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Development of Coherent Germanium Neutrino Technology (CoGeNT) for Reactor Safeguards

Belkis Cabrera-Palmer
David Reyna

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Belkis Cabrera-Palmer
David Reyna
Radiation and Nuclear Detection Department (8132)
Sandia National Laboratories
7011 East Avenue
Livermore, California 94550-MS9406

Abstract

Antineutrinos are extremely penetrating elementary particles that have unique features of interest for safeguards at nuclear reactors. Current antineutrino detectors systems have large size and often use hazardous materials, presenting concerns to the safeguards agencies. We propose a new antineutrino detector, based on HPGe detector technology, which is much smaller and safer and therefore more likely to find widespread acceptance as a monitoring tool. The proposed system should be sensitive to a universally predicted but as-yet undetected antineutrino signature, the coherent neutrino-nucleus scattering, for which an unprecedentedly low noise threshold is required. Based on the noise analysis of an existing HPGe detector and the results of noise tests, a new system was designed and fabricated in collaboration with LBNL, though a full noise optimization has not been possible. Shielding design has been analyzed in the context of other deployment results, and an anticoincidence veto with high neutron efficiency has been tested.

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NOMENCLATURE

BEGe	Broad Energy Germanium
CoGeNT	Coherent Germanium Neutrino Technology
CNNS	Coherent Neutrino-Nucleus Scattering
DAQ	Data Acquisition System
DOE	Department of Energy
FWHM	Full Width at Half Maximum
IAEA	International Atomic Energy Agency
HPGe	High Purity Germanium
JFET	Junction Field Effect Transistor
m.w.e.	meters of water equivalent
LBNL	Lawrence Berkeley National Laboratories
LLNL	Lawrence Livermore National Laboratories
PMT	Photo Multiplier Tube
PPC	P-type Point Contact
RMS	Root-Mean-Square
SNL	Sandia National Laboratories
SONGS	San Onofre Nuclear Generating Station

1. INTRODUCTION

Antineutrinos are extremely penetrating elementary particles that have unique features of interest for safeguards at nuclear reactors. They cannot be shielded, are inextricably linked with the fission process, and provide direct real-time measurements of the operational status, power and fissile content of reactor cores using equipment that is independent of reactor operation. The potential for reactor monitoring offered by antineutrino detection has been demonstrated by Sandia National Laboratories (SNL) and Lawrence Livermore National Laboratory (LLNL) using a liquid scintillator detector that relies in inverse beta decay interaction [1,2].

Based largely on the above-mentioned work, the International Atomic Energy Agency (IAEA) Novel Technologies division identified antineutrino detection as a "highly promising technology for safeguards applications" at nuclear reactors [3]. However, the same IAEA report expressed concerns over the size of current antineutrino detectors (~3m x 3m x 4m) and their use of hazardous materials. Specifically, this report pointed out to three technical limitations that prevent immediate incorporation of antineutrino detectors in the safeguards regime: the toxicity and flammability of liquid scintillator materials, shielding against cosmic backgrounds, and the physical footprint of the detectors. Other safer materials with high efficiency for inverse beta decay, like plastic scintillator and water, still require large target volumes to achieve detectable signal rates. Since most of antineutrino detectors require a sizable shielding, and inherently large footprint is usually associated with hydrogenous-material antineutrino systems.

Our project rests on the proposition of a novel antineutrino detector that is safer and potentially much smaller than previous designs, and therefore more likely to find widespread acceptance as a monitoring tool. This detector is based on High Purity Germanium (HPGe) detector technology, which has been widely used for gamma-ray spectroscopy, including by the nuclear power industry. The antineutrino detection mechanism in a germanium detector is given by the Coherent Neutrino-Nucleus Scattering (CNNS), a process universally predicted by the Standard Model of particles, but yet unobserved due to its very-low energy signature. Nevertheless, CNNS has a much higher probability of interaction than inverse beta decay, such that a germanium detector of 10 kg would have similar sensitivity to 1 ton of the current scintillator based detection technology. This should allow a significant reduction in the necessary scale for a complete detector system and more flexibility in finding locations suitable for detector installation, leading to a viable technology for reactor monitoring that could be easily incorporated into the global nuclear safeguards regime. If successful, the Coherent Germanium Neutrino Technology (CoGeNT) could yield higher sensitivity to reactor fuel composition variation, with CNNS rates changing by nearly 25% during a reactor full cycle, compared to a 10% change in inverse-beta decay rates.

