Neutrino physics: Theory and experiment (SS2021)
Coherent neutrino scattering

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1. Lecture 8: Coherent neutrino scattering

In this lecture, we discuss the coherent neutrino-nucleus scattering (CEνNS) process. This reaction has the largest cross-section among the neutrino interactions but was measured only in 2017. After a description of CEνNS and a motivation, we will discuss the related experimental challenges and the actual current experiments.

1.1. The coherent neutrino-nucleus scattering process

In this process, a **neutrino interacts with a nucleus** via exchange of a Z-boson. It is a neutral current reaction in which the nucleus recoils as a whole (see figure 1 for a schematic representation)

$$\nu + A \rightarrow \nu + A. \tag{1}$$

The CEνNS is a **coherent process** for neutrino energies up to $\mathrm{E}_\nu \sim 50\,\mathrm{MeV}$ and for medium size nuclei. This is valid as long as the momentum transfer Q in the process is low, which translates into the condition $Q \lesssim 1/R$, where R is the nuclear radius.

Being a coherent process, the cross section for this process is enhanced. Actually, it is a rather **large cross section** for neutrino standards. The right side of figure 1 compares the cross section for CEνNS for cesium with other neutrino cross sections. The elastic scattering on electrons and the inverse beta decay are displayed among others. The cross-section for neutrino-induced neutron (NIN) generation in lead is also shown (background to the CEνNS measurement).

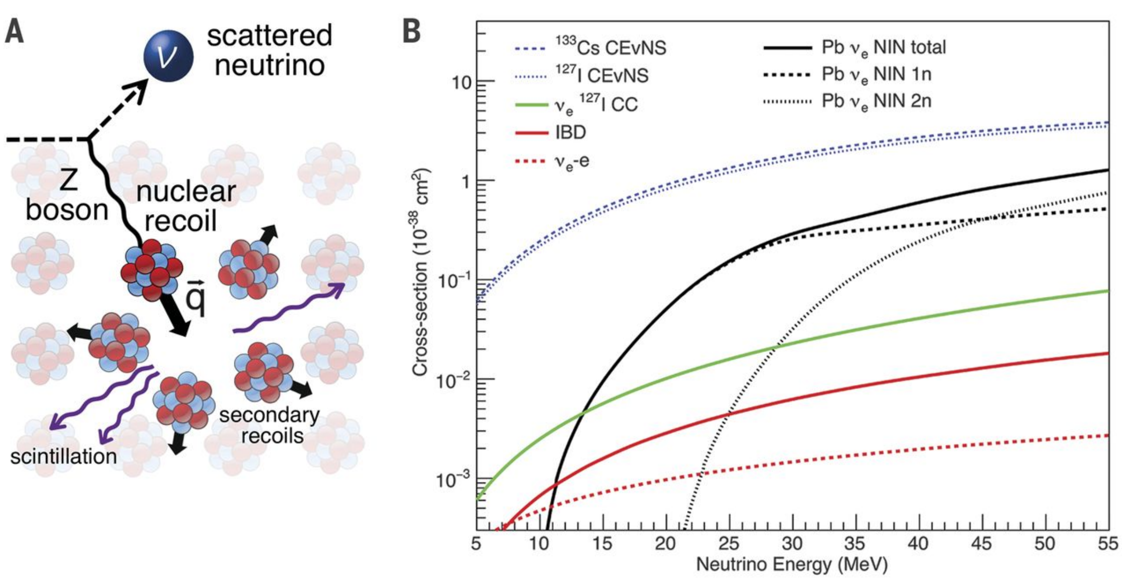

Figure 1. A: Schematic representation of the coherent elastic neutrino-nucleus scattering process. B: Total cross-sections from CEνNS and some known neutrino couplings. Included are neutrino-electron scattering, charged-current (CC) interaction with iodine, and inverse beta decay (IBD). Figure from [1].

The cross section under given approximations is given by

$$\frac{d\sigma}{dE} \sim \frac{G_F^2 \cdot M}{2\pi} \cdot \frac{Q_W^2}{4} \cdot F^2(Q) \cdot \left(2 - \frac{M \cdot E}{E_\nu^2}\right) \tag{2}$$

- where G_F is the Fermi constant,
- M the nuclear mass,
- Q_W^2 the weak nuclear charge,
- F the form factor,
- E_ν the incident neutrino energy,
- and E the nuclear recoil energy.

