A novel experiment for coherent elastic neutrino nucleus scattering: CONUS

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Abstract. The CONUS experiment (**CO**herent elastic **N**e**U**trino nucleus **S**cattering) aims at detecting coherent elastic neutrino nucleus scattering of reactor antineutrinos on Germanium. The experiment will be set up at the commercial nuclear power plant of Brokdorf, Germany, at a distance of ∼17 m to the reactor core. The recoil of the nuclei hit by the antineutrinos is detected with four high-purity point contact Germanium detectors with a very low threshold and an overall mass of about 4 kg. To suppress the background, the setup is equipped with a shell-like passive shield and an active muon veto system. The shield and the muon veto have successfully been tested at the shallow depth laboratory at Max-Planck-Institut für Kernphysik. Monte Carlo simulations have been performed to reproduce the prompt muon-induced background and to examine the induced neutron spectrum. Currently, the low threshold Germanium detectors are characterized and the experiment is prepared for commissioning.

1. Introduction: Coherent elastic neutrino nucleus scattering (CEνNS)

In coherent elastic neutrino nucleus scattering the neutrino interact simultaneously with all nuclei of a nucleus. The cross section scales with N^2, where N is the number of neutrons in the nucleus. To ensure a coherent interaction, the wavelength of the momentum transfer must be larger than the size of the nucleus, which results in an upper limit for the neutrino energy (for Germanium (Ge): full coherency below 30 MeV, semi-coherent up to 50 MeV). Predicted as a standard model interaction in 1974 [1], its precise measurement can be used to test the model and each deviation found can point at physics beyond the standard model [2]. The interaction is also relevant for dark matter experiments looking for weakly interacting massive particles, which are supposed to leave a signature indistinguishable to CEνNS in the detector. Thus CEνNS is forming a background, which needs to be understood and quantified [3]. Moreover, coherent scattering occurs in star collapses, where most of the released energy is carried away by neutrinos and therefore CEνNS has to be taken into account in the respective models [4]. Furthermore, the CEνNS cross section contains the Weinberg angle θ_W, which is usually determined at high energies in the GeV region at colliders [5]. CEνNS gives an excellent opportunity to evaluate the value in the MeV region, given a precise enough measurement of the cross section.

CEνNS has been first detected very recently by the COHERENT collaboration with 14.6 kg of CsI crystals at a neutron spallation source with neutrino energies of several tens of MeV [6]. The results are in agreement with the standard model within one sigma, with 134±22 events

detected and 173±48 predicted. The CONUS experiment, described in the following in detail, aims at detecting CEνNS on Ge nuclei at energies below 8 MeV, as the antineutrino source will be a nuclear power plant.

2. Requirements for the detection of CEνNS

CEνNS is detected by the recoil of the nucleus hit by the neutrino. The recoil scales with $\frac{1}{m_N}$, m_N being the mass of the nucleus. This leads to a push-pull situation as the cross section is proportional to the neutron number squared. Therefore, neither low nor high mass nuclei are beneficial for detection, but something in between like e.g. Ge. For example a 10 MeV neutrino will induce a maximum recoil of 3 keV in Ge. However, this energy is not fully available for detection, but because of the quenching effect only a fraction of this energy will be converted into ionization energy. This is commonly described by the Lindhard theory, which predicts for 3 keV recoil in Ge a quenching factor of ∼0.2, leading to a detectable ionization energy below 600 eV [7]. Especially towards low energies relevant for CEνNS, up to now, there are no precise measurements of the quenching factor (for Ge), which is a large source of uncertainty in the interpretation of the measurement results (see Figure 1 for the influence of quenching on the signal).

