy neutrino exchanges a virtual Z boson (neutral current process) with a nucleus producing a tiny recoil of the nucleus. The smallness of the nucleus recoil energy is one of the main reasons why it took more than 40 years for CE ν NS be detected. Part of the improvements on low background and low threshold detectors needed to overcome this problem was carried out by of the community for direct Dark Matter searches (DM), which shows the synergy between CE ν NS and DM research.

The nucleus recoils as an intact unit when the product between the three-momentum transfer (q) and the nuclear radius (R) is small, $qR \ll 1$. Under this condition, the nucleon wave function in the target nucleus are all in phase with each other. This coherent interaction is dominant for energies below about 50 MeV for a medium-sized element. The differential cross section for the coherent elastic scattering of antineutrinos off a nucleus at rest is given by [1]

$$\frac{d\sigma_{SM}}{dE_R}(E_{\bar{\nu}_e}) = \frac{G_F^2}{8\pi} Q_W^2 \left[2 - \frac{2E_R}{E_{\bar{\nu}_e}} + \left(\frac{E_R}{E_{\bar{\nu}_e}} \right)^2 - \frac{ME_R}{E_{\bar{\nu}_e}^2} \right] M |F(q)|^2, \quad (1)$$

where G_F the Fermi coupling constant, $E_{\bar{\nu}_e}$ the antineutrino energy, M the mass of the nucleus, E_R the nuclear recoil energy, $F(q)$ is the nuclear form factor, and Q_W is the weak charge given by

$$Q_W = N - (1 - 4\sin^2\theta_W)Z, \quad (2)$$



with $Z(N)$ being the number of protons (neutrons) on the target and θ_W the weak mixing angle. Thanks to the coherence of the interaction we have an enhancement of the cross section, given by the dependence with N^2 , of about two orders of magnitude larger than for quasi-elastic interactions. In combination with high-flux neutrino sources, this permits the use of small detectors, at the kilogram scale, as compared to the large masses needed to detect neutrinos in other processes.

The recent $\text{CE}\nu\text{NS}$ detection and the capabilities of $\text{CE}\nu\text{NS}$ experiments to study MeV-scale neutrino interactions involving physics within and beyond the Standard Model opens up a large window of possibilities. As examples, we can mention studies on $\text{CE}\nu\text{NS}$ cross section measurements [3, 4], nuclear physics and weak mixing angle measurements [5, 6, 7, 8], neutrino non-standard interactions (NSI) [9, 10, 11, 12], neutrino electromagnetic properties [13], axion-like particles [14, 15], light mediations [16, 17, 18, 19], light sterile neutrinos [20, 21, 22], and dark matter [23, 24]. In astrophysics, the understanding of MeV-neutrinos is relevant for energy transport in supernovae and is a limiting factor in ongoing efforts for developing new models. Also, supernova neutrinos might be detected through $\text{CE}\nu\text{NS}$ by using large detector volumes (~ 1 ton) [25, 26]. In addition, there has been a growing interest in recent years on nuclear reactor monitoring using neutrinos [27]. On the other hand, the coherent scattering from solar, atmospheric and diffuse supernova neutrino background has been identified as a limiting background for future dark matter searches [28].

2. Neutrino sources for $\text{CE}\nu\text{NS}$

Despite the enhancement due to the coherence effect, we need the highest possible neutrino flux so as to be able to build compact detectors and get the desired detection significance for $\text{CE}\nu\text{NS}$ detection in a short amount of time. Also, the source should produce neutrinos in the energy range where the $\text{CE}\nu\text{NS}$ regime is valid, i.e., less than 50-100 MeV depending on the target composition. Since the recoil energy increases with the square of the neutrino energy, the highest this energy the highest the recoil energy is and as a consequence its detection becomes more accessible. Also the neutrino source has to be very well understood so the flux is known to good precision in order to predict how many neutrinos are interacting with the detector. Basically, there are two types of neutrino sources that fulfil these needs: stopped-pion sources and nuclear reactors.