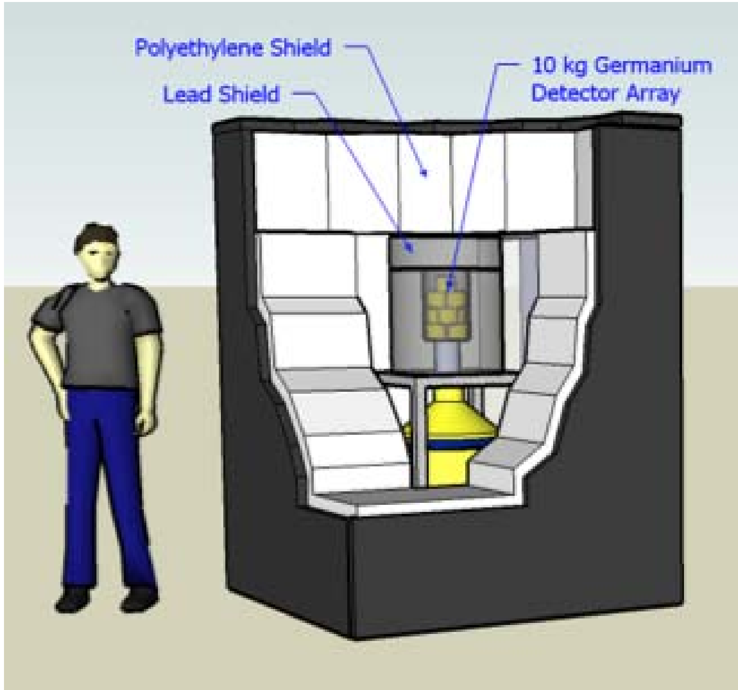


Figure 1. Diagrammatic view of a complete detector system including all shielding. This represents a significant reduction in scale from existing antineutrino detectors.

1.1. Detection of CNNS with HPGe detector

Coherent neutrino-nucleus scattering in germanium or any other material has never been observed due to its extremely low energy signature. The interaction consists of a neutrino (or antineutrino) elastically scattering off a target nucleus, and as a result, producing a recoiling nucleus with kinetic energy inverse to its mass. For ~10 MeV as the upper bound of reactor antineutrinos energy range, a germanium nucleus will always recoil with less than 3keV. Of that total recoil energy, only 20% is released into the ionization of electron-hole pairs while the rest is converted into vibrational energy of the germanium crystal. Therefore, detectors only sensitive to the ionization channel need an electronic threshold lower than 600 eV to individually register any CNNS event above electronic noise.

However, due to the drop in reactor antineutrinos spectrum as shown in Figure 2, detectable signal rates will require lower threshold values (see Table 1), with <100eV as our ideal target. It is customary and usually correct to estimate the threshold value as 5 to 6 times the electronic RMS. Since the electronic RMS is 2.35 times the Full Width at Half Maximum (FWHM) of a pulser peak, we could therefore express our target electronic noise for CNNS detection at a reactor site with a HPGe detector as ~50 eV FWHM. This value is readily available in commercial x-ray detectors [4], but due to their small mass (usually < 5g) an array of hundreds of these detectors would be necessary in order to achieve a significant signal rate. On the other hand, the demonstrated performance of the small-mass HPGe detectors lends motivation to investigate the possibility of achieving such low-noise figures with kg-scale crystals.

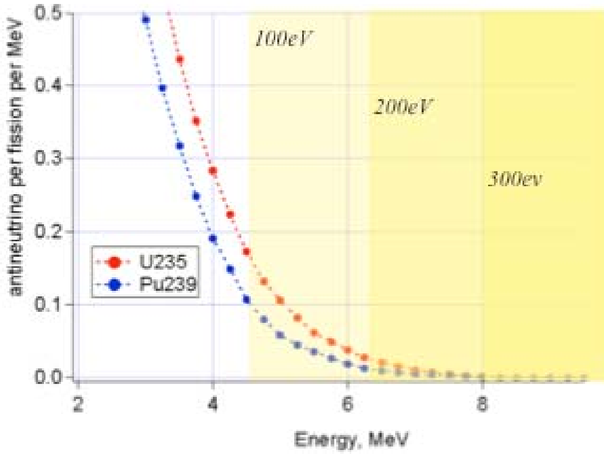


Figure 2. Reactor antineutrino spectrum per fission of ^{235}U (red) and ^{239}Pu (blue). Shaded areas indicate the region of antineutrino energies detectable via CNNS for various HPGe detector thresholds (indicated by values in eV).

Table 1: CNNS counts per day per kg of HPGe, at 25m from reactor core.

HPGe detector electronic threshold	Estimated counts above threshold
300 eV	0.08
200 eV	0.60
100 eV	5.12

In recent years, there has been a qualitative advance in the development of a new type of HPGe detector that combines a large-mass crystal with very low electronic noise. As first proposed by Lawrence Berkeley National Laboratory (LBNL) [5], the electronic noise is significantly reduced by changing the center electrode to a point contact, as compared to a bore hole contact in standard coaxial HPGe detectors. Commercial versions of the point-contact model produced by CANBERRA Industries Inc [4], known as Broad-Energy Ge or BEGe detectors, found applications in high-energy resolution X-ray and gamma-ray spectroscopy, and more recently in astroparticle and neutrino physics [6,7,8,9]. Relevant to this work is the development of a 450g BEGe detector deployed by the CoGeNT collaboration (University of Chicago, SNL, LLNL, and CANBERRA) at the San Onofre Nuclear Generating station (SONGS)[8]. Though state-of-the-art at the time, the detector's electronic noise of 163eV FWHM yielded a threshold still too high for CNNS observation. However, as a main accomplishment, the experiment showed for the first time stable operation at very low threshold in a long-term field deployment. Also of great significance is the demonstration that a near sea-level deployment (30 m.w.e.), with shielding of manageable size (~1.5m^3), should not suffer from a prohibited background in the energy region of interest (<3keV) originated from cosmic rays and ambient radioactivity.

Taking the point-contact detector technology as a starting point, this project began with the goal of investigating and isolating the sources of noise of a BEGe detector in our possession, and of developing a new type of electronic readout system that would enable sensitivity to CNNS at a reactor site.

