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PNNL-25297

Prepared for the U.S. Department of Energy
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Characterization of a Commercial Silicon Beta Cell

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March 2016

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1.0 Introduction

Silicon detectors are of interest for the verification of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) due to their enhanced energy resolution compared to plastic scintillators beta cells. Previous work developing a figure-of-merit (FOM) for comparison of beta cells suggests that the minimum detectable activity (MDA) could be reduced by a factor of two to three with the use of silicon detectors[1]. Silicon beta cells have been developed by CEA (France)[2] and Lares Ltd. (Russia)[3], with the passivated implanted planar silicon beta cell (PIPSBox) developed by CEA being commercially available from Canberra for approximately $35k, but there is still uncertainty about the reproducibility of the capabilities in the field. PNNL is developing a high-resolution beta-gamma detector system in the shallow underground laboratory, which will utilize and characterize the operation of the PIPSBox detector. Throughout this report, we examine the capabilities of the PIPSBox as developed by CEA. The lessons learned through the testing and use of the PIPSBox will allow PNNL to strategically develop a silicon detector optimized to better suit the communities needs in the future.

2.0 Measurement Setup

Prior to deploying the PIPSBox (**Figure 1**) within the low-background underground measurement system that uses HPGe detectors (**Figure 2**) it was tested in an aboveground setup with NaI detectors in order to verify the previously stated detector parameters. Data acquisition was performed using a PXI platform with a XIA Pixie-4 card installed. A CAEN A1422 preamplifier was used to supply the high voltage bias to and output the signal from the PIPSBox Si detectors. The complete setup can be seen in **Figure 3**. While the HPGe gamma efficiency cannot be measured aboveground, the beta efficiency and energy resolution were measured with the NaI detector setup.

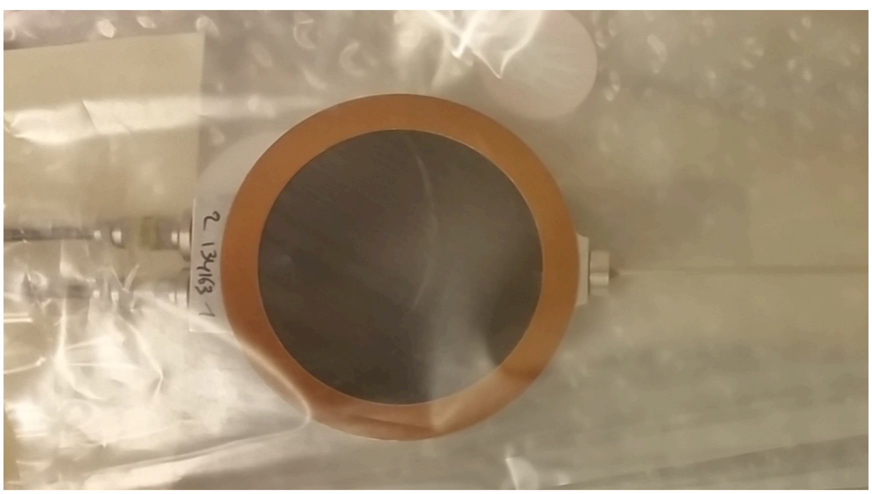

Figure 1: The PIPSBox detector ready for testing at PNNL.

Figure 2: HPGe detectors that will act as the gamma detectors for the PIPSBox underground setup.

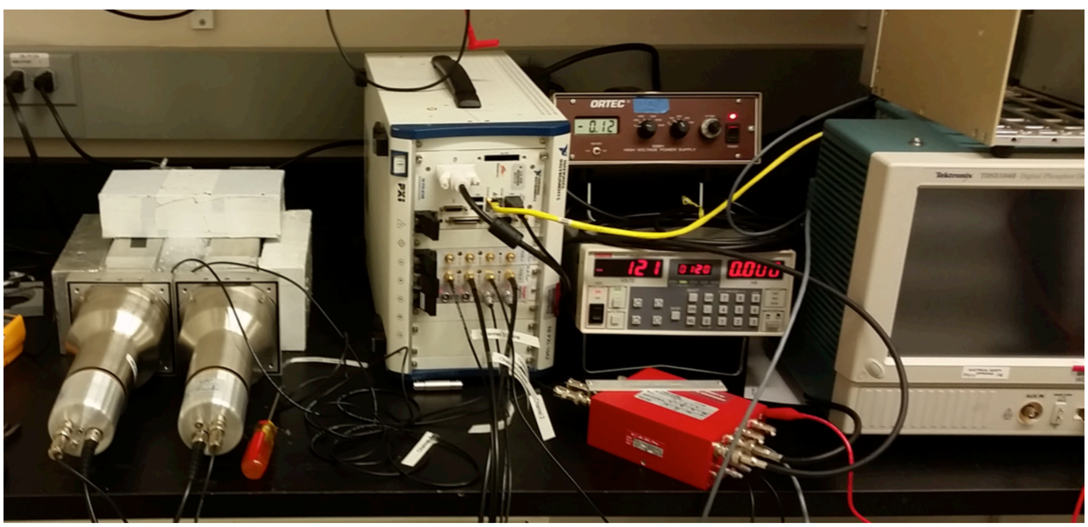

Figure 3: Aboveground measurement setup with the PIPSBox between two NaI detectors.

