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Results from 2015 and the 2016 upgrade of the CONNIE experiment for detecting coherent neutrino nucleus scattering

B. Kilminster, on behalf of the CONNIE collaboration
{ A. Aguilar-Arevalo[1], X. Bertou[2], C. Bonifazi[3], M. Butner[4], G. Cancelo[4], A. Castaneda Vazquez[1], B. Cervantes Vergara[1], C.R. Chavez[5], H. Da Motta[6], J.C. D'Olivo[1], J. Dos Anjos[6], J. Estrada[4], G. Fernandez Moroni[7,8], R. Ford[4], A. Foguel[3,6], K.P. Hernandez Torres[1], F. Izraelevitch[4], A. Kavner[9], B. Kilminster[10], K. Kuk[4], H.P. Lima Jr.[6], M. Makler[6], J. Molina[5], J.M. Moro[11], E.E. Paolini[7,12], Y. Sarkis[1], M. Sofo Haro[2], J. Tiffenberg[4], and S. Wagner[6,13] }

[1]Universidad Nacional Autónoma de México, Ciudad de México, México
[2]Centro Atómico Bariloche - Instituto Balseiro, CNEA/CONICET, Argentina
[3]Universidade Federal do Rio de Janeiro, Instituto de Física, Rio de Janeiro, Brazil
[4]Fermi National Accelerator Laboratory, Batavia, IL, U.S.A.
[5]Facultad de Ingeniería - Universidad Nacional de Asunción, Paraguay
[6]Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
[7]Departamento de Ingeniera Eléctrica y de Computadores, Universidad Nacional del Sur, Bahía Blanca, Argentina
[8]Instituto de Investigaciones en Ingeniería Eléctrica "Alfredo Desages", CONICET - Universidad Nacional del Sur, Bahía Blanca, Argentina
[9]University of Michigan, Ann Arbor, MI, U.S.A.
[10]Universität Zürich Physik Institut, Zurich, Switzerland
[11]Depto. de Ingeniería, Universidad Nacional del Sur, Bahía Blanca, Argentina
[12]Comisión de Investigaciones Científicas Provincia Buenos Aires, La Plata, Argentina
[13]Pontificia Universidade Católica, Rio de Janeiro, Brazil

E-mail: `ben.kilminster AT physik.uzh.ch`

Abstract. The CONNIE Experiment (Coherent Neutrino Nucleus Interaction Experiment) is currently collecting reactor neutrino data to search for the undiscovered standard model process of coherent neutrino-nucleus scattering (CNNS). The detector is composed of a silicon target of thick, fully-depleted, low-noise CCD detectors. Results from data collected in 2015 indicate backgrounds are controlled, and allow an estimate of sensitivity to be presented for a larger scale detector. A 2016 upgrade, adding additional target mass, and reducing readout noise, has been performed, increasing the total yield of signal events by a factor of 30, and already yielding science-quality data. Low-energy nuclear calibrations have been performed, enabling calibration down to the device energy threshold. An estimate of the sensitivity expected for measuring the coherent neutrino process is presented. Future prospects with improved detector energy thresholds are estimated.

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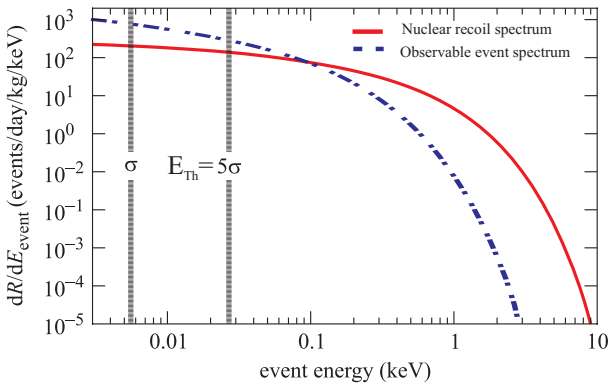

Figure 1. The nuclear recoil spectrum produced from reactor neutrinos on silicon is shown in solid red. The observable ionization yield in silicon detectors expected for this spectrum is shown in dashed blue. The σ represents the noise previously achieved with the CONNIE CCDs. The detection threshold is set to 5σ to suppress electronic noise.

1. Introduction

The standard-model process of neutrinos coherently interacting with the nucleons of a nucleus was predicted in 1974 [1], but has not yet been measured. The rate is higher than other neutrino interactions due to the coherent enhancement proportional to the square of the atomic number Z and neutron number N. Despite this higher rate, the process has escaped detection, since for neutrino energies in the MeV-range as produced by nuclear reactors, the nuclear recoil energies are only in the keV range,

$$E_r = \frac{2}{3}\frac{(E_\nu/MeV)^2}{A} keV. \tag{1}$$

This signal is further stifled by the low ionization signal produced in a nuclear recoil. For detectors composed of silicon nuclei, predictions from the Lindhard theory [2], show a non-linear decrease in this ionization efficiency that decreases to less than 20% for nuclear recoils with energy below 1 keV.