2. ELECTRONIC NOISE

Our first task was to fully characterize the noise performance of a new 800g BEGe P-type detector that we had previously acquired from CANBERRA. Noise measurements showed a very reproducible electronics noise with a minimum at 147eV FWHM, as shown in Figure 3. The measured noise FWHM can be described as a function of shaping time constant τ by three main components:

$$FWHM^2 = \frac{S}{\tau} + F + P\tau$$

the series component S, inverse with τ; the parallel component P, linear with τ; and the flat component F (also known as 1/f noise), independent of τ. From the general theory of electronic noise in semiconductor detectors, the series component depend on the input capacitance to the first amplification stage, in this case, a Junction Field Effect transistor, or JFET. Our direct measurements indicated a detector capacitance of ~1.5pF, a value characteristic of point contact detectors, and very low when compared to the 20pF standard in coaxial detectors. The feedback, JFET and stray capacitances also contribute to the total input capacitance. The parallel noise component is directly proportional the detector leakage current, which typically depends on the crystal fabrication and operating temperature. In our case, the measured leakage current was about 2pA.

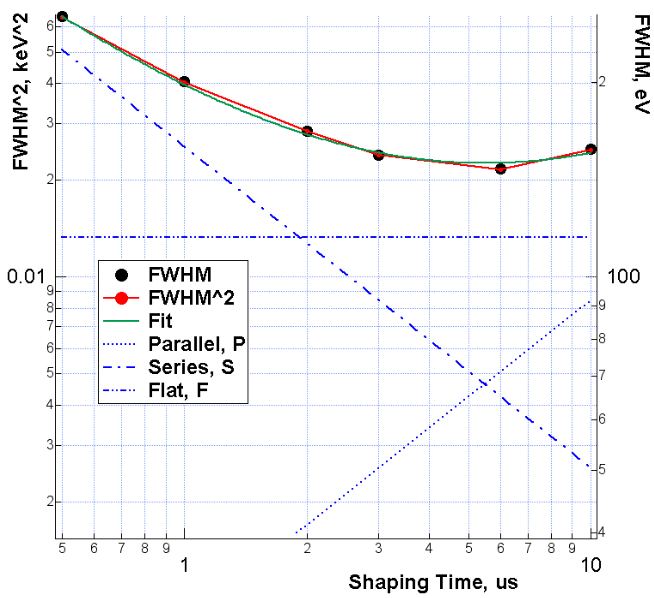


Figure 3. Measured electronic noise (black, in eV-FWHM) of our BEGe detector in the original CANBERA system, as a function of shaping time (in microseconds). Depending on behavior with shaping time, the noise can be separated in three components (parallel, series and flat), each associated with physical parameters. In this BEGe detector, the flat "1/f" component is the largest contributor to noise.

As can be appreciated from Figure 3, the largest noise contribution originates from the 1/f component. This component often depends on the input capacitance, but it can also depend on other physical conditions, like the contact of lossy dielectric materials with the JFET input. However, the origin of 1/f noise in analog electronics is not always well understood. Therefore, we started this project with a detailed study of all aspects of the CANBERRA electronics and understanding how they relate to the existing noise performance with the hope of discovering modification of the analog circuitry that could lower the measured noise floor. Two SNL analog engineers, Kurt Wessendorf and Daniel Savignon from 01732, were in charge of executing this study. While in contact with the CANBERRA electrical designers, our engineers performed SPICE simulations of various components, reproducing the operational tests on the existing detector. They concluded that the existing analog circuit was already optimal, and did not find any modification of the circuitry beyond the first amplification stage (*i.e.* the JFET assembly) that could improve on current noise performance. This conclusion was confirmed by the noise performance of small-mass CANBERRA detectors with similar analog electronics that have achieved electronic noise as low as 52eV. As our original assumption that the electronic readout was the cause of the observed noise was incorrect, we had to refocus our investigations for FY1 and FY12.

While these studies did not yield any easy solutions, we were able to eliminate the pre-amplifier and the high-voltage circuitry as generating the observed noise behavior. As a result, we had isolated the source of unwanted noise contributions to the germanium detector element itself, the JFET assembly, and the specific interfaces where the germanium crystal comes in contact with the preamp front-end and the surrounding mounting systems. To further our understanding of these sources and investigate possible improvements, we established collaboration with a group from LBNL that develops novel germanium detector systems for radiation detection. The LBNL group developed a novel mounting and electronic front-end system that minimizes any contact between the crystal and any outside materials. Specifically, they have demonstrated a 20g P-type Point-Contact (PPC) germanium detector with 85eV FWHM of electronic noise [11] – which would be sufficient for CNNS demonstration if this performance could be maintained in a larger detector.

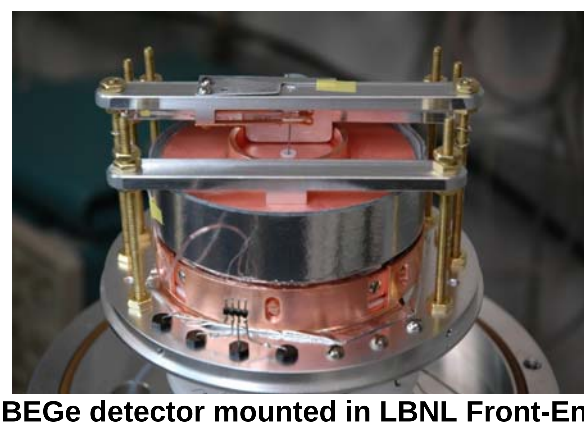


Figure 4. BEGe detector mounted in LBNL Front-End readout.