The **cross section** scales with Q_W^2 which depends on the proton number (Z) and neutrino number (N) as:

$$\sigma \propto Q_W^2 \propto (N - (1 - 4 \cdot \sin^2\theta_W)Z)^2 \tag{3}$$

and, as $\sin^2\theta_W$ is about 1/4, the second term is close to zero and the cross section scales with the number of neutrons squared:

$$\sigma \propto N^2. \tag{4}$$

Figure 2 shows this N^2 **dependence of the cross section** for several isotopes used in the COHERENT experiment (see section 1.4) as target materials. While the

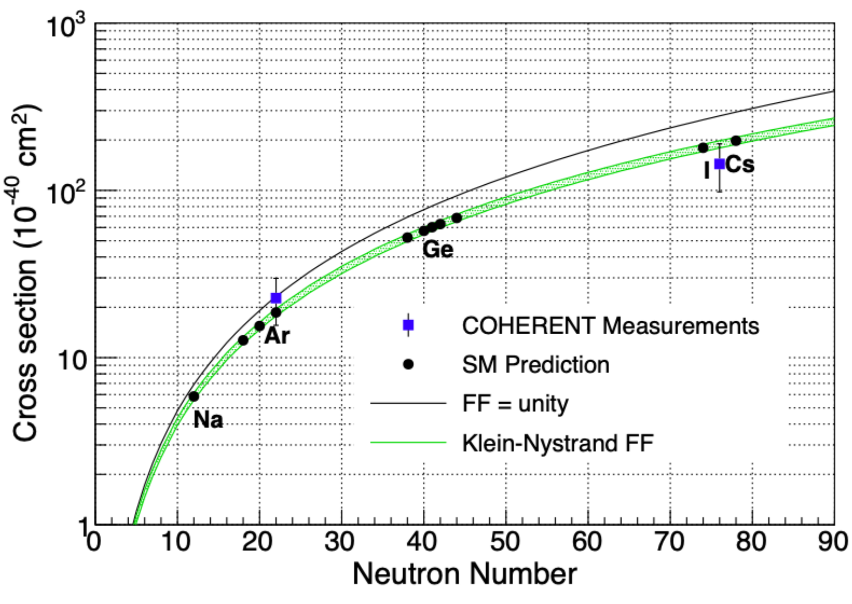

Figure 2. N^2 dependence of the CEνNS cross section showing explicitly the values for certain isotopes. The black line corresponds to the cross section assuming a form factor equal to 1. The green line has an assumed form factor. The blue datapoint corresponds to the measurement by COHERENT [1]. Figure from [2].

black line represents a form factor of unity, the green band represent an assumed form factor with a ±3 % uncertainty on the neutron radius.

1.2. Physics motivation

The coherent neutrino-nucleus scattering process (CEνNS) was originally suggested by D. Freedman in 1974 [3] and already at that time, he pointed out the difficulties to test it. Indeed, it took **more than 40 years** to finally measure nuclear recoils originating from this neutrino interaction. Although CEνNS has a relatively large cross section when considering neutrino interactions, the **tiny nuclear recoil** of a few keV (or below) makes its detection very challenging.

Besides the aim of measuring this process for the first time on different nuclei, the interest on this process goes beyond particle physics in the Standard Model. It has been suggested as a **powerful tool to search for new physics** or as a probe of nuclear structure. Some of the possible applications are briefly summarized below.

- The observation of neutrino oscillations imply that the neutrinos have mass and therefore, a magnetic moment of $\mu_\nu \sim 10^{-20}\mu_B$ with μ_B the Bohr magneton. A larger μ_ν would be a sign of new physics and would have an effect on the CEνNS spectral shape (see figure 3). A deviation of the expected spectrum (in black) towards larger rate at low energies would point to a **neutrino magnetic moment**. The coloured lines in the figure show different values of the neutrino magnetic moment.