Accounting for the neutrino energy spectra produced in a nuclear reactor, the expected cross-section for neutrino-nucleus interactions, the produced nuclear recoil energy, and the ionization yield that would be produced in silicon, the energy distribution that needs to be measured is mostly below 100 eV, as is shown in Figure 1. The small energy deposits are the reason that this process has not yet been observed. Shown also in this figure are the noise and energy threshold achieved by the CONNIE experiment, which is outlined in the following sections.

2. CONNIE experiment using CCD detectors

The CONNIE Experiment (Coherent Neutrino Nucleus Interaction Experiment) makes use of CCD detectors to detect nuclear recoils of neutrino interactions. The CCDs designed by LBNL[3] are thick, silicon semi-conductor devices with a low-electronics noise of < 1.8 e$^-$, making them ideal for searching for low-energy scattering. These CCD detectors have been used in searches for the nuclear recoils of low mass dark matter [4][5]. To suppress this noise, an energy threshold 5 times larger is used to search for signal.

3. 2015 engineering run at Angra-II

Using four 1-gram CCD detectors, a prototype experiment to measure coherent neutrino scattering was conducted at the Angra 2 reactor facility in Brazil. The experiment is located

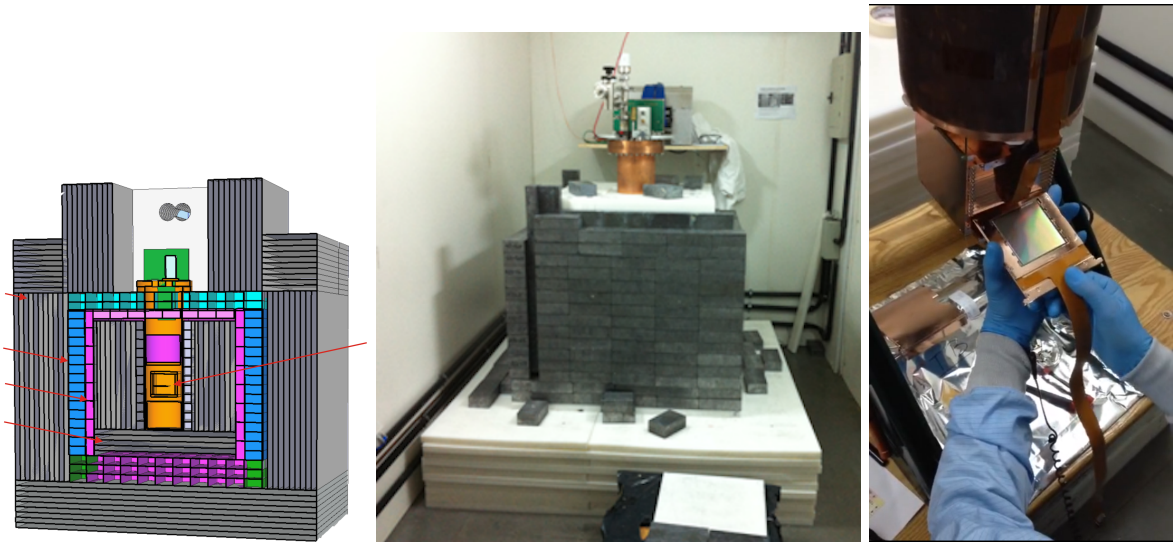

Figure 2. Left: design of the CONNIE experiment. Grey represents polyethylene, blue, pink and green are lead, and the orange is the copper dewar. Middle: Partial assembly of CONNIE shielding showing the top of the copper dewar which holds the detectors, along with the readout electronics on top, Right: CCD detectors being installed in the copper box in the dewar.

in a shipping container located 30 meters from the core of Angra 2, which produces 3.8 GW_{th}, such that the flux of neutrinos at the detector is $7.8{\cdot}10^{-12}$ ν/s/cm^2. Data were collected during periods with the reactor on and off (R_{ON} and R_{OFF}) in order to identify backgrounds from the reactor. The CCDs were maintained at -140 °C inside a copper box in a copper vacuum vessel (10^{-7} torr), that is shielded from radioactive backgrounds. Aspects of the detector are shown in Figure 2. More information on the experimental setup is found in Ref. [6].

4. CCD calibration and backgrounds

The energy scale and energy resolution of the CCD devices have been calibrated using electron recoils from X-rays with an energy range from 277 eV to 60 keV. In addition, an in situ calibration was done during data taking, taking advantage of known K_α and K_β copper fluorescence peaks produced by gamma backgrounds. Rate measurements of these peaks show no increase in gamma background was found between the R_{ON} and R_{OFF} datasets. The rate of muon backgrounds, prevalent at a surface detector, have a unique signature of a cluster of pixels in a straight line, and were also verified.

Nuclear recoils from neutron interactions leave an indistinguishable signature from the neutrino signal, and it is important to establish the level of cosmogenic neutrons as well as those from the reactor. However, neutrons also provide a calibration source for the ionization efficiency. Members of our collaboration have produced, with others, two independent calibrations of the nuclear recoil ionization efficiency down to low nuclear recoil energies [8][9]. The results of these indicate a consistent departure from the Lindhard theory at low energies. Whereas Lindhard theory has been assumed for the analysis of the 2015 data, future CONNIE results will utilize these new calibrations.