While the CANBERRA small commercial detectors have exhibited even better performance, the LBNL mounting and readout offered more flexibility for isolating the noise sources, while also allowing to test our known detector in an environment where the interfaces between the crystal and the electronics were significantly different from the CANBERRA design. Figure 4 shows our BEGe detector inserted in the LBNL front-end readout, and Figure 5 shows the corresponding electronic noise measurement. This measurement, performed by our LBNL collaborators, showed no change in any noise component compared to the CANBERRA system (Figure 3), indicating that the noise is arising from the detector element itself and not from the readout. A further test where the detector was replaced with a higher capacitance capacitor (2.5pF) showed an increase in the 1/f noise, strongly suggesting that the 1/f noise of the front-end is mainly capacity dependent. This is an important conclusion as it indicated that the BEGe detector performance was limited by its own capacitance. Since in point-contact detectors the capacitance is given by the contact diameter, we set as the next step to fabricate and test a new detector element with a 1mm contact, a significant reduction from the 4mm-diameter of our initial BEGe.

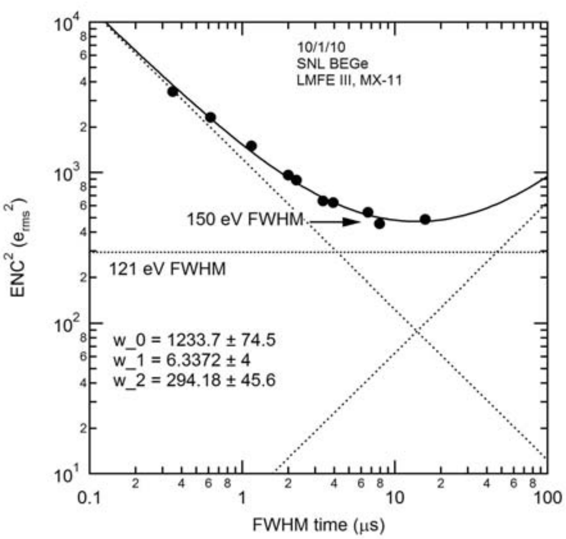


Figure 5. Right: Measured electronic noise of our BEGe detector mounted in the LBNL front-end readout. The noise minimum of 150eV FWHM is equivalent to the value measured the CANBERRA system.

Our collaborators at LBNL fabricated a new 1-kg PPC detector, shown in Figure 6, with a 1mm-point contact and ~1pF of capacitance. Proving that fabricating good detectors is a hard craft, this detector turned out with poor charge collection and thus, will never be used for particle detection. However, our collaborators initially believed that it could still be useful for the front-end noise optimization effort. For that purpose, SNL customized a CANBERRA cryostat and fabricated a holder to host the detector and the LBNL front-end board, shown in Figure 6. After preliminary assembly and testing of the whole system, it was discovered that the new detector suffered from leakage current values that render its use for noise measurements prohibited. We also experienced other difficulties inherent to the process of creating a new system, for example, some cryostat parts did not fit and had to be remanufactured, the JFET board had failing connections that had to be fixed, and the cryostat temperature at the detector location was higher that expected. In the end, all these delays prevented us from completing a full noise optimization test of a 1-kg PPC detector with a 1mm contact diameter within this project's timeframe.

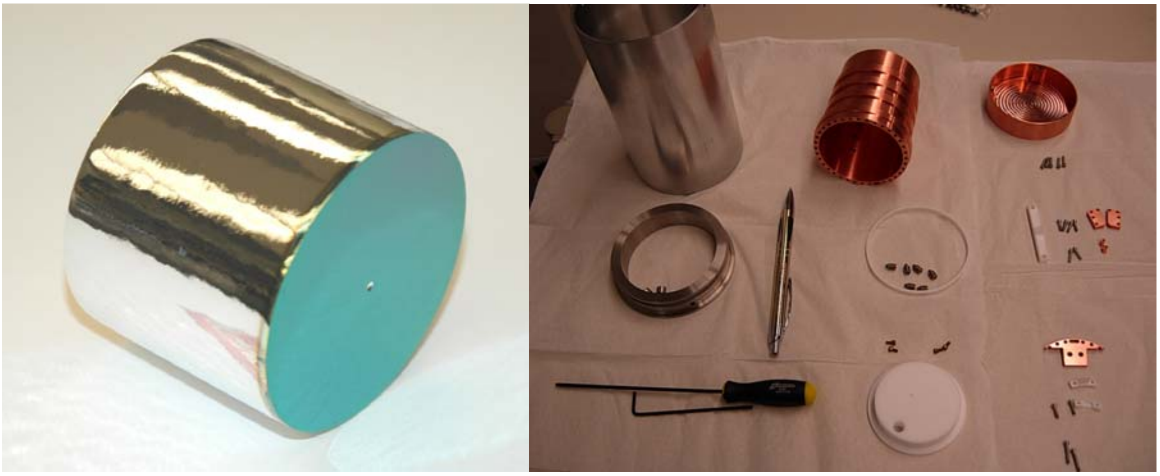


Figure 6. Left: 1-kg PPC detector fabricated by LBNL. Right: Detector and front-end holders, fabricated by SNL.

