New Instrument for Neutrino Detection: Coherent Neutrino-Nucleus Interaction Experiment (CONNIE)

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Abstract: The capabilities and bases of a new instrument for neutrino detection using CCDs are presented. Improvements in the CCDs fabrication processes has allowed the development of devices with larger mass (from 1g to 10g are available nowadays), which together with other good features such as their extremely low energy threshold (7eV RMS) and their good spatial resolution (15um), makes them a perfect candidate for neutrinos detection. This new technique opens a new window in neutrino detection because it allows the construction of small size neutrino detectors where the reduction in the expected event rate because of the smaller volume is fully compensated by the detection of additional very low energy events. The article is intended to cover the mayor features of scientific CCDs, the relevant physics involved in the neutrino detection, and an explanation of the neutrino detection system being assembled at Fermilab, which is planned to be tested at the Angra Nuclear Power Plant in Brazil by the middle of the year (2013). The constanction, installation and running of a CCD system for detecting neutrinos is part of the CONNIE (Coherent Neutrino-Nucleus Experiment) experiment.

Keywords: neutrino detection, CCD, nuclear reactor antineutrino, Charge Coupled Devices

1 Introduction

One of the most important features of CCDs is their very low noise (7eV RMS) [3], which allows the detection of low energy depositions by neutrinos, in particular from low energy nuclear-reactor neutrinos. This low threshold enables the detection of nuclear recoils from neutrino-nucleus coherent scattering interactions, which in turns leads to an enhancement of the detectors cross section. The increase of the detected events compensates the low mass of the devices making the CCD technology competitive with current tons-massive nuclear-reactor neutrino detectors.

2 Expected events in CCDs

The neutrino-nucleus coherent scatering differential cross section is given by [7]

$$\frac{d\sigma}{dE_{rec}} = \frac{G_F{}^2}{8\pi}[Z(4sin^2\theta_w - 1) + N]^2 M(2 - \frac{E_{rec}M}{E_v{}^2})|f(q)|^2$$

where M, N and Z are the mass, neutron number and atomic number of the nucleus, respectively, E_v is the neutrino energy and E_{rec} is the nucleus recoil energy, $f(q)$ is the nucleus form factor at momentum transfer q. This form factor can be used in good approximation as $|f(q)| \sim 1$ (the corrections are a few percent only). This formula is applicable at $E_v < 50$ MeV where the momentum transfer (Q^2) is small such that $Q^2R^2 < 1$, where R is the nuclear size. At low momentum transfer, the nucleon wave function amplitudes are in phase and add coherently, so the cross section is enhanced by $\sim N^2$.

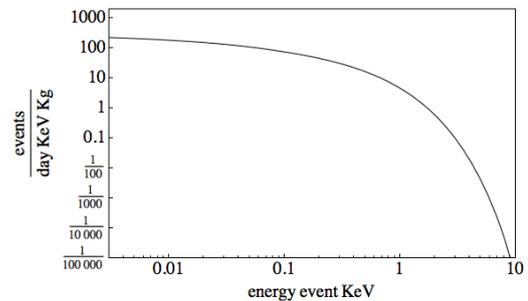Using the differential cross section, the nuclear-reactor

Figure 1: Expected nuclear recoils events from neutrinos.

antineutrino spectrum from [8, 7] and assuming a CCD at 30 meters from a nuclear reactor of 3.9GW (normal operation conditions at Angra nuclear plant) the spectrum of expected events in the detector is depicted in figure 1.

3 General aspects of the shielding design

All the experiments have to face the problem of detecting similar events produced by background particles. In particular those that are not deep underground and also have contribution from the cosmic background. From the CCD point of view, any particle that produces a ionization point event in the silicon, grouping one or a few pixels, is considered an important background signal because they cannot easily separated from a neutrino signal. Within this group are predominantly neutrons and low energy electrons and photons. Any other kind of signature on the CCD can be easily rejected by an image processing software. This last case corresponds to muons, energetic protons, energetic electrons, alpha particles, etc. Figure 2 shows a compendium of differ-
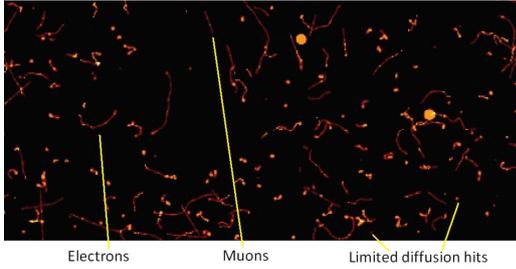
Electrons   Muons   Limited diffusion hits

Figure 2: Different kind of particles detected by a 250um-thick CCD.
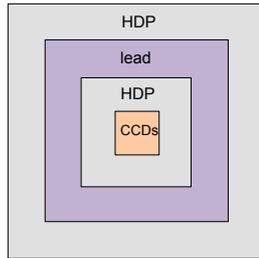
Figure 3: Sketch of the final design of the shield for the CONNIE experiment.

dev. from backg. rate	Conf. level	Running time
[units of backg. rate]	[%]	[days]
1	85	40
1.5	94	90
2	98	160
2.5	99.4	250
3	99.87	360

Table 1: Accuracy and Running time of the experiment.