5. Data analysis

In 2015, the CCD detectors collected 14.8 days of R_{ON} data and 18.8 days of R_{OFF} data. Signal events were selected by summing up the energies of neighboring pixels into circular clusters, and

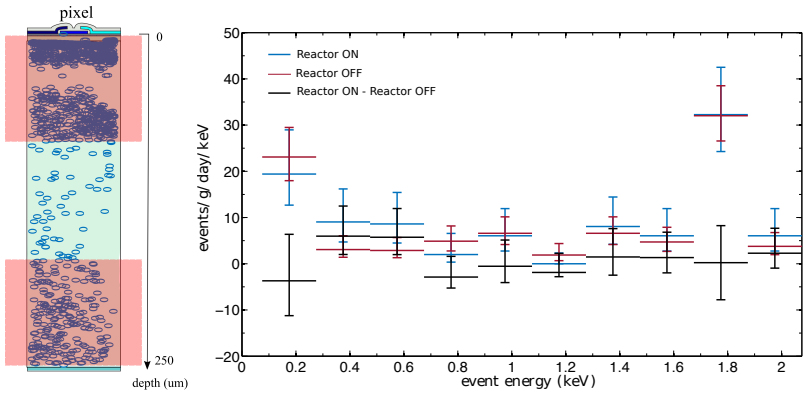

Figure 3. Left: Location of signal candidates within the detector as determined by the lateral size of the pixel clusters. Right : Energy spectrum of events in the CONNIE data set, for both R_{ON}, R_{ON}, and R_{ON}-R_{OFF}.

selecting events with energy in the range between 75 eV and 1 keV. Events occurring near the surfaces of the detector are rejected using cuts on the RMS size of the cluster which depends on the depth in the CCD. Figure 3 shows the event candidates as a function of depth and the energy spectrum of the R_{ON}, R_{OFF} and R_{ON}-R_{OFF} data. There is no statistically significant difference in the background rates with the reactor on and off, which is consistent with expectations from the reactor particle flux, with simulated shielding configurations. Results of the 2015 CONNIE experiment can also be found in Ref. [6] and [7].

6. CONNIE 2016/2017 prospects

After the 2015 run, CONNIE was upgraded in 2016. The CCD packaging was modified to remove observed 15 keV peaks in the 2015 energy spectrum that were attributed to ^{238}U decay chain products in the CCD frame. New thicker, larger CCDs were fabricated, increasing the mass of each detector. The number of CCDs was increased from 4 CCDs up to 14 CCDs. The energy threshold was lowered to 35 eV, after a charge-injection problem was identified in the CCD output stage that was causing the noise to be 2.7 e- in the 2015 run rather than the expected 1.8 e-. Using extrapolations based on these improvements, it was estimated that a 3σ detection of CNNS could be possible with 150 days of R_{ON} data. The planned improvements were all implemented in 2016, and data has since been accumulated.

7. CONNIE beyond-2017 prospects

We have demonstrated several methods for reducing readout noise that can be used to improve the sensitivity to CNNS by increasing the accepted signal events above the energy threshold. Digital filtering of the video signal has achieved 0.5 e^- [10] noise, and non-destructive "skipper" CCD readout has achieved 0.2 e^-[11]. Deploying such techniques would allow the CCD detectors to measure more of the low-energy part of the spectrum, allowing them to measure the CNNS process with more precision or with lighter devices. The gains in energy threshold from these techniques are shown in Figure 4.

8. Summary

The engineering run of the CONNIE experiment in 2015 has shown promising results in terms of understanding detector response and backgrounds. An upgrade of the CONNIE experiment in 2016 has increased the expected signal yield by more than a factor of 20, and evidence of the

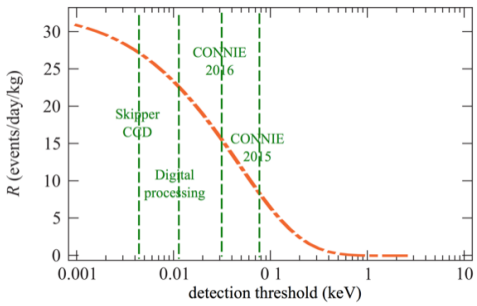

Figure 4. Improvements in the detector energy threshold, compared to the expected energy spectrum of CNNS interactions.

CNNS process seems soon within reach. Future detectors using energy thresholds a factor of 10 smaller have been demonstrated and would enhance sensitivity significantly, also allowing for smaller devices, that could be capable of detecting neutrinos from reactors.

Table 1. Improvements in CONNIE 2016/2017

Improvement	2015	2016/2017
# CCDs	4	14
Single detector mass [g]	1	5.97
Detector thickness [μm]	250	675
Detector mass [g]	4	83
CCD noise [e-]	2.7	1.8
Energy threshold [eV]	75	35
#ν/kg/d	8	13
Total # neutrinos per year	$\sim$ 12	$\sim$ 400

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