3. CNNS AND BACKGROUND SIGNALS

In addition to the electronics work, our second goal has been the study of the environmental constraints that may reduce the effectiveness of the coherent germanium-neutrino technology for reactor monitoring. These are background signals, which originate from cosmic rays, ambient radioactivity and the detector's own radioactivity, and are generated mainly by neutrons and gammas interacting in the germanium. Neutrons are an especially important background since they produce germanium recoils identical to the CNNS signal. We note that solar and geo neutrinos, though also producing an interaction identical to our searched antineutrino signal since the CNNS does not distinguish among neutrino flavors, do not generate high enough rates to be a concern. Hadron particles like neutrons and protons, from the same cosmic and ambient sources, can also activate the germanium nuclei, which will then decay emitting gammas, X-rays and Auger electrons and depositing energy in our region of interest. The low signal rates presented in Section 1.1 indicate that stringent suppression of all these background rates is necessary for CNNS observation with a 1-kg detector and also to employ this technology in reactor monitoring.

Similar to other antineutrino systems, significant shielding from cosmic rays can be readily achieved by deploying in an underground location, like a reactor tendon gallery, that provides some degree of overburden. An external shield, illustrated in Figure 7, should consist of a highly efficient muon veto surrounding a 20-inch layer of high-density polyethylene to moderate neutrons, and a 2-inch layer of borated poly to absorb thermal neutrons. A 6.5-inch thick, ultra low-background Lead shield, supplied by CANBERRA, should hermetically surround the HPGe detector to shield against external gammas. In a final system, all parts next to the HPGe crystal should be made out of ultra radio clean materials with low concentrations of radio impurities of K, Th and U. The most internal shield component is an anticoincidence detector that encloses the HPGe detector (see Figure 7 and section 3.1), and is intended as a veto for those neutrons and gammas that interact in both detectors.

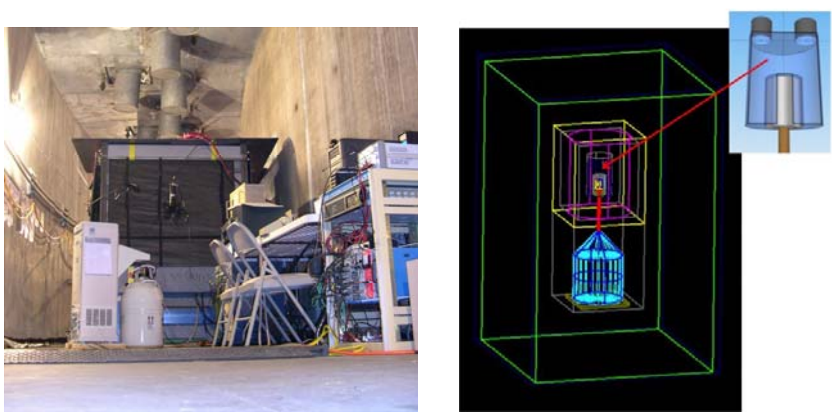


Figure 7. Left: 2009 CoGeNT deployment of a BEGe detector at SONGS tendon Gallery, showing (1.5m x 1.5m) shielding footprint. Right: Diagram of proposed shielding with same footprint dimensions. Showed enlarged is the inner anti-coincidence Plastic Scintillator detector to veto neutrons and gammas.

The effectiveness of this shielding design has been experimentally verified by the above-mentioned deployment [8] of a 450g BEGe detector in the tendon gallery in one of the SONGS reactors, at about 30 m.w.e. of overburden. The same system was also deployed by the CoGeNT collaboration (without SNL participation) in a deep underground mine at ~2000 m.w.e. of overburden [9], upgraded with a thicker thermal neutron absorber of 2 inches. The near-threshold background rates (energy region from 0.4-1keV) of these two deployments are 22counts/keV-kg-day at 30m.w.e. versus 8counts/keV-kg-day at 2000m.w.e.. Comparing these results shows that the tendon gallery deployment, with the same shielding footprint (~1.5m x 1.5m, as shown in Figure 7), did not suffer from a significant increase in background originated in cosmic rays. In fact, [9] showed that a large portion of the excess background counts in the tendon gallery deployment could have been eliminated through signal processing (factor of 2) and with a thicker thermal neutron absorber.

Using the background rates measured in those deployments, we calculated the threshold value for a significant observation CNNS signal above background. The plot in Figure 8 represents the upper bound in background rate that would allow success as a function of energy threshold. So, at 8 counts per kg per day, as measured in [9] in the range < 600 eV, an observation of on/off reactor transition in 30 days with 3 sigma confidence level will required about 145 eV of threshold, while a 3 sigma in 7 days will require 110eV.

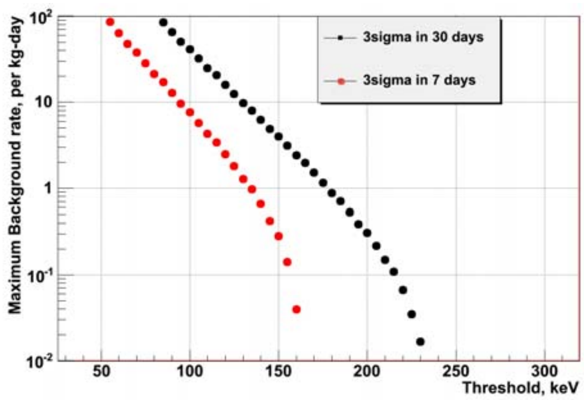


Figure 8. Estimated maximum background rate (per kg-day) in the CNNS signal region, as a function of energy threshold, that would allow a 3-sigma observation of CNNS.

