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The CONUS+ experiment

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With the CONUS reactor antineutrino experiment, the coherent elastic neutrino nucleus scattering (CEνNS) on germanium nuclei was studied at a nuclear power plant in Brokdorf, Germany. Very low energy thresholds of about 210 eV were achieved in four 1 kg point contact germanium detectors equipped with electric cryocooling. Strong constraints on the CEνNS rate which are less than a factor 2 above the signal predicted by the Standard Model were achieved. In 2023, the CONUS setup was moved to a new site, a power plant in Leibstadt, Switzerland. There the CONUS+ experiment continues data taking with improved detectors at even lower energy thresholds and an optimised shield design. The setup was positioned at a distance of about 20.7 m from the center of the reactor core. The detector performances after the first few months of data taking will be described and future perspectives are discussed based on the recently collected new data.

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1. Introduction

The most common channel to detect electron antineutrinos emitted from nuclear reactors is the inverse beta decay (IBD) on free protons. In coherent elastic neutrino nucleus scattering (CEνNS), first predicted on the basis of the Standard Model (SM) in 1974 [1], the cross section is orders of magnitudes higher than in IBD or neutrino-electron scattering processes as shown in Fig. 1. For this reason, detectors based on CEνNS can in principle be built much more compact, kilogram instead of ton scale, as compared to IBD based setups. The CEνNS cross section scales with the squared number of neutrons in the target nuclei. On the other hand, the nuclear recoil energy is inversely proportional to the mass of the target nucleus.

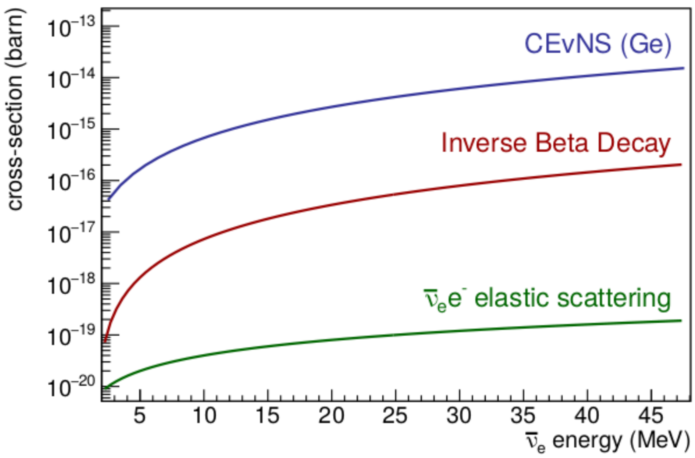

Figure 1: The energy dependent cross sections of an antineutrino interacting with an electron (scattering), a proton (IBD) or a Ge nucleus (CEνNS) are compared. The CEνNS cross section increases for higher mass nuclei.

To detect a neutrino signal, the nuclear recoils of the target nuclei need to be measured. The challenge is the low energy of such events. The first CEνNS observation was achieved in the COHERENT experiment [2]. In this case, a spallation neutron source (SNS) produced neutrinos of different flavors in pion decays at rest. The energies of the neutrinos created in the SNS are up to 50 MeV. More recently hints for CEνNS interactions from solar neutrinos were found in liquid xenon detectors constructed for direct dark matter detection [3, 4]. Nuclear reactors are a strong source of pure electron antineutrinos with energies in the range of few MeV. In this energy regime, the nuclear form factor is close to 1 which assures full coherency. Therefore, the sensitivity for some beyond the SM (BSM) physics is enhanced as compared to pion decay at rest sources.

In general, three main requirements have to be fulfilled for CEνNS detection. First, one needs a strong neutrino source to collect sufficient statistics. Second, a low background environment is mandatory. One challenge in this regard is, that the detectors are typically operated at shallow depth, close to the sources which are on the Earth surface. Finally, the detector technology has to guarantee a very low energy threshold to be able to detect the tiny nuclear recoil energies.

2. Results from the CONUS experiment at the Brokdorf reactor

In the CONUS experiment [5], the detector was positioned at 17.1 m from the 3.9 GW (thermal power) reactor core of the nuclear power plant in Brokdorf, Germany (KBR). At maximum power, the estimated neutrino flux at the detector location was $2.3 \cdot 10^{13}\ \mathrm{s}^{-1}\mathrm{cm}^{-2}$. The integrated effective overburden at the experimental site was calculated to be about 24 m w.e. Four p-type point contact high purity germanium (HPGe) detectors [6] with a diode crystal mass of about 1 kg each were used to search for the CEνNS signals. These HPGe detectors are characterized by a high pulser resolution and extremely low background rates. Due to safety constraints when operating in the control zone of a nuclear reactor, an electrical cryo-cooling system was attached to the detectors. The detectors were surrounded by a compact shield with a mass of about 11 tons. Layers of radiopure lead supress background from external γ-rays, layers of polyethylene were included to reduce the neutron flux and finally plates of plastic scintillators were used as an active muon veto system. This shield design provides an overall background reduction of about four orders of magnitude. This way, a background rate of about 10 counts/(keV kg d) was found below 1 keV [7].