Figure 4: Neutron spectra of different background sources.

ent kind of events detected using a CCD, where the limited diffusion hits are the point events expected from neutrinos. For a detector running at sea level we have four mayor source of background: cosmic neutrons, neutrons produced by muons in the shield materials, the electromagnetic cascade (primarily photons and electrons) produced by natural radioactive contamination of materials surrounding the detector, and the electromagnetic cascade produced by neutron capture in the polyethylene of the shield. In order to lower this four contributions, the final design for the shield is a combination of high density polyethylene (HDP) and lead like it is sketched in fig. 3, where the total poly thickness moderates cosmic neutrons, the lead shield for stopping electromagnetic radiation, and the inner polyethylene layer serves as moderator for the neutrons produced by muons inside the lead.

As part of the design, it must be known the necessary fraction of reduction of the background. This quantity is related to the rate of event of neutrinos and how long the experiment is intended to be running. From last section, it is possible to calculate that the rate of neutrino events is 0.25 events/day for a total mass of 10 grams of silicon. If we assume a conservative scenario where the background signal ten times higher than the neutrino signal, the running period can be evaluated for different levels of accuracy of detection of the neutrino signal. Table 1 shows this three quantities for five different levels of accuracy.

The following subsections describe the design of the shield based on each significant source of background. It is considered that the final rate of each source has to be similar to the neutrino rate in the energy range of interest (94% of the nuclear recoils are under 2KeV). This is the criterion adopted for the design of the shield.

3.1 Cosmic neutron source of background

Figure 4 shows the expected comic neutron spectrum at sea level [4] in the blue curve, normalized to 1 neutron. The total cosmic flux is 0.035 neutrons per second, but not all the neutrons have enough energy to produce a detectable event on the CCD, only those with energy above aproxi-

mately 1KeV. This corresponds to 80% of the neutrons. The total flux crossing a single detector without any shield is $0.035[n/s/cm^2] \times 3cm \times 6cm = 0.63 \ [n/s]$.

Using the neutron spectrum and flux, and the differential cross section of silicon for neutrons, it is possible to evaluate the expected neutron event spectrum in the detector which is shown in figure 5 for different neutron energy ranges. Comparing this plot to the curve in figure 1, it is clear that the number of events produced by cosmic neutrons is much higher than the events from neutrinos by aproximately three orders of magnitud and mostly of these events are produced by cosmic neutrons with energy below 1MeV. Therefore, it is needed the use of a moderator material. In this case it has been chosen high density polyethylene as moderator because of its easy handling.

In order to account the moderation action, figure 6 shows how the spectrum of neutrons is reduced in the range of interest by different thickness of polyethylene around the detector. The three orders of magnitud reduction is obtained for thickness above 40cm. The simulation was made using Geant4. The simulation geometry is a sphere with a inner radius of 12cm (radius of the dewar radius) and an outer radius of 12cm plus the simulated thickness. In the center of the sphere a silicon box of 6x6x4cm was placed like the detector, simulating a stack of 6 CCDs. This simulation is conservative in the sense that the stack of CCDs that not fill all the volume of the simulated silicon box, and all the simulated neutrons are focused to the center of the copper box. Also, it does not take into account other shielding materials like lead and Copper that are also present in the final design of the shield.

3.2 Neutrons produced by muons in shielding materials

Muons can produce neutrons inside the shielding materials through two main mechanisms: muon capture, and spallation. The former process is very well known [ref][ref][ref] and the flux and spectrum of neutron production can be fairly well calculated. In the other hand, for spallation the available bibliography is not so conclusive [ref] [ref]. The production of neutrons by both mechanism are different in each material, but the general tendency is that higher
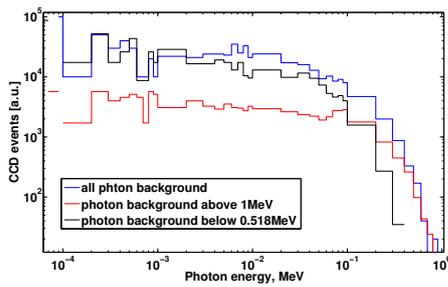
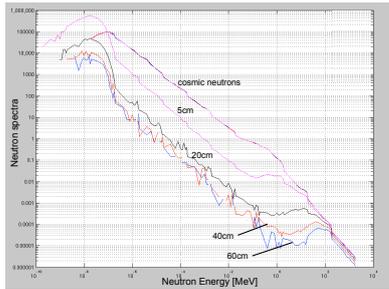**Figure 5**: Cosmic neutrons events spectrum in a CCD.