3.1. Development of Anticoincidence Inner Veto

Neutrons are a competing background signal since they also produce germanium nucleus recoils. Therefore, we have built and tested an anticoincidence internal veto, seen enlarged in Figure 7, made of plastic organic scintillator in order to increase sensitivity to neutrons in the vicinity of the HPGe detector. Other experiments [8,9,10] have used inorganic scintillators for the anticoincidence veto, like NaI(Tl) and CsI(Tl), which have high sensitivity for gammas but not for neutrons. However, by carefully choosing the detector materials, the internal gamma radioactivity background can be controlled. On the other hand, neutrons penetrating the external shield, if un-vetoed, could create a ubiquitous background in the near-threshold energy region.

The dimensions of the full anticoincidence inner veto are such that it fits exactly in the cylindrical cavity inside the CANBERRA lead shield. The inner veto consists of a cylindrical Eljen-200 plastic scintillator block with a central well to slide around the germanium detector, all wrapped with a GORE® Diffuse Reflector sheet except at four circular holes at the top cylinder face, where four low-background R6041 Hamamatsu PMTs are inserted. This PMT model is only 3 inches long, and was selected due to the spatial constraints within the lead shield. The four PMT channels are read synchronously after a single PMT trigger and the four signals are combined to create a pulse height histogram.

Figure 9. Left: Anticoincidence inner veto made of Ej200 Plastic Scintillator, wrapped in GORE diffuse reflector. Four low background R6041 Hamamatsu PMTs read scintillation light from the top. Right: Experimental set-up for source scans along the veto vertical side, in order to determine light collection uniformity and threshold.

Given the vertical asymmetry in the shape of the inner veto and the location of the PMTs, investigated the light collection uniformity by scanning several collimated gamma the vertical side of the inner veto cylinder. The results for four vertical positions and two ^{137}Cs and ^{133}Ba, are plotted in Figure 10 and

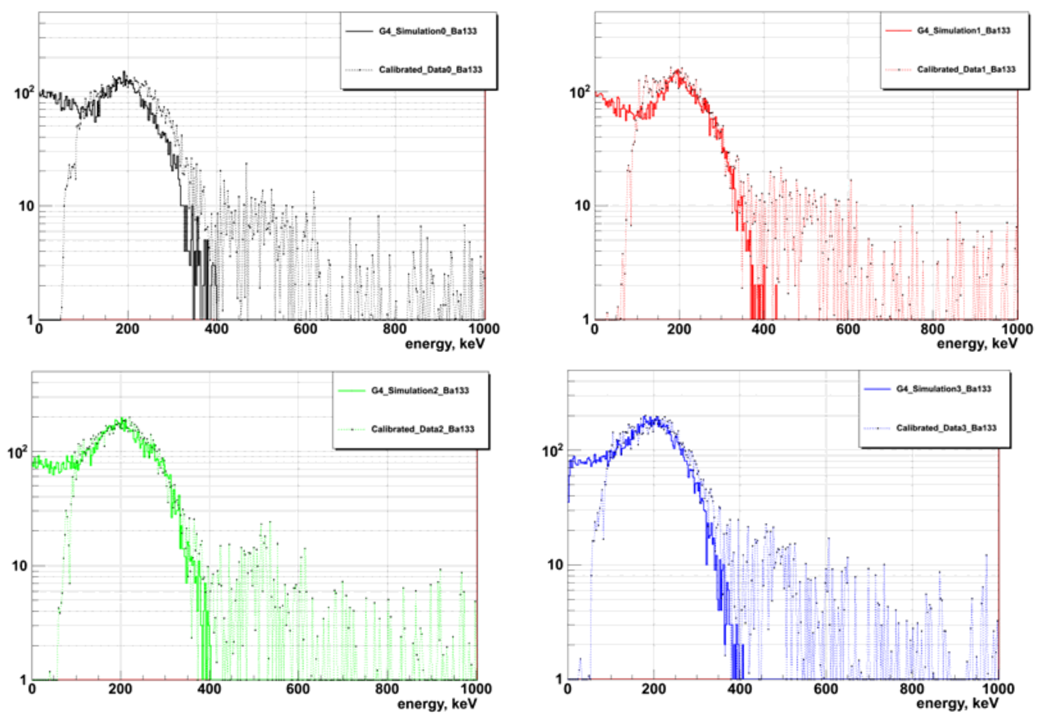


Figure 11. Also plotted are the corresponding Geant4 (G4) simulations that modeled the particle interactions, scintillation and optical photon propagation, and were used to derive the energy calibration and resolution. As it can be observed, there is almost no variation in the position of the Compton edge of the resulting spectra showing very good

light collection uniformity across the plastic scintillator volume, including the bottom region farther away from the PMTs and around the germanium detector where high detection efficiency is more important. G4 simulation of optical photons uniformly generated in all the veto volume, and using the optical boundary conditions that matched scans data, (Figure 10 and

