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Upgraded CONNIE experiment with Skipper CCDs

/ *CONNIE First results with Skipper-CCDs*

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The Coherent Neutrino-Nucleus Interaction Experiment (CONNIE) is located at a distance of 30 m from the core of the Angra-2 nuclear reactor in Rio de Janeiro, Brazil. Its goal is to detect the coherent elastic scattering of reactor antineutrinos, known as CEνNS, off silicon nuclei using fully depleted high-resistivity charge-coupled devices (CCDs). Running since 2016, the experiment has set upper limits on the CEνNS rate and placed stringent constraints on some scenarios beyond the Standard Model involving light mediators. Recently, the collaboration has also explored the experiment's sensitivity to other exotic scenarios such as millicharged particles. With the purpose of further reducing the energy threshold, two Skipper CCDs were installed in the summer of 2021. The collaboration has demonstrated stable operation of the new sensors with a readout noise of 0.15 electrons and a single-electron rate of 0.05 e-/pix/day. New techniques have been developed to reduce the effects of instrumental backgrounds, allowing to reach a threshold of 15 eV. In this presentation, the performance of Skipper CCDs, along with the enhanced data selection techniques employed are discussed. Preliminary results of the low energy spectrum from the Skipper data are presented. Finally, future prospects for detecting CEνNS with Skipper CCD technology are briefly mentioned.

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1. Introduction

The main goal of the CONNIE experiment is to detect the coherent elastic neutrino nucleus scattering (CEνNS) of reactor-produced $\bar{\nu}_e$ off silicon (Si) nuclei, and use this channel to search for physics beyond the Standard Model (BSM). It uses as target the high resistivity Si of thick ($>$ 600 μm) scientific charge coupled devices (CCDs) operated at cryogenic temperatures (<100 K). Ionization events liberate charge carriers that are drifted by an electric field towards the CCD surface where a series of 3-phase electrodes define a 2D pixelated structure of potential wells. Charge is collected in the wells during an exposure, after which it is physically displaced pixel by pixel by means of high frequency clocking pulses, until it reaches an amplifier where it is read out. Standard scientific CCDs have been shown to achieve very low noise (2 e^-) and low dark current (3 e^-/pix/day), leading to an energy threshold of order 50 eV. In addition to their excellent spatial resolution, owed to a 15 μm pixel size, 3D reconstruction can be achieved thanks to the effect of charge diffusion, since charge produced a distance from the top surface electrodes will tend to spread as it drifts towards them in a predictable manner. The size *vs* depth relation of energy depositions in CCDs can be used to define a fiducial volume in the Si bulk. The experiment is located in the Almirante Alvaro Alberto nuclear power plant near Rio de Janeiro, Brazil, 30 m away from the 3.95 GW$_{\text{th}}$ Angra-2 reactor core, in a standard shipping container just outside the containment dome, where it observes a flux of $\sim 7.8 \times 10^{12}$ $\bar{\nu}_e$ cm^{-2}s^{-1}. The detector (see Figure 1) was installed in 2014 and had two major upgrades, one in 2016, and one in 2021. From the outside in, an outer passive shield made of a 30 cm layer of polyethylene followed by 15 cm of lead (Pb), and then by a second 30 cm layer of polyethylene, encloses a copper (Cu) vacuum dewar inside of which a cooled Cu box holds the array of detectors located under a Pb bucket to shield them from gammas from the electronics located on the outside of the dewar and connected to the CCDs by flex cables passed through a vacuum interface board (VIB). In different phases of the experiment only the array of CCDs inside the Cu box, the VIB and the electronics have changed. Detailed descriptions of the setups and results from the earlier phases can be found elsewhere [1, 2].

2. Brief summary of CONNIE results with standard CCDs

In both, the 2016-2018 and the 2019 runs, the reactor ON and OFF spectra were consistent with one another within uncertainties, therefore the experiment reported limits on the CEνNS rate.

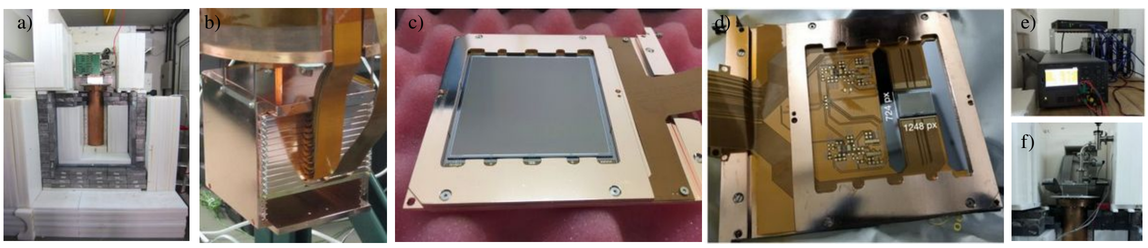

Figure 1: a) CONNIE detector; b) CCD box *c.a.* 2016; c) 16 Mpix standard CCD; d) 0.9 Mpix Skipper CCD; e) LTA electronics; f) New VIB for Skippers.