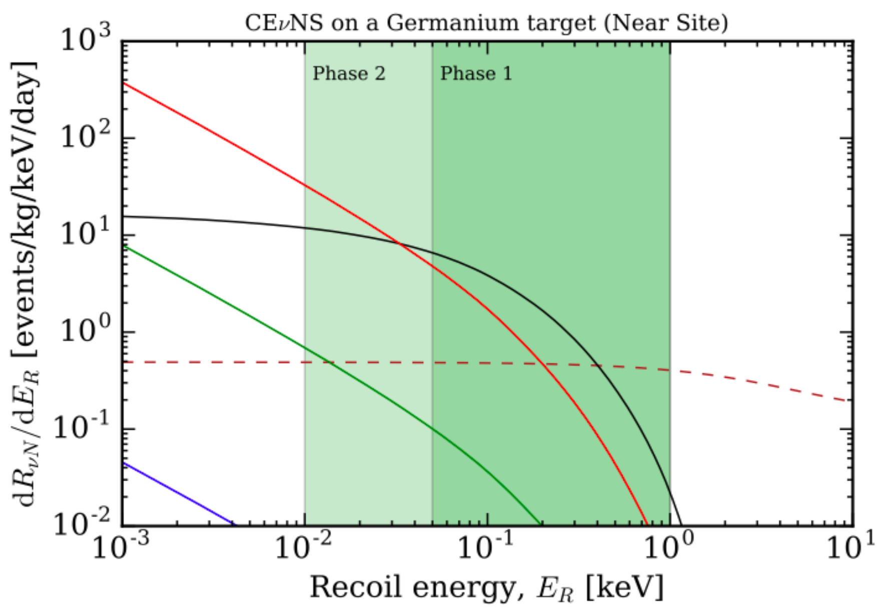

Figure 3. Nuclear recoil rate off a germanium target for the Standard Model CEνNS (solid black), as well as the contribution for different values of the neutrino magnetic moment (blue, green and red for 2.2×10^{-12}, 2.9×10^{-11} and 3×10^{-10} μ_B, respectively). The dashed line represent an assumed typical background level. Figure from [4].

- New **non-standard neutrino interactions** or **exotic neutral current interactions** would increase/decrease the overall rate of the CEνNS process compared to the standard model prediction [5].

  Figure 4 shows the rate increase or decrease for these two new interactions. The ε parameters in the left figure are the non-standard vector and axial-vector coupling constants. Similarly, the ξ are parameters representing the new couplings.

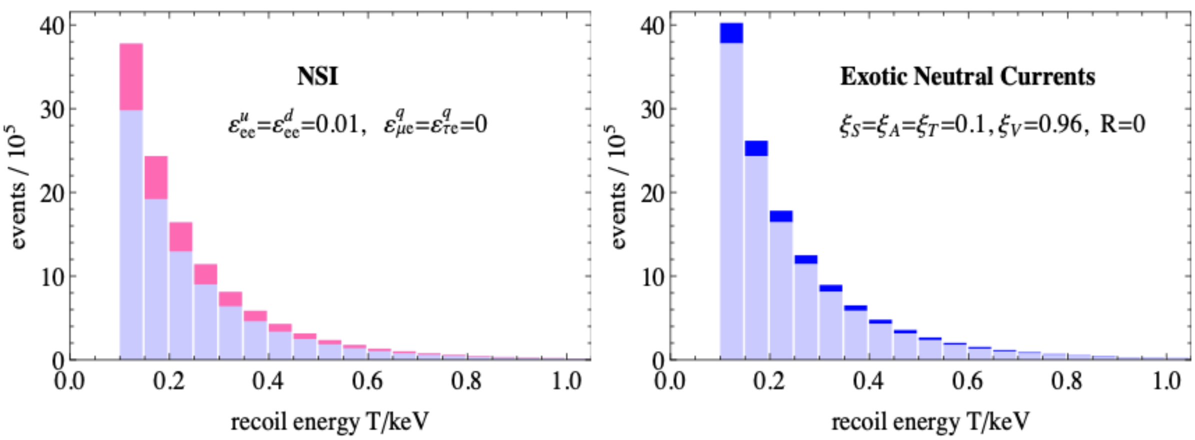

Figure 4. Event excess (pink) / deficit (dark blue) due to different physics beyond the standard model. Figure from [5].

- The search for **light sterile neutrino** at relatively short-baseline experiments can be also carried out for using neutral CEνNS reactions [6].

- The **Weinberg angle**, θ_W, is a fundamental parameter of the electroweak theory of the Standard Model, usually expressed as $\sin^2\theta_W$. It determines the relative strength between the weak neutral current and the electromagnetic interaction. The CEνNS measurement can also provide improved constraints on the value of the weak nuclear charge [7] (see also equation 3) at low momentum transfer (see figure 5). Such a measurement would allow in the future for a precision test of the Standard Model.