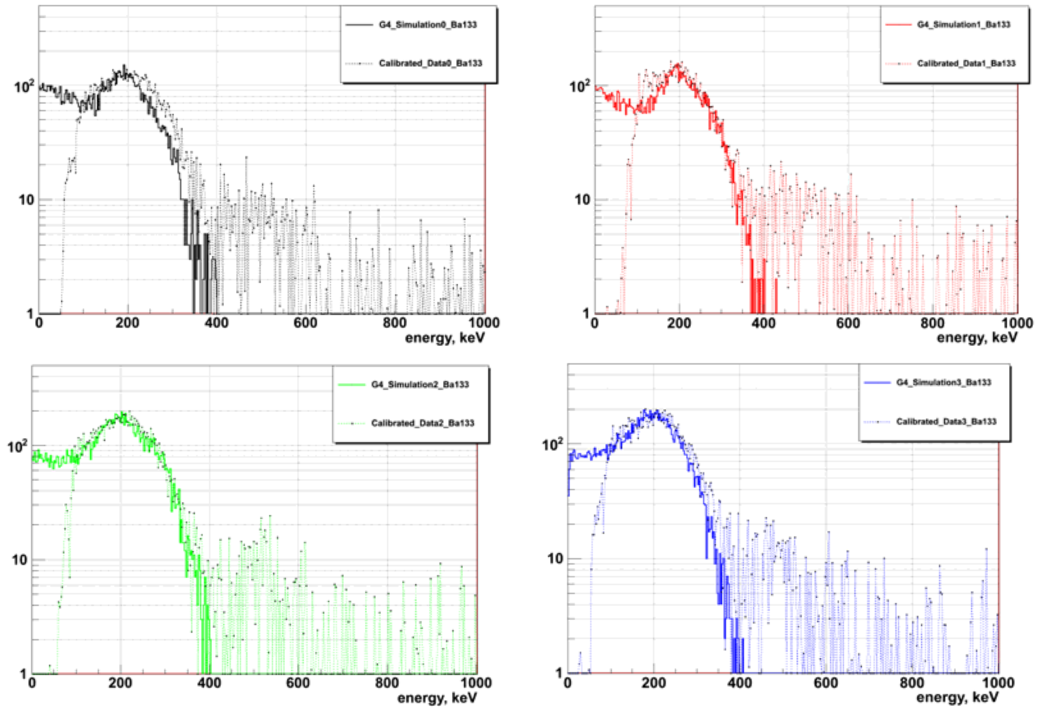


Figure 11) , also showed spatial uniformity in light collection. Plotted in Figure 12 is the natural background histogram where the K and Th Compton edges are well evident. Something to notice is the good energy resolution obtained thanks to the high reflectivity of the GORE® Diffuse Reflector.

We were able to set a hardware threshold corresponding to 100keVee (keV electron equivalent) of electron energy before the PMTs dark current rate became significant. Considering that the NaI(Tl) anticoincidence veto of [8] had a 10 keVee threshold, and taking into account the lower gamma efficiency of plastic scintillators, it is evident that the use of this anticoincidence veto will impose especial emphasis in choosing low radioactivity materials, including the materials of the veto itself. However, as a trade-off, the plastic scintillator veto offers a much higher efficiency for detection of energetic neutrons that traverse the shield. To convert the 100keVee threshold to incoming neutron energy, we use data of a similar plastic scintillator [13,14] for which a 110keV electron produces about the same scintillation response of a 1MeV proton. Therefore, we verified that this plastic scintillator anticoincidence detector is able to detect neutron interactions that deposit energies of ~1 MeV or larger anywhere in its volume.

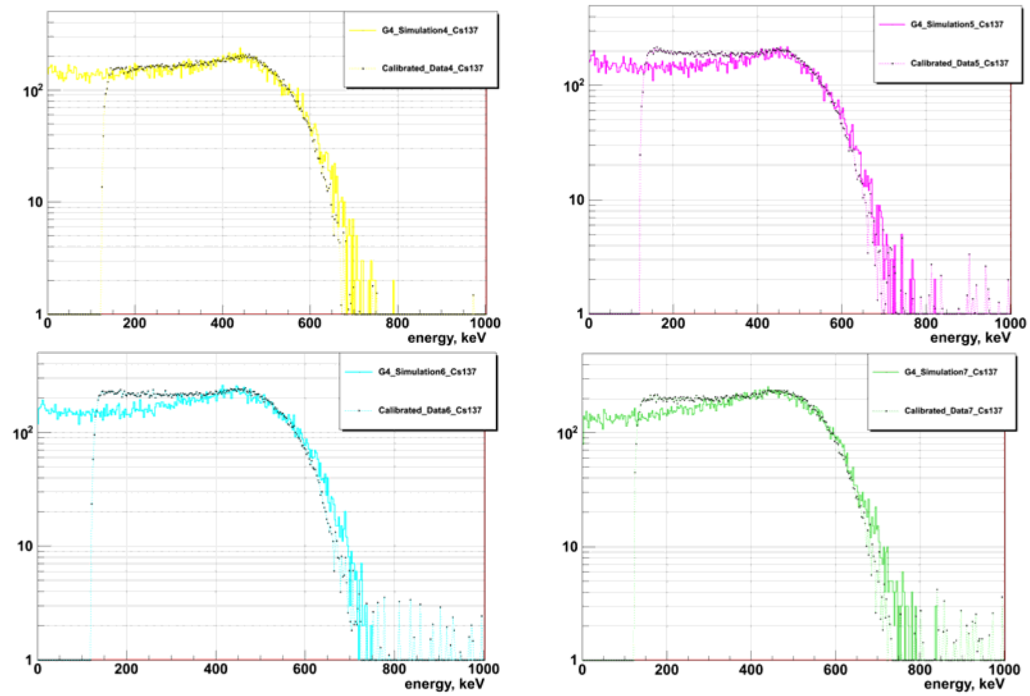


Figure 10. Energy Histograms obtained by a vertical scan along the inner veto vertical side, with a ^{137}Cs source at 25.4mm (yellow), 101.6mm (pink), 177.8mm (blue), and 254.0mm(green) from the bottom face. The solid lines are G4 simulations and black dots represent data.