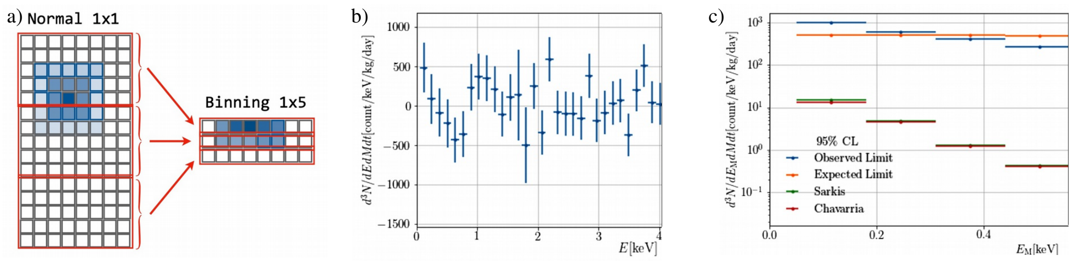

Figure 2: CONNIE 2019 data: a) Illustration of 1×5 harware binning; b) reactor ON-OFF spectrum; c) CEνNS 95% C.L. limit. (b) and (c) were adapted from Ref [1], 2022.

With the 2016-2018 data a 95% C.L. limit was placed on the CEνNS rate at 40 times the SM prediction (Ref. [1], 2019). This limit was used to impose the first competitive constraints at the time on scenarios beyond the Standard Model (BSM) with light vector and scalar mediators using CEνNS at reactors [2]. In 2019 several improvements in data acquisition and analysis techniques were implemented: *i)* a 1×5 hardware rebinning to reduce the CCD readout noise (see Figure 2-(a)); *ii)* an improved size-depth calibration based on column-aligned muon tracks and a better energy calibration; *iii)* simulation of a partial charge collection layer (PCC) in the back of the sensor improved the predicted energy spectrum; *iv)* Better characterization and reduction of low energy backgrounds resulting in a reduction of the threshold to 50 eV; *v)* used the Sarkis quenching factor model [5] for the ionization efficiency of nuclear recoils at low energies; *vi)* blind analysis and other cross checks. The 2019 data (see Figure 2-(a),(b)) yielded a softer CEνNS limit of 66-75 times the SM prediction (Ref. [1], 2022), depending on the quenching factor used, due to an upward fluctuation in the ON-OFF spectrum in the lowest energy bins. The rapid rise in the low-energy spectrum observed in the 2016-2018 run was significantly reduced in the 2019 run. A search for relativistic millicharged particles (mCP) of charge $q = \varepsilon e$ and mass $m_{\chi_q} < 1$ MeV is being conducted, based on an analysis similar to that presented in Ref. [6], using an appropriate model [7] to calculate the differential cross-section for energy transfers by the χ_q to the Si atoms. Preliminary results indicate a competitive sensitivity and will be published soon.

3. CONNIE with Skipper CCDs

In July of 2021 two 682×1022 pixels, 675 μm thick Skipper CCDs were installed in the CONNIE cold Cu box, together with the newly developed low threshold acquisition (LTA) electronics [4], and a new VIB (Figure 1-(d),(e),(f)). Skipper CCDs differ from standard CCDs in their readout stage, which is modified to allow the non-destructive repeated measurement of the pixel charges obtaining a precise average [3]. This results in a dramatic reducton of the electronic noise, allowing to count individual electrons. Typically hundreds of samplings are required to reach sub-electron resolution, significantly increasing the readout time. For this reason the Skipper CCDs were operated in "continuous readout" mode, where a non-uniform exposure is taken as the CCD is being read out. In this situation the exposure time is half of the readout time. Each sensor is read out simultaneously by two amplifiers, one for each half of 341×1022 pixels, with 400 samplings per pixel, giving a total readout time of about 2 hr per CCD.

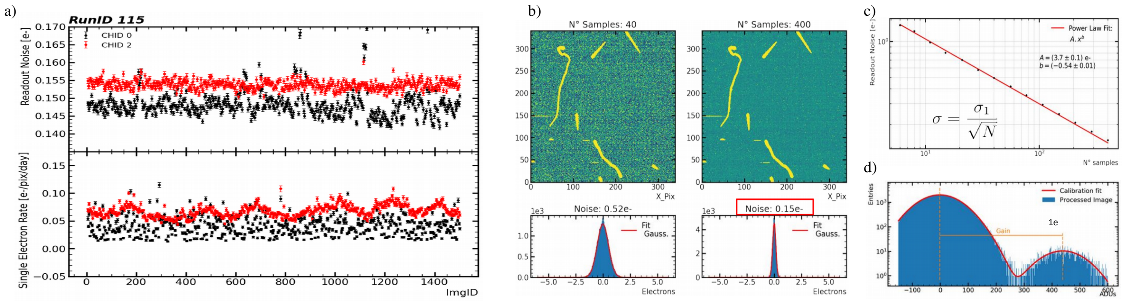

Figure 3: a) Stability of noise and $1e^-$ rate; b) Image quality with number of smples $N = 40$ and $N = 400$; c) Noise dependence on the number of samples d) The $1e^-$ and $2e^-$ peaks (3.7 eV $\approx$ 440 ADU).