- CEνNS provides a way to probe **nuclear structure** specially the neutron part of it [9]. First measurements have so far large errors bars but with sufficient statistics theoretically predicted form factors will be tested (see figure 2).

- In addition, there is an interest of measuring this reaction as a **background for direct dark matter searches** (see section 1.5 for more details).

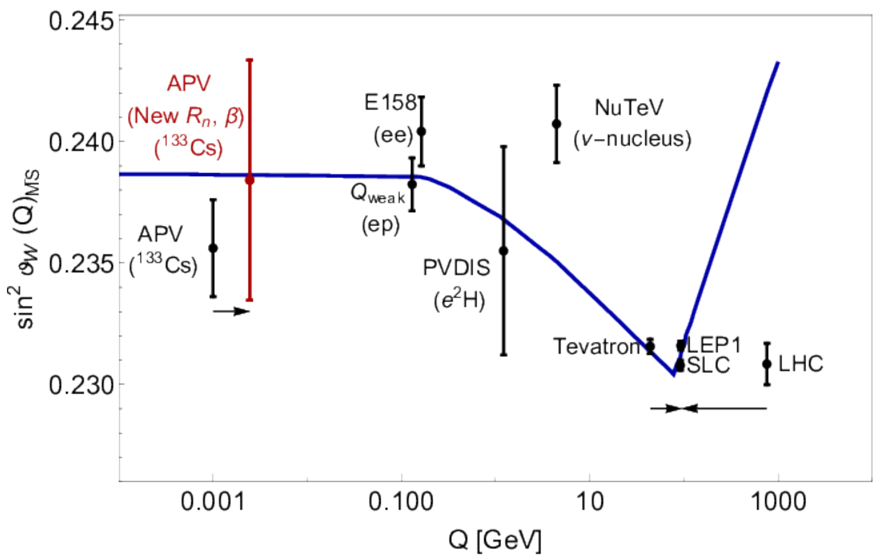

Figure 5. Variation of $\sin^2 \theta_W$ with energy Q. Various measurements are shown in black together with the Standard Model prediction (blue curve). The red data point is obtained correcting the atomic parity violation (APV) value with the new cesium neutron-distribution radius using the CEνNS measurement of COHERENT. Figure from [8]. For clarity, the old APV point, the Tevatron and the LHC points are shifted horizontally (see arrows).

1.3. How to measure CEνNS

Despite the large cross section of the CEνNS process, its measurement is highly challenging. The main reason for this is the small nuclear recoil energy deposited in the detection medium. Typical neutrino detector materials contain carbon (liquid scintillator) or oxygen (water Cherenkov detector) in the target. The maximum recoil energy is in the sub-MeV range for energies of $\sim 50\,\text{MeV}$ [10]. These energies are below the typical detection threshold of the conventional large neutrino detectors (for Super-Kamiokande it is $\sim 4\,\text{MeV}$).

Over the last years, a great effort has been devoted to develop novel **ultra-low threshold detectors** having many of them the aim of detecting nuclear recoils from weakly interacting massive particles (dark matter candidates). These experiments have shown that thresholds below 1 keV are possible.

Currently two types of neutrino sources are considered in CEνNS experiments:

- A **spallation neutron source**, where the neutrinos are produced from the decay of pions (see section 1.4)
- **Nuclear reactors**, where the neutrinos are produced in beta decays of fissions fragments (see lecture on reactor neutrinos)

Finally, **shielding** from natural radioactivity or source-induced backgrounds is required. Shields made out of combinations of lead, polyethylene, scintillators and copper are assembled around the target (see more details in the following sections).

1.4. The COHERENT experiment

COHERENT is the first experiment which has measured nuclear recoils from CEνNS in 2017 [1]. It is a multi-target experiment located at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. The **spallation neutron source** generates the most intense pulse neutron beam to date. Neutrons are produced through the interaction of high energy protons (of about 1 GeV) with a mercury target, and are employed for various applications including neutron-scattering experiments and interdisciplinary users. In such sources, neutrinos are produced in the decay of pions. These pions appear as a byproduct of the proton interacting at the target. They decay at rest giving low **neutrino energies** $\sim$ **30 MeV** which are of interest for detecting CEνNS.

