Ultra-Low Noise Germanium Neutrino Detection System (ULGeN)

SL13-ULGeN-PD2Lb, LB13-ULGeN-PD2Lb

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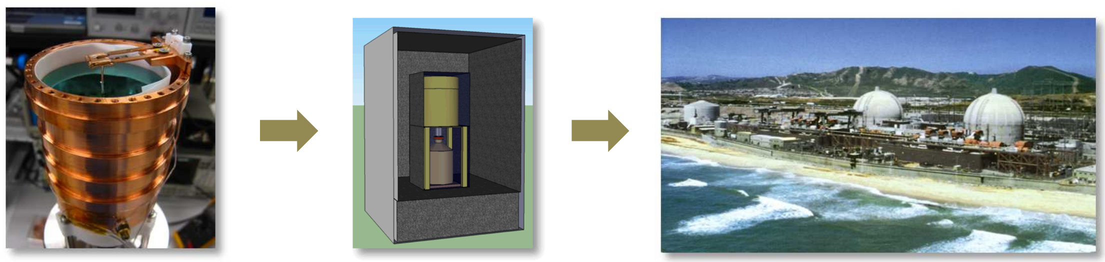
1. INTRODUCTION

This project aims at the development of advanced low-threshold Ge detection technology and proof of its applicability to reactor monitoring via the as-yet undetected coherent neutrino nucleus scattering (CNNS) process. For this application, the hardware



Ge Detector FWHM<100eV   Active and passive Shielding   Deployment at Nuclear Power Plant (NPP)

requirements on an HPGe detection system are kg-scale mass and ultra-low energy threshold (<500 eV), allowing an adequate detection rate of Ge recoils. Our Year 1 work with the JFET-based readout has revealed noise levels not yet sufficient for the detection of CNNS at a power reactor. Thus, a novel approach based on CMOS-readout at low temperatures is being developed to improve upon the state of the art in JFET-based front end electronics for P-type point contact (PPC) detectors. A parallel occurrence affecting the course of the project was the permanent shutdown of our projected deployment site, the San Onofre Nuclear Generating Station (SONGS). While deployment at a nuclear power plant constitutes the final demonstration of this technology, a first time confirmation of the existence of CNNS is of great relevance to the applicability case. For this purpose, we are involved with a newly formed collaboration [1] to measure CNNS at the Spallation Neutron Source (SNS) at ORNL, where the possibility of using existing conventional (higher energy threshold) HPGe will enable our goal of proving the applicability of germanium technology to reactor monitoring.

If successful, this work will provide unprecedented sensitivity in the detection of antineutrinos for the monitoring of nuclear power plants and other safeguards and non-proliferation activities related to the nuclear fission process. Because the cross-section for CNNS is several orders of magnitude larger than the inverse beta decay process of traditional antineutrino detection systems, a CNNS-based antineutrino detection system can be orders of magnitude smaller than its large-scale stationary inverse-beta decay-based counterpart. Very compact and potentially mobile systems can be envisioned. As such, users interested in this project's application to reactor monitoring or to the detection of other nuclear activities might include, DoD DTRA, the intelligence community, and the non-proliferation mission areas of DOE NNSA particularly in connection with safeguards efforts driven by IAEA.

Advances in large-mass ultra-low noise HPGe technologies are of great interest to the science community, including users like DOE HEP and NP. In particular, experiments that will benefit are those searching for rare physics events related to weak interaction processes, such as CNNS detection or the cold dark matter search. In addition, the new technology will provide unparalleled energy resolution HPGe instruments for detecting x-rays and gamma rays from very low energies (<1 keV) to high energies (>MeV), critical for nuclear forensics. An additional benefit of the CMOS-based readout developments will be its applicability to other photon and particle detection systems when requirements include: low noise, low-power, low background, and high channel count.

2. DEVELOPMENT OF ULTRA-LOW NOISE FRONT-END ELECTRONICS

While commercial detector vendors recognized a market in ultra low-noise large mass HPGe detectors for physics applications, and now offer low-noise options, these products may not be sufficient for detection of CNNS at a power reactor. This project originally foresaw a potential limitation to the JFET-based approach, which was confirmed in our first year and further motivated our efforts to advance the state of the art.

In this second year, focus was shifted from JFET to cold (<80 K) CMOS front-end electronics. Two low-vibration variable temperature cryostats were designed and fabricated. The first was based on a LN_2-cooled dipstick for testing detector and front end performance above ~80 K. A second cryostat was designed around a nm-scale-vibration optical cryostat, cooled with a standard compressor and 4 K cold head, with a detector temperature of 8 K possible. This technology has the advantage of being readily scalable and removes reliance on liquid cryogens.

While low-noise JFETs exist, their production remains an art practiced by few smaller foundries. Meanwhile, CMOS application specific integrated circuits (ASICs) and their foundries are the heart of the silicon industry. If low-noise technology nodes and processes can be identified, significant economies of scale are possible, in both design and production cycles. For this reason two such CMOS technologies are being evaluated.