For the final period of data taking at KBR (Run-5) a new DAQ system was utilized. The more sophisticated trigger algorithms of this system allowed to reduce electronic noise contributions as compared to previous datasets. Moreover, microphonic noise from the detector cryocoolers was significantly reduced by a reduction and stabililization of the room temperature. With these improvements, it was possible to lower the detection threshold from about 300 eV to 210 eV. The spectrum in the energy region of interest is well described by our physical background model. Microphonic or electronic noise contributions were becoming subdominant.

The data with reactor-on and off are fitted simultaneously for all detectors with a likelihood function. An important contribution to the systematic uncertainties arises from ionization quenching in the germanium material. The quenching factor, which is defined by the ratio of the ionization signals of nuclear recoils over the one from electrons of the identical energy, can be described by the modified Lindhard theory [8]. This quenching factor and the related quenching parameter k of the Lindhard theory was measured for nuclear recoil energies in the range of 0.4−6.3 keV using a neutron beam at the Physikalisch-Technische Bundesanstalt in Braunschweig, Germany. Good agreement between the Lindhard theory and the experimental data was found at a quenching parameter of $k = 0.162 \pm 0.004$ [11]. A reported CEνNS signal [9] at a nuclear reactor prefers ionization quenching that significantly deviates from the modified Lindhard theory at sub-keV energy. Such an excess of the quenching factor at low energies as compared to the theory predictions was found in [10], conflicting with the results in [11]. Nevertheless, measurements from the datasets in [10] (iron-filtered and photo-neutron data) were also tested in the CONUS Run-5 analysis [12]. A linear fit has been used for the iron-filtered data below 1.35 keV$_{nr}$, whereas a cubic-like fit was used for the photo-neutron data as shown in figure 2.

The predicted number of CEνNS events in the CONUS detectors are given in table 1. From the combined likelihood fit, an upper limit at 90% C.L. of less than a factor 2 above the predicted value using the Lindhard theory was found. This corresponds to a sensitivity improvement of an order of magnitude as compared to the previous CONUS analysis [5]. In the same table, signal predictions and CONUS constraints are listed for enhanced quenching factors towards lower energies which lead to higher predictions for the antineutrino interaction rate. There is partly tension with the

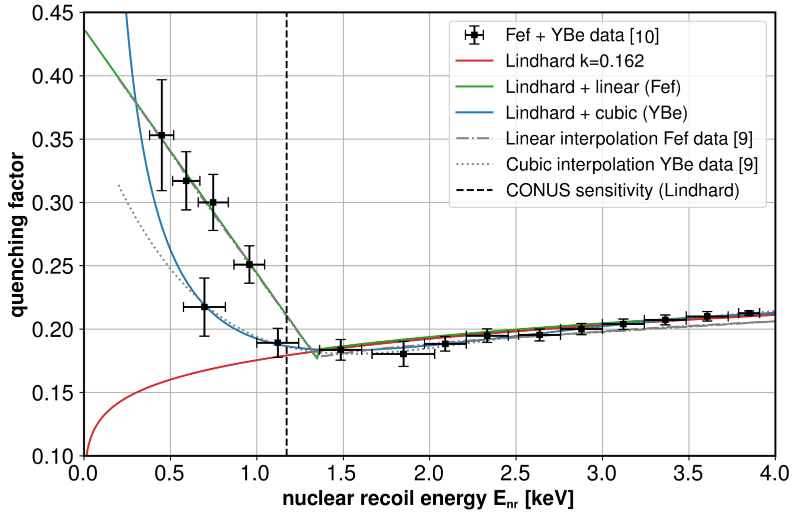

Figure 2: Quenching descriptions used in the final CONUS analysis. A rising quenching factor has been measured in [10], while the Lindhard model has been confirmed by [11]. The vertical dashed line indicates the mean effective threshold of the CONUS detectors in the Lindhard model. For the other descriptions this line would shift towards lower energies, but not below 0.5 keV$_{nr}$.

CONUS data, in particular for the prediction based on the data using the iron-filtered neutron beam.

Table 1: Predicted signal events for the CONUS Run-5 exposure and experimental constraints for different quenching descriptions extracted from a one-sided hypothesis test [12].

quenching description	prediction	Run-5 limit (90% C.L.)
Lindhard (k=0.162 [11])	91^{+11}_{-9}	143
linear low E excess [10]	645^{+59}_{-90}	99
cubic low E excess [10]	115^{+13}_{-11}	122

These results indicate either a bias in part of the quenching measurements of [10], an underestimated reactor-correlated background in [9], or BSM physics beyond the CEνNS rate estimated in [9]. Independent of the correct quenching factor, from a comparison of the experimental parameters in CONUS and in the experiment at the Dresden-II reactor such as background level, energy resolution, threshold and statistics, a signal should have been seen in the Run-5 CONUS data in case the excess reported in [9] originates from CEνNS or BSM neutrino physics.