2.1. Stopped-pion sources

Spallation sources can be used as neutrino sources for $\text{CE}\nu\text{NS}$ purposes. Here, the pions are produced by the collision between a proton beam with a target. The produced pions lose energy as they propagate in the target decaying at rest into muons and muon-neutrinos. Then the muons, which have a much longer lifetime than the pions, decay into electrons, electron-neutrinos and muon-antineutrinos. Hence, for each pion produced, 3 neutrino flavors are generated that will interact via $\text{CE}\nu\text{NS}$ with identical cross-sections. The muon-neutrino is known as the prompt component and, since it comes from a two-body interaction, its energy is monochromatic ($E_{\nu_\mu} \sim 30$ MeV). The other two components, electron-neutrinos and muon-antineutrinos, follow a continuous distribution with maximum energy of ~ 50 MeV and ~ 100 MeV respectively [29].

This kind of spallation source has a sharply-pulsed beam timing, which is key for background rejection when the detectors employed have good time resolution. If the beam pulses are shorter than the muon lifetime (i.e. less than $2.2 \mu\text{s}$) then, the prompt signal can be separated from the other two neutrino flavors. The first $\text{CE}\nu\text{NS}$ detection was obtained by the COHERENT experiment [2] using a stopped-pion source, the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory, which is the most intense pulsed neutron beams in the world to date. In figure 4 we can see the neutrino production rate as a function of energy (left) and time (right) calculated using Geant4 for SNS [2]. Other facilities are available or under construction, such

as LANSCE-Lujan at Los Alamos [31], the European Spallation Source [32], and the China Spallation Neutron Source [33].

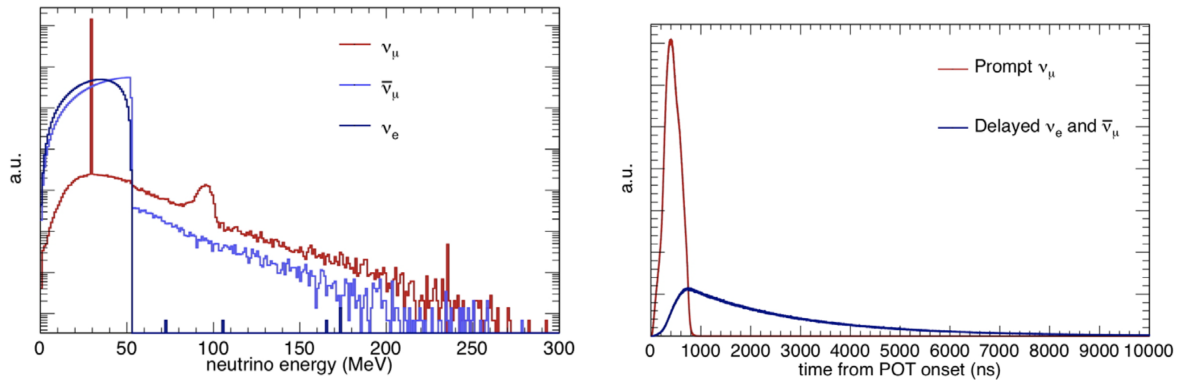


Figure 1. Energy distribution (left) and time profile (right) for the neutrinos produced by the SNS at the detector position calculated by the COHERENT collaboration using Geant4 [30].

2.2. Nuclear reactors

Reactor sources provide extremely large electron-antineutrinos fluxes, producing about 2×10^{20} neutrinos per second per GW of thermal power. This is roughly 4 orders of magnitude larger than the flux produced at the SNS. Nevertheless, as the neutrino emission is isotropic, the flux in the detector will strongly depend on its distance from the core of the reactor. Electron-antineutrinos are predominantly produced through beta-decays of the fission products [34]. More than 99% of those neutrinos come from the fission of four isotopes ^{235}U , ^{238}U , ^{239}Pu , and ^{241}Pu . In figure 2 the resulting neutrino flux, obtained from the superposition of thousands of beta-decay branches of the fission fragments of those four isotopes, is shown (solid line). Figure 2 also shows the contribution to the neutrino flux due to the neutron capture in ^{238}U (dashed line) at the lowest energies (below 1.3 MeV) [35]. It is well known that the neutrino flux changes during the fuel burning cycle. Using a detector sensitive enough this variation could be detected.

The $\text{CE}\nu\text{NS}$ detection using reactor neutrinos is challenging since the neutrino energy is much lower than the neutrino energies generated at spallation sources, hence, the recoil energies are small. In addition, reactors are mostly steady-state sources, which is a challenge for background rejection. Notwithstanding, several experiments are taking data or being installed at reactor sites. One advantage is that predictions for neutrinos from nuclear reactors are nearly free from the uncertainties coming from the not well known nuclear structure, as the form factor in equation 1 is close to 1 at lower energies. The low energy range is also particularly suitable to probe new physics through NSI. As an example, the CONNIE collaboration has set restrictive limits for simplified light mediator models [16].