To be able to detect such a low signal, several requirements have to be met. A neutrino source with a high flux and energies within the coherent regime is required, which for CONUS will be a commercial nuclear power plant. Moreover, detectors with a sufficiently low energy threshold are needed, which are novel high-purity point contact Ge detectors for CONUS. To make the signal clearly visible, the background has to be suppressed as much as possible and thus CONUS has a shell-like passive shield against external natural radiation and an active muon veto. The three components of the experiment will be discussed in detail in the following.
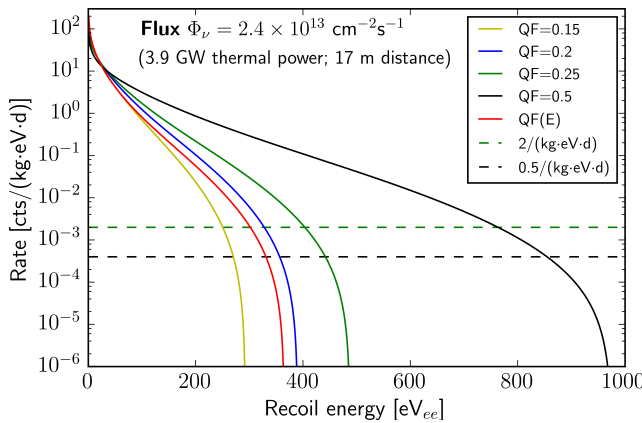

Figure 1. Feasibility study by CONUS collaboration (3.9 GW reactor at 17 m distance to reactor core): Expected CEνNS signal for various values of the quenching factor and different background levels. The energy-dependent quenching factor QF(E) is given by the Lindhard theory.

3. The source: Nuclear reactor

The CONUS experiment will be set up at the nuclear power plant in Brokdorf, Germany, at a distance of about 17 m to the reactor core. The commercial nuclear power plant has a maximum thermal power of 3.9 GW and a high duty cycle guaranteeing a constantly high antineutrino flux of more than 10^{13} s^{-1}cm^{-2} at the experimental site. The experiment will be located within the containment sphere of the reactor where an overburden of ∼10-45 m w.e. depending on the zenith angle shields against cosmic radiation. The antineutrino energies reach up to 8 MeV meaning all interactions will be well within the coherent regime. The reactor undergoes downtimes regularly for two to three weeks, which gives the possibility to measure the background and subtract it from the spectrum detected when the reactor is on.

4. Detectors for CONUS: Threshold + Quenching

To detect the CEνNS signal, a low enough energy threshold is required. A feasibility study by the CONUS collaboration for a Ge based reactor experiment at 17 m distance from the reactor core suggests that the threshold should be not much higher than 300 eV, especially regarding the large uncertainties on the quenching factor (see Figure 1). For CONUS this will be achieved with high-purity point contact Ge detectors with a total mass of about 4 kg (manufacturer Mirion Technologies). To enable the low energy threshold an important contribution is provided by electrical cryocooling, which is also beneficial for the reactor environment for safety reasons. Figure 1 illustrates as well how important a low background is to make the signal clearly visible. To achieve this background regarding the detectors, electro-polished copper cryostats have been constructed. Additionally, all parts inside the cryostat are tested on their radioactive purity and selected such to minize their contribution to the background. Cryostats and diodes are stored underground whenever feasible to avoid cosmogenic activation.

5. CONUS shield

5.1. Shield concept

Background suppression at shallow depth is a special challenge as the muon flux is only slightly reduced by the overburden. The CONUS shield is based on the shield design for the Ge spectrometer GIOVE at the shallow depth laboratory of Max-Planck-Institut für Kernphysik (MPIK) ($\sim$15 m w.e.) [8]. The GIOVE shield consists of a shell-like passive shield and an active muon veto. It could be demonstrated successfully that background rates comparable to low background Ge detectors located up to several 100 m w.e. deeper underground can be achieved. In particular, the background rate in the energy interval [45,50] keV lies below the one of other Ge based reactor experiments even with a larger overburden (see Table 1). The GIOVE detector does not have a particularly low energy threshold, however, a flat background except for lines is assumed towards energies below 45 keV as found in comparable experiments [9, 10].