Six different detectors are installed in a corridor parallel to the proton beam (see figure 6). Three of them aim to measure CEνNS:

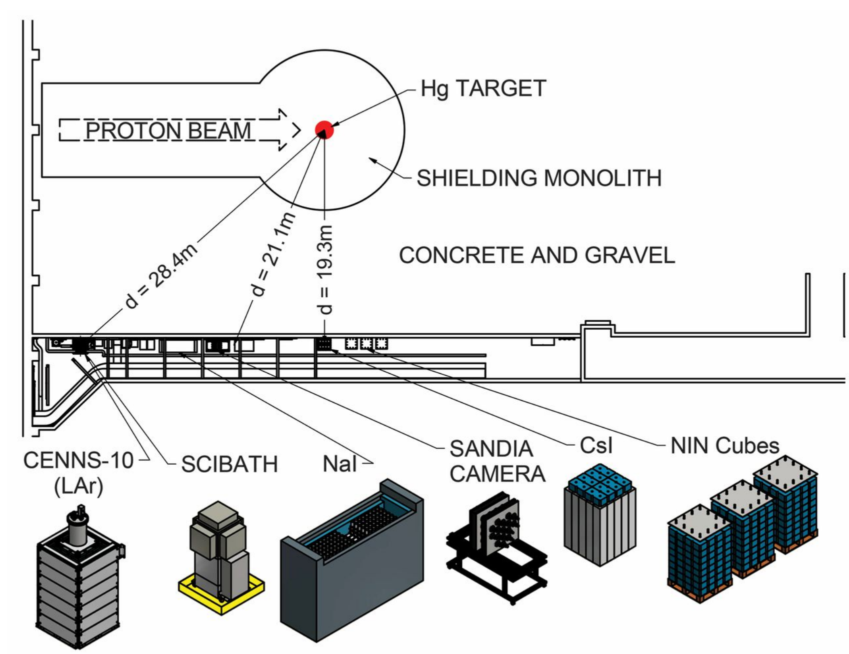

Figure 6. COHERENT detectors and their location in the 'neutrino alley' at the SNS. Figure from [1].

- a single-phase 24 kg liquid argon (CENNS-10) detector
- a 14.6 kg cesium iodine (CsI[Na]) crystal and
- a 185-kg sodium iodine (NaI[Tl]) scintillator.

While the SANDIA Camera and SCIBATH measure the prompt neutron rate at multiple positions along the alley, the NIN cubes determine the cross section for neutrino-induced neutrons in Pb and Fe.

The collaboration released in 2017 [1] the **first observation of CEνNS** from the 14.6 kg, low-background, low-threshold CsI[Na] detector. Figure 8 shows the data derived from fifteen months of accumulated live-time. While the right part of the figure shows the CsI[Na] signals immediately after (12 μs) the trigger, the left side shows the signals 12 μs before the trigger. An excess of events was observed on the data after the