Figure 6: Neutron moderation by high density polyethylene.

density materials have more production of neutrons. After some calculation using the references cited before, it is possible to calculate the production of neutrons by muons at sea level 2 per grame of shield material, and the spectra are the red and black curves in figure 4, respectively. Both processes contributions are added. It is clear to see that the shape of the spectrum of neutrons generated in the shield is similar to the cosmic neutrons in the atmosphere at sea level. This aproximation is important at the design stage, because it allows you to simply the first order calculation because we already know the effect of this type of spectra over a CCD and how it can be moderated using HDP from last section from the cosmic neutrons calculations in previus subsection. Therefore it is possible to keep the calculations only looking at the flux of thesse sources.

Not all the neutron produced in the shield reach the detec-

material	muon capture	fast muons
lead	8.2×10^{-6}	6.2×10^{-6}
HDP	2.9×10^{-7}	1.9×10^{-7}

Table 2: Neutron production by muons in the shield [n/g/s].

tors, so a simulation using Geant4 is performed to address this number. Again, a simulation of a sphere layer of HDP or Pb sorrowding the detectors is used. The results for different geometries are tabulated in table 3. For the HDP the inner radius is always 12cm, because it will conform the inner layer of polyethylene in figure 3. In the other hand, the inner radius of the lead depends on the final thickness of the polyethylene layer.

Two observations from the numbers of the HDP layer: the first one is that almost all the neutron reaching the stack of detectors are produced in the first inner 10cm layer of the shield, increasing thickness beyond this point does not have mayor insidence in the final number of incidente neutrons because the polyethylene itself starts stopping them efficiently. The second fact is that the flux in the stack is less than 3 orders of magnitude of the flux expected from cosmic neutrons without any shield, and therefore the desing

size outer/ inner radius	total neut. produc. $\geq 1\mathrm{KeV}$, [n/s]	flux at CCD stack
17/12(HDP)	0.005	1×10^{-4}
22/12(HDP)	0.014	3.7×10^{-4}
22/12(HDP)	0.0033	4×10^{-4}
27/12(lead)	11.2	0.4
47/32(lead)	44	0.48
57/32(lead)	68.8	0.48

Table 3: Total neutron production in the shield layers and flux at the detectors.
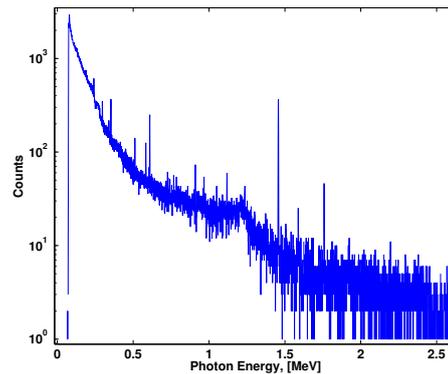

Figure 7: Measured photon background spectrum

criterium is accomplished. This means that placing HDP around the detectors adds a source of neutrons that meets the criterium of design.

For the lead case, always a thickness of 15cm is considered as a requirement for reducing the photon background. The conclusions here are: the number of neutrons reaching the stack for the different sizes, but keeping the same thickness, are similar. This suggests that it mainly depends on the thickness of the shield and not so much on the separation of the layer to the detector. The second observation is that the number of neutrons reaching the stack of CCDs is less, but comparable to the flux of cosmic neutrons crossing a CCD without any shield. We have shown in section 3.1 that this number is not acceptable for the experiment, and therefore some polyethyelen should be fit inside the lead layer. As the spectrum of this neutrons is similar to the cosmic ones, we can use again figure 6 and make the election of the necesary thickness for the inner polyethylene shield of 30/40 cm would be enough to get the required 3 orders of magnitud reduction of neutrons.

3.3 Photons background from natural radioactivity

Although this part of the design seems to be the easiest one due to the vast bibliography about electromagnetic processes, it complicates when considering the a priory unknown radioactivity contamination of available materials, like the lead.