For the CONUS experiment the GIOVE design was used as starting point and was optimized with focus on lower energies (see Figure 2). Like for GIOVE, there is an active muon veto system consisting of plastic scintillator plates equipped with two to four photomultiplier tubes. The shell-like passive shield consists of several layers of lead (25 cm in total) to shield against natural radioactivity. Especially the innermost layer is also made out of lead in contrast to the GIOVE shield. Borated polyethylene layers are employed to moderate and capture neutrons and the whole shield is enclosed in a radon tight steel cage. The shield has been set up for testing at the shallow depth laboratory at MPIK, where the GIOVE detector is located as well. In the first phase, the high-purity coaxial Ge detector CONRAD ($m_{act} \approx 1.9$ kg) is used to examine the radiopurity of the shield and the muon veto performance.
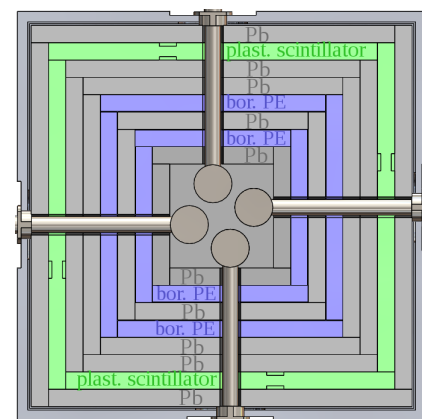

Figure 2. CONUS shield, view from above.

5.2. Measured background in CONUS shield with CONRAD detector

The measured background of the CONRAD detector in the CONUS shield compared to the GIOVE setup is displayed in Figure 3, both with active muon veto turned off. At the shallow depth of 15 m w.e. the background is dominated by muon-induced bremsstrahlung in the shield layers. It is clearly visible that below $\sim$700 keV the background in the CONUS shield is significantly lower than in the GIOVE shield. This is because the innermost layer in the
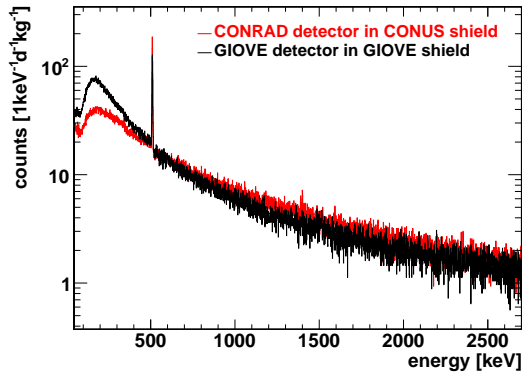
Figure 3. Comparison of muon-induced background in GIOVE and CONUS shield with active muon veto turned off.
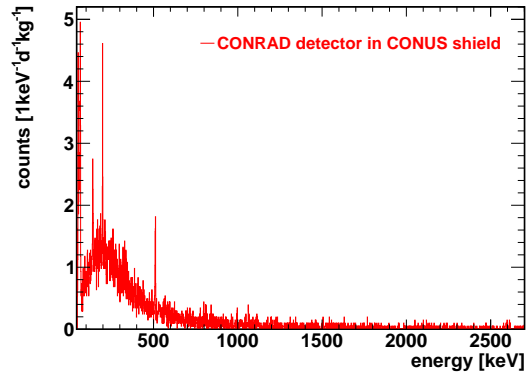

Figure 4. Background spectrum in CONUS shield with active muon veto, measured with CONRAD detector.

CONUS shield is lead, while for the GIOVE shield it is copper. In lead muons induce more bremsstrahlung than in copper ($\propto Z^2$ with Z the atomic number), however, the self-shielding is even better ($\propto Z^5$), resulting in an overall lower background in the low energy region.

When switching on the active muon veto, the background drops by two orders of magnitude as displayed in Figure 4. Overall, a veto efficiency close to 99% is achieved comparable to the GIOVE setup. In the remaining background nearly no lines from radioactive contaminations are visible. The only apparent lines are the 511 keV line and lines from neutron-induced metastable Ge isotopes with lifetimes longer than the veto window of 160 μs. All in all, Table 1 shows that the desired low background level in the [45,50] keV energy interval has been achieved, even though the integral is slightly larger than for GIOVE.