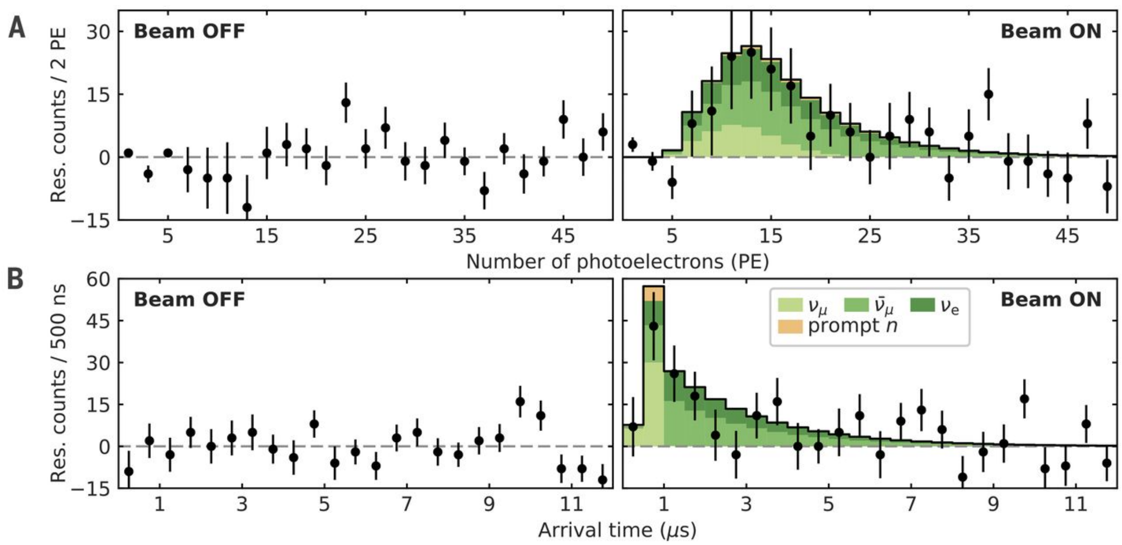

Figure 7. Observation of coherent elastic neutrino-nucleus scattering: Residual differences between signals 12 μs after and before the trigger. Figure from [1].

trigger, visible in both the energy spectrum (top panel) and the distribution of signal-arrival times (bottom panel). The excess had a signature which matches the CEνNS expectation and contain only a small contamination of beam-related **backgrounds**. The contribution of neutrino-induced neutrons is smaller than the prompt neutrons showed in yellow in the figure.

The signal derived from this measurement was consistent with the Standard Model prediction at one sigma level (figure 2). While (134 ± 22) events were predicted, (173 ± 48) events were observed. A profile likelihood analysis [1] favours the CEνNS process over the background-only hypothesis **at 6.7** σ.

As a next step of the multi-target COHERENT program, 24 kg of liquid argon (active mass, single phase) were deployed (CENNS-10 in figure 6). The aim of this measurement was to provide a low-N observation of the CEνNS process which would complement the measurement with CsI[Na]. In March 2020, the collaboration reported on the **detection of CEνNS in argon with a significance greater than 3** σ [2].

The measured cross section is also compatible with the Standard Model prediction (see figure 2). This measurement allows to verify the neutron-number dependance of the cross section and it is a first step to constrain non-standard neutrino interactions.

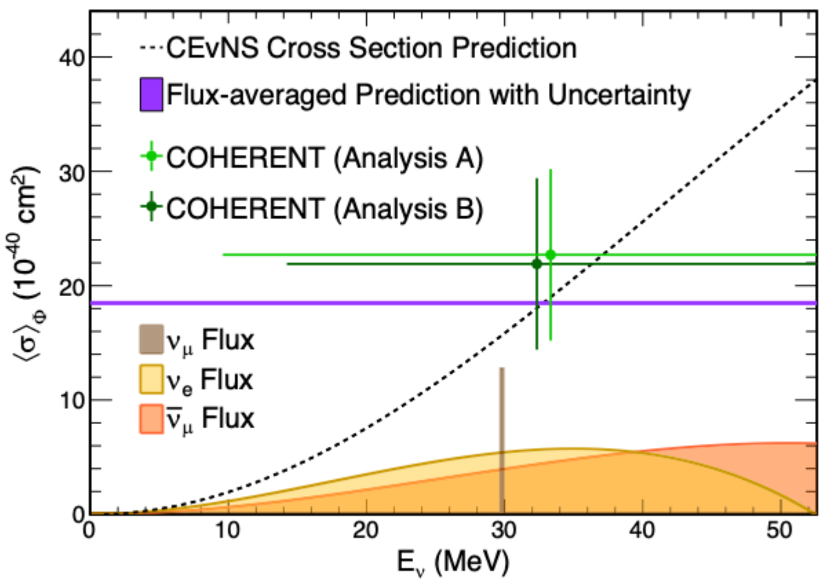

Figure 8. Measured CEνNS flux-averaged cross section for two analyses carried out togehter with the standard model prediction. The horizontal bars represent the energy range of the flux contributing. The SNS neutrino flux is shown with an arbitrary normalization. Figure from [2].

1.5. Other possible CEνNS measurements

In addition to the successful COHERENT experiment, there is a number of other experiments proposed, under construction or already running to measure CEνNS. Most of them aim to measure this process using the lower energies of **neutrinos from reactors**. An advantage of using neutrinos from reactors are the low energies of the neutrinos. At their $(2-10)$ MeV, the neutrinos are in the **fully coherent regime** and no form factor correction and related uncertainties are necessary (see figure 2). This could eventually help to disentangle new physics from nuclear physics effects.

Note that the experiments listed below are at different stages, while the first are running, the other are being commissioned or constructed.