The performance of the Skipper CCDs is shown in Figure 3. The stability of the readout noise at 0.147 (0.153) e^- and single electron rate (SER) of 0.04 (0.07) e^-/pix/day for CCD Ch0 (Ch2) is shown in (a), while the plots in (b) demonstrate the increased ability to identify events and the expected $1/\sqrt{N}$ dependence of the noise with the number of samples. In (d) the self-calibration of the Skipper CCD is achieved by identification of the $1e^-$ and $2e^-$ peaks to determine the gain.

3.1 Suppression of the rise in the low-energy spectrum

Four cuts were used to select events from the Skipper CCDs. I) All events must have energies above the 15 eV threshold and come from good quality images (noise <0.17 e^- and SER < 0.14 e/pix/day). II) An acceptance cut removes 10 pixels at the edge of the active region. III) A mask is formed to remove hot pixels, entire rows and columns with a large number of hot pixels, as well as rows containing any serial register events (SREs). Events with barycenter in a masked area are discarded. IV) A cut on the size of the event from a 2D Gaussian fit requiring $\sigma^X_{\rm Fit}$ and $\sigma^Y_{\rm Fit}$ to be larger than 0.2 pixels (limited by our reconstruction) and less than 0.95 pixels (from 2019 PCC layer analysis). The progressive effect of the cuts is shown in Figure 4-(a). The higer background rate around 1.74 keV is due to Si fluorescence x-rays.

SREs are short horizontal segment-like artifacts generated when a particle interacts with a region of inactive Si freeing charges that reach the horizontal serial register of the CCD during readout. An example SRE can be seen in Figure 4-(b). SREs often break up into small clusters of charge that can be misidentified as genuine low energy events. To suppress this background,

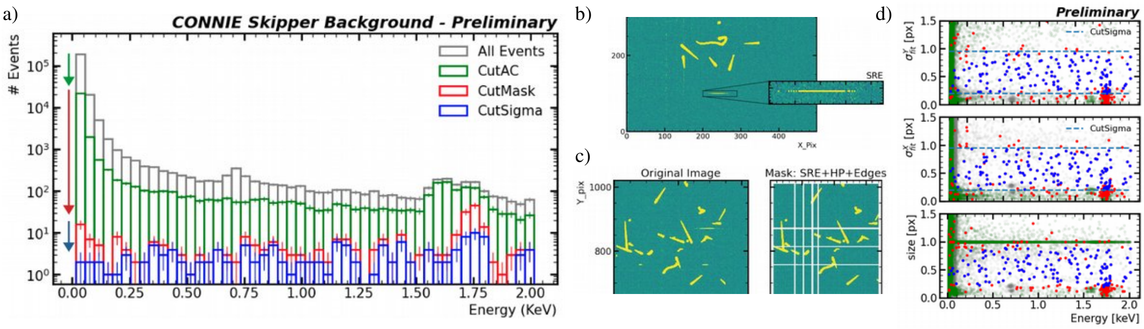

Figure 4: a) Background spectrum with progressive cuts; b) a SRE identified; c) image Mask; d) $\sigma^{X,Y}_{\rm Fit}$ cuts.

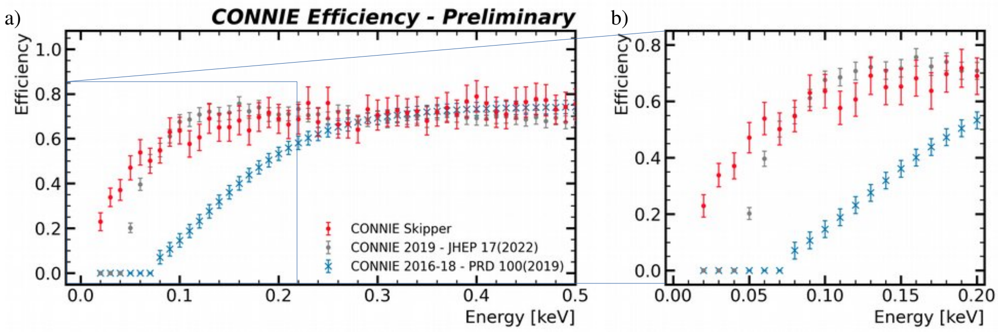

Figure 5: Comparison of the event selection efficiency in the three physics runs of CONNIE. a) In the range from 0 to 2 keV. b) Zoom to the $E < 0.2$ keV region.

an aggressive approach was adopted where the whole row containing a SRE is masked. The SRE component of the mask has the largest impact on the spectrum, seen going from the green to the red histogram in Figure 4-(a). This cut is responsible for the flattening of the low energy spectrum, demonstrating that the low-energy rise previously reported in the 2016-2018 and 2019 data (see Figure 6), was predominantly due to spurious events associated with SREs.