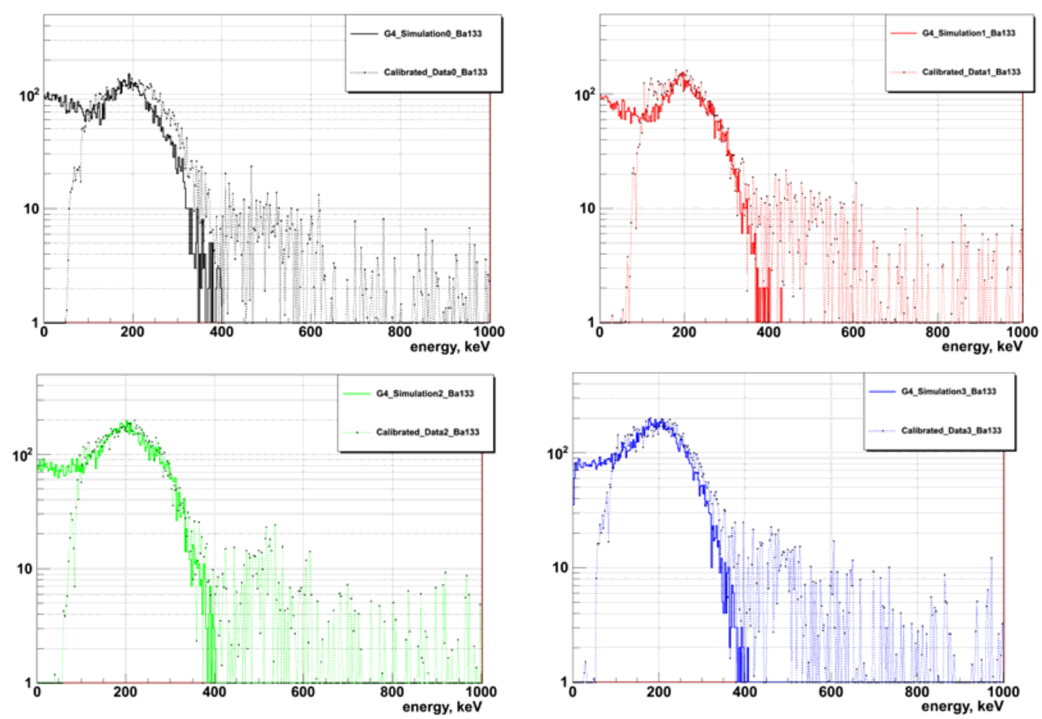
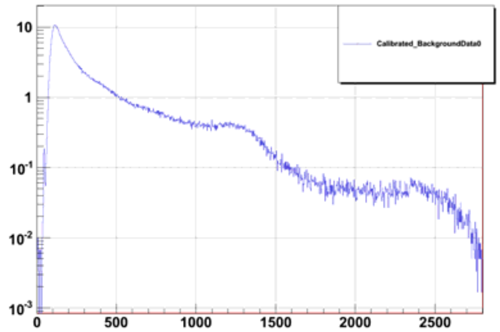


Figure 11. Energy Histograms obtained by a vertical scan along the inner veto vertical side, with a ^{133}Ba source at 25.4mm (black), 101.6mm (red), 177.8mm (green), and 254.0mm(blue) from the bottom face. The solid lines are G4 simulations and black dots represent data.



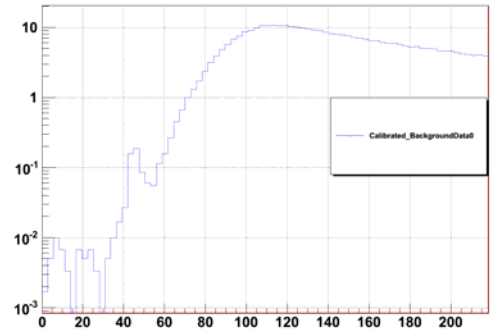


Figure 12. Left: Energy Histogram of ambient background, showing the K and Th Compton edges. Right: A zoom of the lower bins show a hardware threshold at ~110keVee.

4. CONCLUSIONS

The noise analysis of the analog electronics led us to conclude that the preamplifier and high voltage circuits of the BEGe detector were already optimal, and so, no modification of the circuitry beyond the JFET amplification stage should significantly improve its noise performance. Testing the BEGe detector element with the LBNL's front-end and electronics strongly suggested that the main noise component (1/f noise) is mainly capacity dependent, and the BEGe's noise performance was limited by its own capacitance. Fabrication and assembly of a new PPC detector with reduced capacitance and the corresponding mechanical mounting and electrical components have presented issues inherent to the process of creating a novel system with stringent performance constraints. These difficulties have prevented us from having a full noise optimization within this project's timeframe. On the other hand, we might be able to apply the lessons learned and the worked done in this project to a new NA22 project that is currently pending for FY13 funding, and which is set to be a continuation of our current efforts.

Our analysis of the background rates obtained in other deployments validates the intended shielding design. Neutrons require especial attention due to the nature of their background signal, and thus, an anticoincidence internal veto made of plastic organic scintillator was the only shielding component that we decided was worth testing within this project. The anticoincidence veto showed very good light collection uniformity and energy resolution. The resultant hardware threshold with four PMTs is 110keVee. One way to decrease the threshold is by increasing the photocathode coverage by adding more PMTs, but the increase in internal radioactivity must then be considered.

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