3. Experiments for $\text{CE}\nu\text{NS}$

Several experiments designed for the $\text{CE}\nu\text{NS}$ detection are taking data or being installed at different locations around the world. There is also a new generation of experiments being planned, which will profit from the knowledge acquired by the current ones. Some of those current and future experiments are summarized below.

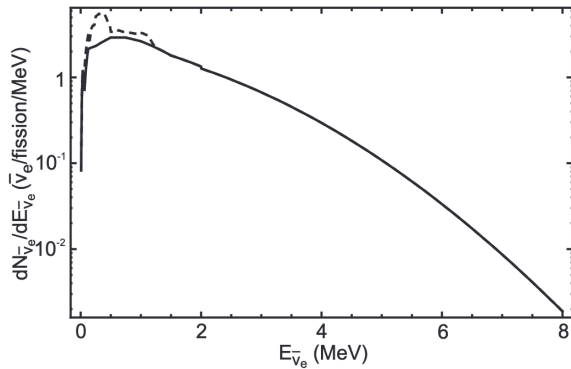


Figure 2. Reactor antineutrino spectrum per fission per MeV for the fissile isotopes contribution (solid line) and including the contribution of the neutron capture in ^{238}U [35, 36].

3.1. COHERENT

The COHERENT experiment is running at the SNS with several detectors deployed at the “Neutrino Alley” with an overburden of 8 m.w.e (meters water-equivalent) [30]. One of the main goals of the COHERENT collaboration is to test the SM prediction of the dependence of the cross section on the square of the neutron number and perform precision cross section measurement to test for NSI. Different available technologies were used for the detectors: CsI[Na] scintillating crystals, p-type point contact (PPC) germanium detectors, single-phase liquid argon, and NaI[Tl] scintillation crystals. The first $\text{CE}\nu\text{NS}$ detection was accomplished in 2017 with a 14.7 kg CsI[Na] crystal located at 19.3 m from the source, with a significance of 6.7σ . More details can be found in [2]. The measurement was consistent with the SM prediction and some constraints on NSI models were derived [37]. In 2020, the COHERENT collaboration reported a new result using the CsI[Na] detector doubling the statistics of the previous measurement. With an improvement on the systematic uncertainties, now reduced to the level of 13%, they reject the no- $\text{CE}\nu\text{NS}$ hypothesis at 11.6σ . Before, the systematics were dominated by the quenching factor (the ionization efficiency used to convert the measured energy into the nuclear recoil energy) uncertainties while now are dominated by the knowledge of the neutrino flux with an uncertainty of about 10%. The result is compatible with the SM within 1σ .

The second $\text{CE}\nu\text{NS}$ detection, also performed by the COHERENT collaboration, was with the single phase liquid Argon detector [38]. The detector is located at 27.5 m from the source with an active mass of 24 kg of atmospheric argon (99.6% ^{40}Ar). Its threshold is 20 keV for nuclear recoil energy. To avoid experimental bias, the analysis method and the event selection was decided prior to analyzing the on-bean data. In addition, two independent analysis were performed. The significance obtained compared to the null hypothesis was $3 - 3.5\sigma$ for both analysis methods, which showed a number of $\text{CE}\nu\text{NS}$ events within 1σ of the SM prediction. Having multiple-target $\text{CE}\nu\text{NS}$ detection allowed the COHERENT collaboration to start to test the neutron number squared dependence of the cross section as can be seen in figure 3. The expected SM cross sections corresponding to the different kinds of detectors installed are shown with black dots, while the two experimental results for the $\text{CE}\nu\text{NS}$ detection with CsI[Na] and the liquid Ar are shown with blue dots. The data taking is continuing and the collaboration expects to reach soon a sensitivity of 5σ with the liquid argon detector.