4. Results from the Skipper CCD run - Background measurement

The cut selection efficiency was calculated by applying the selection criteria to simulated neutrino events injected in the detectors and reconstructed as normal data, and is shown in Figure 5, compared to that obtained in the earlier physics runs of CONNIE (2016-2018 and 2019). As can be seen in the figure, in the three datasets, the efficiency reaches a flat value around 70-75% at high energies. In the 2016-2018 data the efficiency begins to drop towards the 75 eV threshold for energies below $\sim$ 300 eV, while in the 2019 data the drop begins at energies below $\sim$ 120 eV and is much more rapid, reaching a threshold of 50 eV. Compared to the 2019 data, the Skipper CCD run achieved a significant increase in efficiency below 70 eV and a lower threshold, while remaining flat for energies above $\sim$ 100 eV. Right above the threshold of 15 eV the efficiency is $\sim$ 22%.

Neglecting the small amount of CEνNS events on the reactor ON dataset, we combined them with the reactor OFF data to get a higher statistics estimate of the total background level measured with Skipper CCDs. After correcting for the selection cut efficiency, the result is shown in Figure 6, compared to the corresponding efficiency-corrected background measured in the reactor-OFF 2016-2018, and 2019 data.

5. Future perspectives

Assuming a 20 eV threshold, a CEνNS rate 2.2 times higher than in 2019 is expected. A 1 kg Skipper CCD detector at the CONNIE site with a background rate of 4 kdru should observe the reaction at 90% C.L. in 30 days, assuming the Chavarria QF. The current plan is to use the Oscura MultiChip Module (MCM) design [8] in the existing CONNIE dewar and make gradual escalations in the detector mass. CONNIE is studying the possibility to move the detector to a position under the dome, at a distance of 20 m from the reactor core.

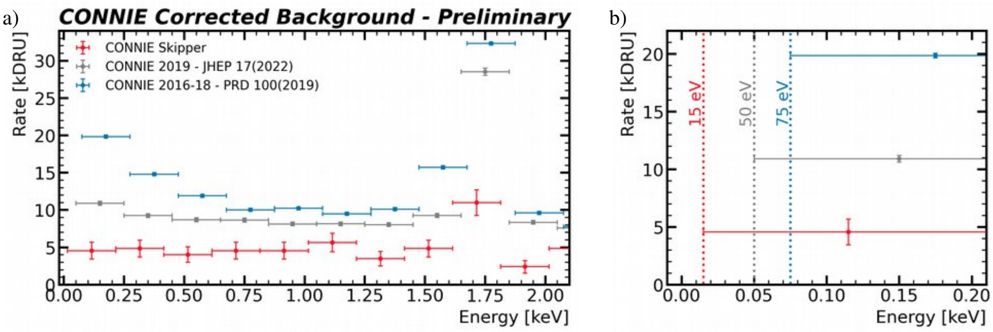

Figure 6: a) Comparison of the background rate in the 2016-2018, 2019, and Skipper CCD runs of CONNIE. b) Detail of the rates in the lowest energy bin for each run showing the energy threshold reached in each case.

6. Acknowledgements

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References

[1] CONNIE Colaboration. A. Aguilar-Arevalo *et al.*, JINST 11, 07, P07024 (2016); Phys. Rev. D 100, 092005 (2019); JHEP 05, 017 (2022)

[2] CONNIE Colaboration. A. Aguilar-Arevalo *et al.* JHEP, 04, 054 (2020)

[3] J. Tiffenberg *et al.*, Phys. Rev. Lett. 119, 131802 (2017)

[4] G. Cancelo *et al.*, J.Astron. Telesc. Instrum. Syst. 7, 1, 015001 (2021)

[5] Y. Sarkis, A. Aguilar-Arevalo and Juan Carlos D'Olivo, Phys. Rev. D 101, 10, 102001 (2020)

[6] TEXONO Collaboration. L. Singh *et al.*, Phys. Rev. D 99, 032009 (2019)

[7] SENSEI Collaboration. Liron Barak *et al.*, [hep-ex] arXiv:2305.04964 (2023).

[8] Oscura Collaboration. B.A. Cervantes-Vergara, *et al.*, JINST 18, P08016 (2023)