- **TEXONO** (TAiwan EXperment On NeutrinO) is located at a nuclear power plant in Taiwan. It employs low-threshold Ge detectors and has been running since several years.
- **CONUS** [11] is a germanium-based detector running close to a nuclear reactor in Germany. More information is given below on this specific experiment.

- **CONNIE** [12] uses low-noise fully depleted charge-coupled devices (CCDs) made out of silicon. It is running at the Angra reactor in Brazil.
- **MINER** [13] is a cryogenic bolometer-based planned experiment which will be located at a research reactor in the Mitchell Institute in Texas (US). Germanium and silicon detectors with a total mass of 10 kg are envisaged.
- **NuCLEUS** [14] is a planned experiment using the cryogenic bolometer technology (as CUORE, discussed in the $0\nu\beta\beta$ lecture). $CaWO_4$ and Al_2O_3 crystals are foreseen with just a few gram masses.
- **Ricochet** is an US-french experiment planning to use cryogenic bolometers to detect phonons induced by CEνNS interactions. The experiment intends to measure neutrinos from the ILL research reactor.
- **RED100** [15] is a $\sim$ 200-kg liquid xenon detector aiming to measure CEνNS at the Kalinin nuclear power plant (Russia). The detector is built and its performance is being characterized.

CONUS [11] is an experiment located **at the Brokdorf nuclear power plant** in Germany about 17 m away from the core. This short distance and the 3.9 GW thermal power of the reactor provide a neutrino flux of more than $10^{13}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$ at the experimental site. The experiment is located within the containment sphere of the reactor and it has an overburden of $\sim (10-45)$ m w.e. (varying depending on the zenith angle). As discussed in lecture 7, the reactor undergoes regularly off times which last two to three weeks. This off periods give the possibility to measure the surrounding background such that it can be subtracted from the spectrum when the reactor is on.

CONUS employs **four 1 kg low-background germanium crystals** with an energy threshold around 300 eV. Figure 9 shows a photograph of the experimental setup including the germanium detectors and the shielding (led in grey, scintillator panels in black and polyethylene in white).

The crystals are installed inside a **multilayer shield**. It consist of several layers of lead adding up to 25 cm in total to shield the detectors from environmental radioactivity. In between there are borated polyethylene layers employed to moderate and capture neutrons. In an outer layer, there is an active muon veto system consisting of plastic scintillator plates equipped with two to four photomultiplier tubes. The shield was set up for testing at the shallow depth laboratory at MPIK and measurements with one germanium detector were taken to investigate the shielding performance.

CONUS has collected an exposure of 245 kg $\cdot$ d with the reactor turned on and 59 kg $\cdot$ d with the reactor turned off [16]. Combining this data, the best limit on CEνNS of $\overline{\nu}_e$ off germanium nuclei has been placed. Further data has been collected which will significantly reduce the statistical uncertainty allowing eventually for a measurement of this process.