3.2. CONNIE

CONNIE (COherent Neutrino-Nucleus Interaction Experiment) aims to measure the $\text{CE}\nu\text{NS}$ in charge-coupled devices (CCDs) and search for physics beyond the Standard Model. It is installed in a commercial container at the Almirante Álvaro Alberto nuclear power plant, in Angra dos Reis, in Rio de Janeiro state (Brazil). It is located at about 30 m from the core of the 3.95 GW thermal power Angra 2 reactor [40]. The experiment is composed of 14 CCDs of 6 g each and

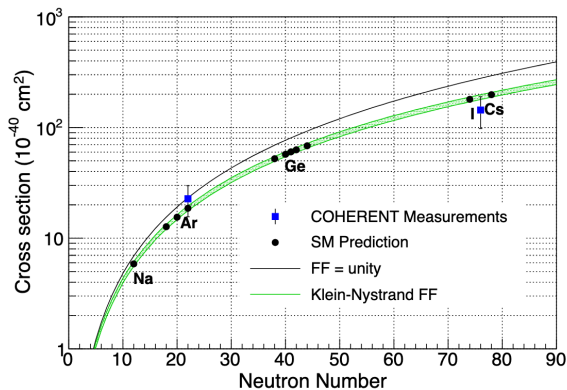


Figure 3. The measured $\text{CE}\nu\text{NS}$ cross section with the CsI[Na] and liquid argon detectors (see text for details) as a function of the neutron number, extracted from [38]. The expected SM values for COHERENT targets is also shown. Two different values for the form factor (FF) are presented: the unity assumption in black and the Klein-Nystrand [39] in green with a 3% band due to the variation on the neutron radius.

is surrounded by a passive shielding with two 30 cm high-density-polyethylene layers with 15 cm of lead in between that reduces the background in about one order of magnitude. As usual in power reactors there is periodic programmed shutdown for maintenance and change of the nuclear fuel. In the case of Angra 2 this happens roughly once each 14 months and takes 25-35 days. The background measurement is then performed during this reactor-off moment and the $\text{CE}\nu\text{NS}$ analysis is based on the comparison between reactor-on and reactor-off data [41].

Using data collected in 2016-2018 [41], CONNIE has demonstrated its sensitivity to new physics by establishing competitive limits for light mediators at the lowest mediator masses [16]. Recently, the collaboration has reported the analysis of the 2019 data where the experiment operated with a hardware binning of the CCD pixels [42]. The main purpose of this readout mode was to lower the detector threshold down to 50 eV_{ee} and increase the experiment efficiency to the lowest energies. With this new data, the CONNIE collaboration was able to improve also the data analysis and the event selection, and therefore to reduce the background rate at the lowest energies. More details can be found in [43].

Recently the CONNIE collaboration installed at the experiment two Skipper-CCD sensors to further decrease the detection threshold. This new technology, designed at the Lawrence Berkeley National Laboratory (LBNL), is successfully being used by the SENSEI collaboration [45, 46] for DM searches. Thanks to the capability to perform multiple pixel readouts without destroying the charge, it is possible to reach sub-electron readout noise in these detectors [44]. The main objective is to study the response of the sensors at sea level and to determine the background of the experiment for a large-mass future experiment for $\text{CE}\nu\text{NS}$ detection. The performance of those sensors and their first results are discussed in [43, 47]. Also, a couple of months later, another Skipper-CCD was installed by the νIOLETA collaboration [48] at about 12 m from the core of a 2.2 GW thermal power nuclear reactor at Atucha 2, Argentina. The synergy between these two collaborations will allow us to fully understand the detector response for the next generation experiment for the $\text{CE}\nu\text{NS}$ detection with CCDs.

3.3. CONUS

The detector of the CONUS (COherent Neutrino nUcleus Scattering) experiment consists of 4 HPGe point-contact crystals of 1 kg each installed inside a multilayer-active-shield located at 17 m from the core of a 3.9 GW thermal power nuclear plant in Brokdorf, Germany, and is operating since 2018. The detector energy threshold is ~ 300 eV_{ee}. A dedicated campaign was performed to understand the contribution of each background component, showing that the one coming from the reactor is small and that using the muon-veto the muon-induced background was reduced by 2 orders of magnitude [49]. Using the first data set, the CONUS collaboration was able to set the best limit for $\text{CE}\nu\text{NS}$ from reactor neutrinos [50]. Their result is expressed