3. The CONUS+ experiment

Since the operation of the KBR reactor was stopped end of 2021, the CONUS setup was moved to a new location at the nuclear power plant in Leibstadt, Switzerland (KKL). At this boiling water reactor with a nominal thermal power of 3.6 GW, the experiment continues its search for CEνNS under the name CONUS+ [13]. Here, the setup has a distance to the reactor center of 20.7 m providing a neutrino flux of $1.5 \cdot 10^{13}\ \mathrm{s}^{-1}\mathrm{cm}^{-2}$. The effective overburden at KKL is about 7 m w.e.

In the first phase of CONUS+ which started data taking in November 2023, four refurbished HPGe detectors of CONUS were installed at KKL. The energy thresholds and trigger efficiencies improved significantly as compared to the last phase at KBR. To match the new background conditions at KKL the shield configuration had to be modified. In particular, the weaker reactor correlated gamma-ray flux and the smaller overburden at the new location, motivated the replacement of a lead layer by a second active muon veto system. The neutron flux at the KKL site was found more than an order of magnitude higher than at KBR. However, a lower contribution of ^{210}Pb is expected after the upgrade. Moreover, a network connection to the outside of the containment area was established, allowing for a continuous monitoring and control of the experimental parameters including part of the calibration program. To mitigate the contribution of radon and its decay products to the CONUS+ background the detector chamber is flushed contineously with bottles containing pressurised air.

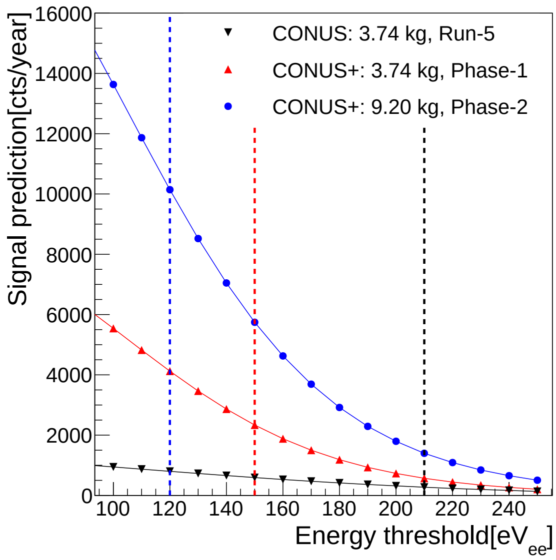

Figure 3: Expected annual integral CEνNS count rates for CONUS at KBR (black), the current CONUS+ phase (red) and after an upgrade with larger detectors of 2.3 kg active mass (blue). The corresponding energy thresholds of 210 eV$_{ee}$ (CONUS, Run-5), 150 eV$_{ee}$ (CONUS+, Run-1) and 120 eV$_{ee}$ (CONUS+ upgrade) are shown with dashed lines [13].

In a second phase of the experiment, it is planned to exchange at least part the Ge detectors by a new generation with larger crystals of about 2.3 kg (active mass) each. Since the detectors fit inside the current CONUS+ setup, no modifications to the shield are required. From preliminary characterisation studies it seems that despite the larger crystal mass the energy threshold can be lowered even more. With a threshold of 120 eV$_{ee}$ an annual count rate of more 10000 events could be achievable as shown in figure 3. This would not only increase the statistics for the CEνNS signal, but also improve the perspectives for studies of beyond the Standard Model (BSM) physics.

4. BSM limits

In the SM of particle physics, neutrinos have no electric charge or magnetic dipole moment μ_ν. However, there are extensions of the SM predicting neutrino magnetic moment values of $\mu_\nu \sim 10^{-14}\,\mu_B$. In case neutrinos are Majorana particles, there are even theoretical predictions with values for $\mu_\nu \sim 10^{-9}\,\mu_B$. Therefore, if there would be an observation for $\mu_\nu > 10^{-14}$, this might be a hint that neutrinos are of Majorana type. A magnetic moment signal in CONUS would manifest in an increased count rate towards low energies which is proportional to $1/T$ with the electron recoil energy T. The limit on the neutrino magnetic moment obtained from CONUS Run-1 and Run-2 [14] was improved after including the Run-5 data to $\mu_\nu < 5.2 \cdot 10^{-11}\,\mu_B$ (90% C.L.) [15]. Moreover, the electrical millicharge of the neutrino q_ν is now constrained to $q_\nu < 1.8 \cdot 10^{-12} e_0$ (90% C.L.) [15] with e_0 being the elementary charge.

Besides the CONUS analyses on the electromagnetic properties of neutrinos, the experiment allows to search for BSM physics such as non-standard interactions (NSIs) or light mediators [16]. Two different channels can be used in the analysis, neutrino-nucleus scattering in the region of interest of the CEνNS studies and neutrino-electron scattering which allows to extend the analysis window to higher energies. Highly competitive limits can be set with the Ge technology applied in CONUS and given the low energy of the reactor neutrinos.

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