The photon spectrum at the nuclear plant was measured with a Germanium detector resulting to be similar to the background measurements at Fermilab, which is plotted in figure 7 in arbitrary units. The flux of photons is 47 counts/kg/s. This helps us to validate our results directly at the Fermilab's labs.

This spectrum of photon produces an event spectrum in the CCD as is shown with blue ink in figure 8 in arbitrary
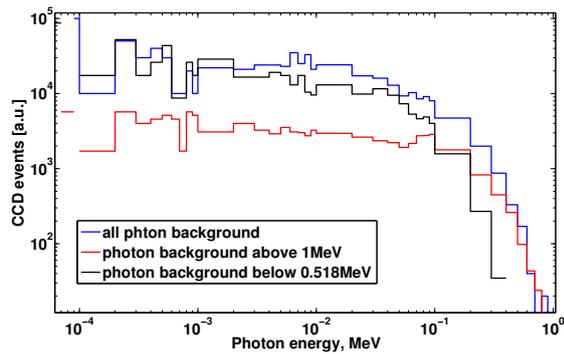
Figure 8: CCD events spectrum produced by photon background.

Figure 9: Photon background by neutron capture inside the HDP layer.

units. This curve shows almost a flat level over the energy range of antineutrinos. This level is 10^5 events/kev/kg/day what also encourages a 3 order of magnitud reduction in the photon shield.

There are two layers for photon attenuation: A very good cuality copper box 1.2mm thick that sorrounds and holds the CCDs this layer is very close to the detectors; and the external 15cm lead layer that we have mentioned. Theoretical calculations of this configuration predicte that this layers are thick enough to get the desirable photon background, but the real performance is subject to the radioactive contamination in the lead. Reference [da silva] shows that this levels of low background are achievable using available lead. For the CONNIE experiment, it is planned to use lead from Doe Run which have worked well for the DAMIC1, DAMIC2 and DAMIC3 experiments. If the level of contamination weren't low enough, a 5cm layer around the CCDs should be built.

3.4 Photon background by neutron capture in the inner layer of Polyethylene

Adding the inner layer of HDP for neutron moderation adds a new source of photon background given by neutron capture process. We will show that this new background does not add significant events counts for the experiment. This calculation was made in Geant 4 in two steps: first the neutrons from the muon production in lead where simulated as the source of events outside a spherical layer of polyethylene of different sizes, and the spectrum of gammas where measured inside. The resulting photon spectrum are shown in figure 9 normalized to one simulated neutrons, and the integral of this spectrums are summarized in table 3. These results help to understand how the shielding works. The main portion of photons are produced in the outer 10cm layer of poly (the portion close to the lead) suggesting that the main number of captures take place in this region. Beyond this thickness, the HDP also starts to become efficient stopping some of these photons so photon counting slowly drops increasing this thickness. The second part of the simulation uses these spectra for the generated events around the structure of the copper box and the CCD inside. All kind of events in the CCD are measured and evaluated. The shape of the event spectrum is similar to the spectrum in figure 8 for the enviromental photon. It also shows the flat level in the neutrino energy range. These levels are summarized in table **??** together to some other interesting variables as the size of the polyehtylene layer, the rate of production of neutrons in lead and the corresponding photon rate.
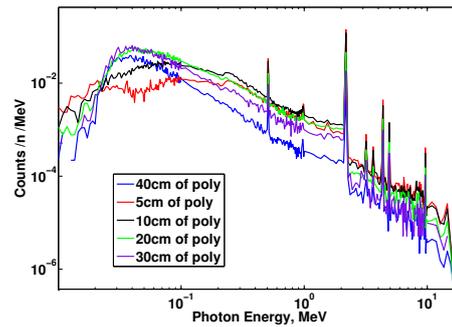
The final number of events is less than 27 events/kg/day/kev which is almost ten times smaller than the number events expected from neutrinos, concluding that this contribution has no significant effect in the experiment performance.

HDP size out/in. radius	γ/n inside sphere	CCD events /CCD/γ	CCD events /Si-kg/n/KeV
17/12	0.021	7×10^{-4}	1.42×10^{-5}
32/12	0.015	4×10^{-4}	5.7×10^{-6}
52/12	0.0044	3×10^{-4}	1.25×10^{-6}

Table 4: Production of gammas and events in the CCD for different HDP geometries.

lead size out/in. radius	HDP thickness	n. prodc n/s	events /Si-kg/day/KeV
32/17	5	22	27
47/32	20	44	27

Table 5: Events in CCD by photon produced by neutron capture in the HDP inner layer.

4 Conclusions

It has been shown that the CCD technology is a promissisng technology for detecting neutrinos.

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