Table 1. Comparison of background rates in [45,50] keV energy interval for Ge based reactor experiments and detectors located at the shallow depth underground laboratory at MPIK.

detector	depth [m w.e.]	μ flux reduction	Bkg rate [45,50] keV [kg^{-1}d^{-1}keV^{-1}]
Gemma-I[9]	70	~ 10	2.1±0.7
Texono[10]	25	~ 4	1.3±0.5
GIOVE[8]	15	$\sim$2-3	0.4±0.1
CONRAD	15	$\sim$2-3	0.8±0.1

5.3. Muon-induced background: Monte Carlo simulation for CONRAD detector

The muon-induced background in the CONUS shield with active muon veto off has been successfully reproduced in a Monte Carlo simulation with the simulation framework MaGe [11], based on Geant4 [12, 13]. The procedure, developed for the GIOVE setup [14], starts with the calculation of the muon spectrum in the underground laboratory, which is then used as input for the simulation, where the muons are propagated through the shield and arrive at the detector. Comparing the simulation results to the measured data, the agreement is slightly less than achieved for the GIOVE, but still within 7% (see Figure 5).

5.4. Neutron background in CONUS

From the Monte Carlo simulation output, also the neutron spectrum at the diode is obtained, as depicted in Figure 6, showing that mostly fast neutrons around 1 MeV arrive at the diode.
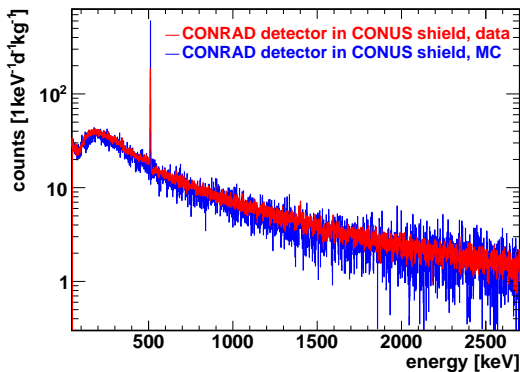
Figure 5. Background spectrum in the CONUS shield with active muon veto off, compared to the results of the Monte Carlo simulation of the muon-induced background.
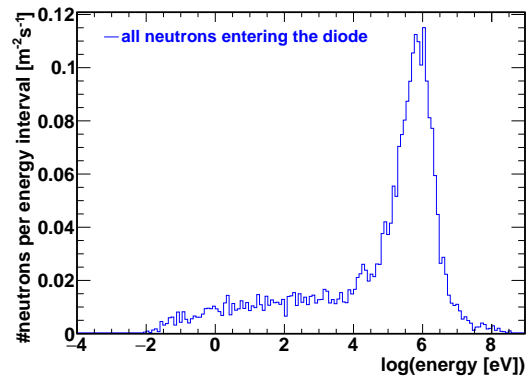

Figure 6. Spectrum from Monte Carlo simulation of all muon-induced neutrons arriving at the diode.

Fast neutrons are an important background component for CEνNS detectors as they can leave a signal-like signature in the detector. For the shallow depth laboratory at MPIK this background contribution can be quantified and understood. Moving to the nuclear power plant at Brokdorf, the overburden will become slightly bigger, but there is an additional potential neutron source, the reactor core. Currently, in cooperation with the National Metrology Institute of Germany (PTB Braunschweig) measurements of the neutron background on site are carried out. Monte Carlo simulations are done as well, propagating the neutrons from the reactor core to the future location of the CONUS experiment. First results indicate that the contribution from the reactor is predominately given by thermal neutrons that can be shielded very well. The majority of fast neutrons will be produced by muons in the shield, comparable to the situation in the laboratory at MPIK.

6. Summary and outlook
The CONUS experiment is looking for coherent elastic neutrino nucleus scattering with high-purity point contact Ge detectors with a total mass of $\sim 4\,\mathrm{kg}$ and very low energy thresholds. The shield has already been set up up at MPIK for testing and the desired background rate of $< 1\,\mathrm{kg}^{-1}\mathrm{d}^{-1}\mathrm{keV}^{-1}$ in the [45,50] keV could be achieved. Next, the experiment will be moved to the nuclear power plant of Brokdorf, Germany, and data acquisition will start within 2017.

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