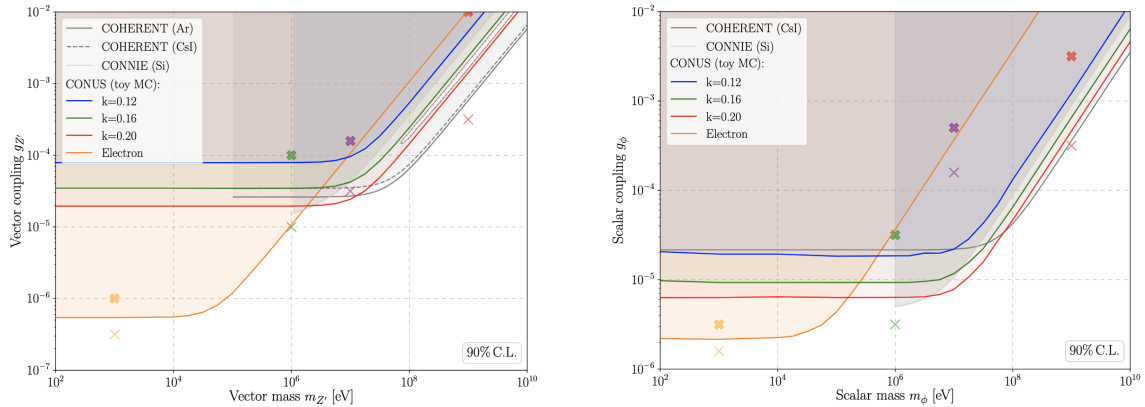


Figure 4. Limits for vector (left) and scalar (right) mediators for the three experiments, COHERENT (90% C.L.), CONNIE (95% C.L.), and CONUS (90% C.L. and for different quenching factor values). Figure extracted from [?].

as a function of a quenching factor parameter and a restriction on its value is set by comparing with the predictions with the upper limit on the observed rate. Based on these results, they established limits on BMS physics, such as NSI. More details can be found in [51]. In figure 3.3, extracted from ref. [19], we see the limits for vector (left) and scalar (right) mediators for the three experiments, COHERENT (90% C.L.), CONNIE (95% C.L.), and CONUS (90% C.L. and for different quenching factor values). These figures show clearly how stopped pion and reactor sources are complementary. For masses above ~ 10 MeV the strongest limits can be set by the COHERENT results, while CONNIE and CONUS are able to set more restrictive bounds for smaller masses, even without detecting CE ν NS yet.

3.4. NUCLEUS

The NUCLEUS collaboration develops novel gram-scale fiducial-volume cryogenic detectors made of CaWO₄ or Al₂O₃ with a threshold about ~ 20 eV. The CE ν NS interaction happening in the cristal volume will cause an increase on the temperature. Since it is a calorimetric detection, the full recoil energy is measured. Therefore, this technique has not the problem of determining the quenching factor at low energies as other experimental techniques have. The NUCLEUS experiment will be installed at the Chooz nuclear power plant in France in 2022. More information can be found in [52, 53].

3.5. NuGeN

The NuGeN experiment consists on high-purity low-threshold germanium detectors located at $\sim 10 - 11$ m from the core of a 3.1 GW thermal power reactor core of Kalinin Nuclear Power Plant, Russia. It is surrounded by a passive and active shielding and is installed below the reactor in a lifting system that permits to change the distance to the core. The first measurements were performed this year and data with the reactor on and off were acquired. A large background rate at the lowest energies was found indicating that a better understanding of the sources of background is needed. More information and details can be found in [54].

3.6. NEON

The Neutrino Elastic-scattering Observation with NaI(Tl) (NEON) experiment is located at 24 m from the core of a 2.4 GW thermal power reactor in Hanbit nuclear power plant, in South

Korea. It is composed of a 15-kg low background NaI(Tl) detector installed inside of 700 liquid scintillators of active shielding surrounded by a passive shield. It was installed in the nuclear plant last year and is taking data since December 2020. Background characterization is on-going and more information can be found in [55].

4. Summary

In this contribution we have briefly reviewed the physics, applications, sources and experiments for $CE\nu NS$. In addition to the experimental effort to measure $CE\nu NS$, it is clear that a precise knowledge of the quenching factor is needed to interpret the results and to perform comparisons with theoretical expectations. Several experimental and theoretical studies are being performed to this end, but are outside the scope of this review.

The study of $CE\nu NS$ is opening a new window to perform precision measurements of the SM and search for BSM physics. We are living an exciting moment as several experiments prepare to measure this interaction using different detection techniques, neutrino sources, and energy ranges. The COHERENT experiment has now achieved this measurement with two detectors using a stopped pion source. Experiments from nuclear reactors expect to achieve this measurement soon, which will enhance the already ongoing complementarity from the results using both neutrino sources.

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