The first CMOS technology is the “CUBE” ASIC from an Italian company XGLab. It boasts a low input capacitance, well matched to the PPC, and purports an electronic noise of 3-4 electrons-rms (25 eV-FWHM for Ge) at low temperatures. Initial bench tests of this ASIC (~200 eV-FWHM) as well as low temperature tests suggest its performance is highly dependent on the implementation. Conversations with XGLab are ongoing to reproduce the reported low-noise capabilities.

The second CMOS technology under evaluation is a collaborative ground-up ASIC from BNL, relying on their significant historical expertise in nuclear signal processing ASIC development. This approach will provide greater flexibility for future designs and will ensure a greater possibility for achieving the requisite ultra-low noise threshold.

Finally, the effects of temperatures below that of LN_2 on HPGe itself are being explored. The literature on this topic is sparse, divided, and/or outdated. Published results will have an impact on many applications relying on Ge detectors, particularly those now being mechanically cooled.

3. BACKGROUND MEASUREMENTS AT THE SNS

The expected most significant background for a CNNS measurement at the SNS are the neutrons created at the SNS target at beam time. These neutrons arrive at the detector simultaneously with the neutrinos one wishes to detect. Since neutrons produce the exact same Ge recoils as neutrinos, measurement and characterization of the neutron flux at SNS locations around 15 to 35 meters from the target source constitutes the first step toward determining feasibility of the CNNS experiment.

Figure 1 shows the results of neutron measurements done with an SNL-developed Neutron Scatter Camera (NSC) at two SNS locations. The first set of measurements was done at the target-hall floor level, between beamlines 13 and 14 (labeled as 13a in figure). The NSC, being a neutron imager and spectrometer, produced a clear image of the neutrons coming from the target direction during a 2.7 μs window at beam time, as well as the corresponding spectrum which is about 5 orders of magnitude higher than the out-of-beam and the beam-off background spectra. A second measurement was done at an SNS basement location, and the results show a significant reduction in beam-associated neutron flux, making the SNS basement a plausible candidate for a future CNNS experiment.

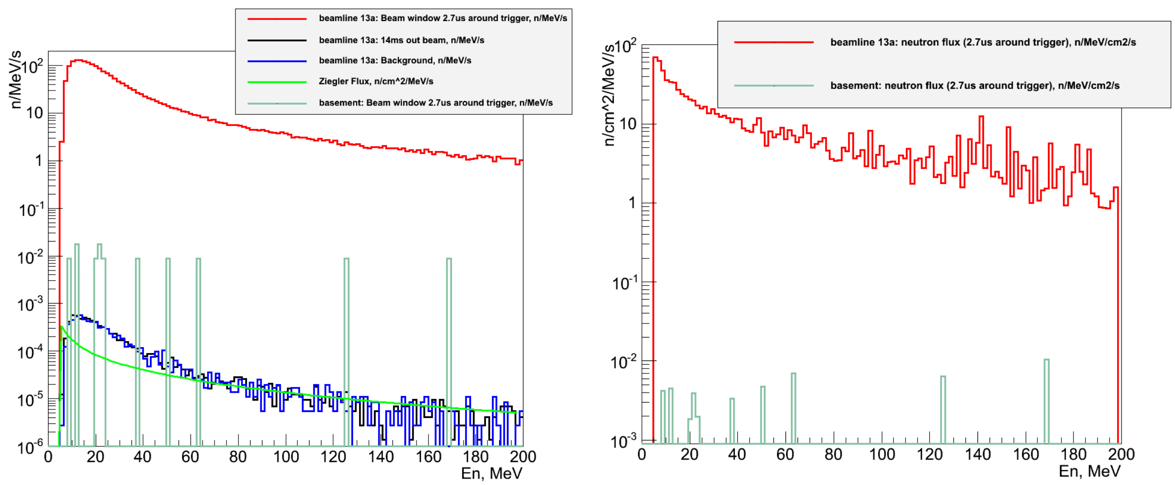


Figure 1: Results of NSC measurements at two SNS locations, beamline 13a and basement. Right: NSC-measured spectral rates for beam-coincident time window, beam-anticoincident time window and beam-off. Ziegler flux of surface cosmic neutrons [2], which was used to estimate NSC efficiency, is also plotted. Left: initial estimation of beam-coincident neutron fluxes at two mentioned locations.

4. RESULTS, DISCUSSION AND CONCLUSIONS

New NSC measurements at another basement position that is better shielded from target neutrons by the building construction are underway. Using the measured fluxes as input to simulations, we expect to down-select locations and determine required shielding using an existing low-noise germanium detector.

HPGe point contact detectors are an important technology for both nuclear security and forensics, as well as in fundamental nuclear physics. Improving the low-energy threshold of these detectors by exploring low temperature (<80 K) CMOS front end electronics will enable new physics to be discovered and new breakthroughs in nuclear security capabilities.

REFERENCES

[1] COHERENT Collaboration, D. Akimov *et al.*, (2013), 1310.0125.
[2] J.F.Ziegler, IBM Journal on Res. Develop., Vol. 40, 1996, pp 19-36.