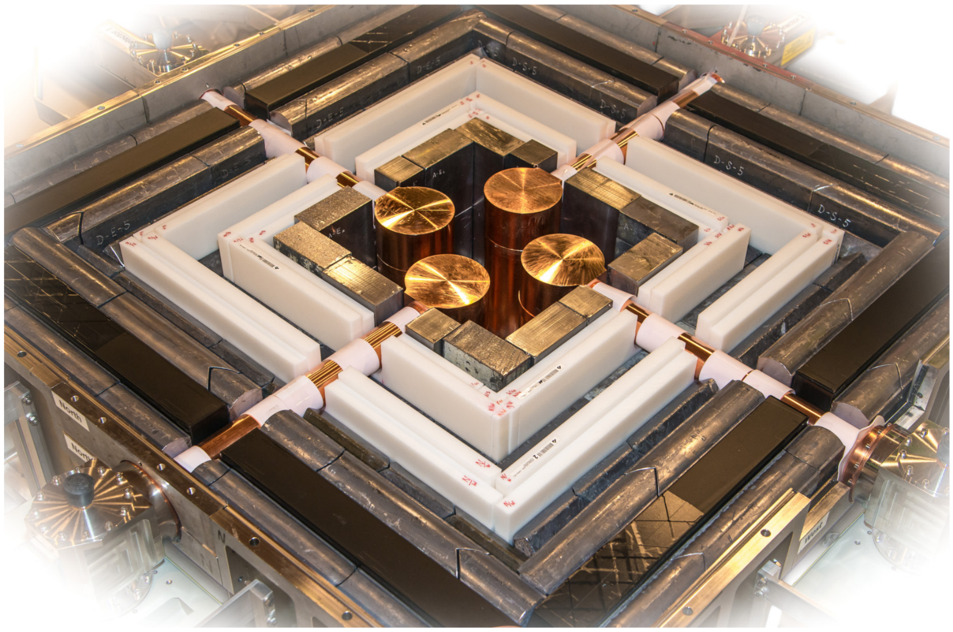

Figure 9. Photograph of the CONUS neutrino experiment at Brokdorf. Figure from the MPIK homepage by R. Lackner.

Experiments aiming to measure **directly dark matter** via elastic scattering off nuclei are currently about to get sensitive to CEνNS. Due to their increasing size and their decreasing energy thresholds, specially the next generation of liquid xenon detectors as XENONnT and LZ will be able to measure CEνNS from solar neutrinos.

Figure 10 shows some of the results from direct dark matter detection together with the so-called **neutrino floor**. The cross section of dark matter to interact with nuclei is shown as function of the dark matter mass tested. The v-shaped curves show exclusion limits from different experiments. The regions above the curve are excluded at a certain confidence level. The thick dotted red line represent the cross section at which neutrinos interact coherently with nuclei posing an important background for dark matter searches.

At low dark matter masses, the coherent scattering of solar neutrinos (^{7}Be and ^{8}B) have the higher cross sections. Above $\approx 10\,\mathrm{GeV}/c^2$, atmospheric neutrinos and the diffuse background of supernova neutrinos limit the reach of dark matter detectors.

1.6. Summary

In this lecture, we have reviewed several aspects of the coherent neutrino-nucleus scattering process. We have learned that its measurement is challenging due to its low nuclear-recoil energy signature but once achieved, it offers plenty of possibilities to measure processes beyond the standard model of particle physics. We have discussed the relative recents measurements by the COHERENT collaboration and also shown

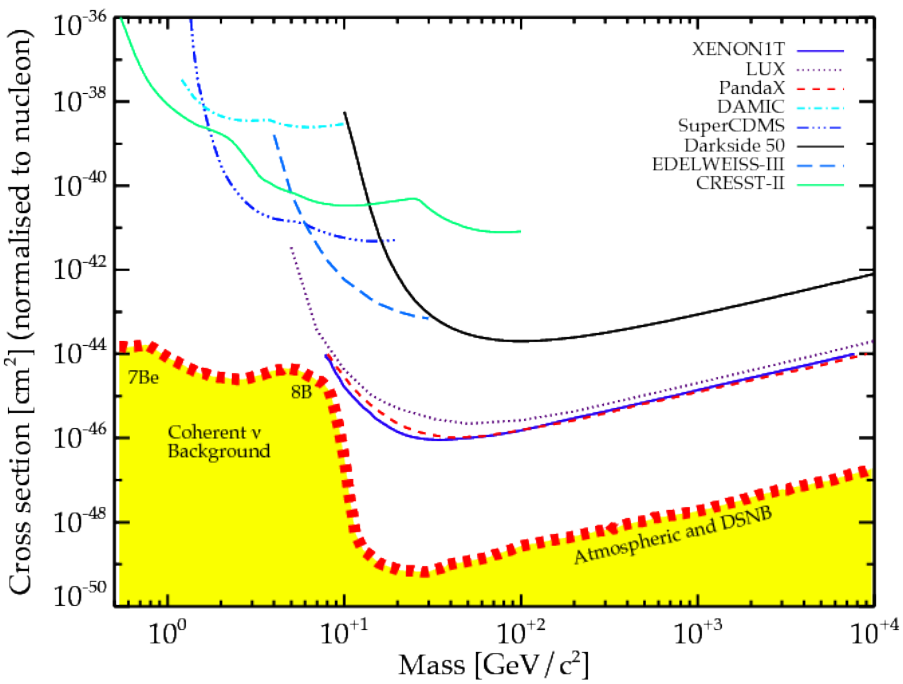

Figure 10. WIMP dark-matter search parameter space, showing 'neutrino floor' from CEνNS of solar, diffuse background from supernova and atmospheric neutrinos as a thick dashed orange line, relevant for spin-independent WIMP-nucleon interactions. Figure from [17].

what is planed for the near future.

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