3.0 Detector Capabilities

In order to characterize a detector with the previously developed figure-of-merit (FOM), the detector efficiency, energy resolution, and memory effect need to be known[1]. Using the aboveground detector setup, the detector parameters were measured for the PIPSBox.

3.1 Energy Resolution

The settings used with the Pixie-4 card were optimized to obtain the best energy resolution from the silicon detectors. The PIPSBox demonstrated an energy resolution of 14% (18 keV) FWHM for the ^{131m}Xe 129-keV conversion electron, **Figure 4**. An energy resolution of 18 keV is approximately 30% worse than that which was presented by CEA[4]. While 14% energy resolution may be enough to separate the ^{131m}Xe and ^{133m}Xe conversion electron peaks, it is not enough to fully separate the two conversion electrons of ^{131m}Xe, **Figure 5**. In addition to the energy resolution, it is desirable obtain a low threshold (minimal detector noise) capable of detecting the low-energy Auger electron events from the radioxenon isotopes, and the backscatter electron events.

With the initial high voltage supply used, the PIPSBox exhibited poor energy resolution (~30%), and it was discovered that the fluctuations of the power supply were the cause of the poor energy resolution. As silicon detectors are used in the future, it is important that the high voltage supply be stable enough to meet the needs for radioxenon detection.

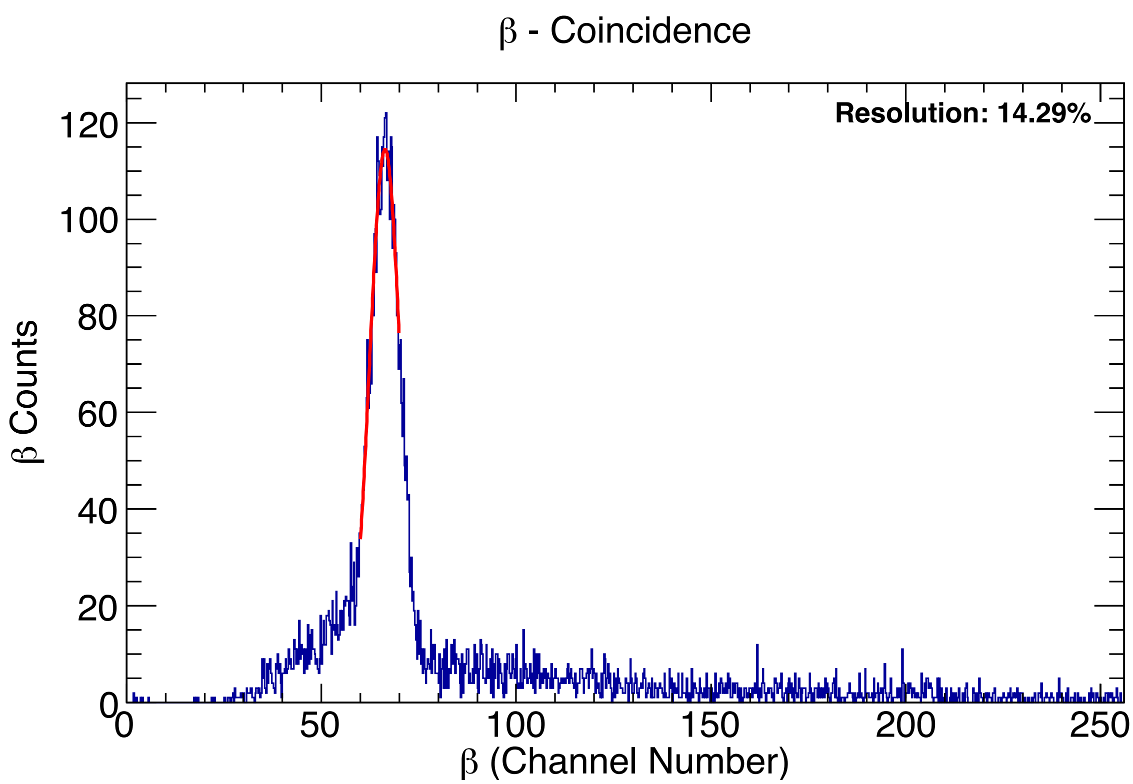

Figure 4: Beta coincidence spectrum for ^{131m}Xe with an energy resolution of 14.29 %.

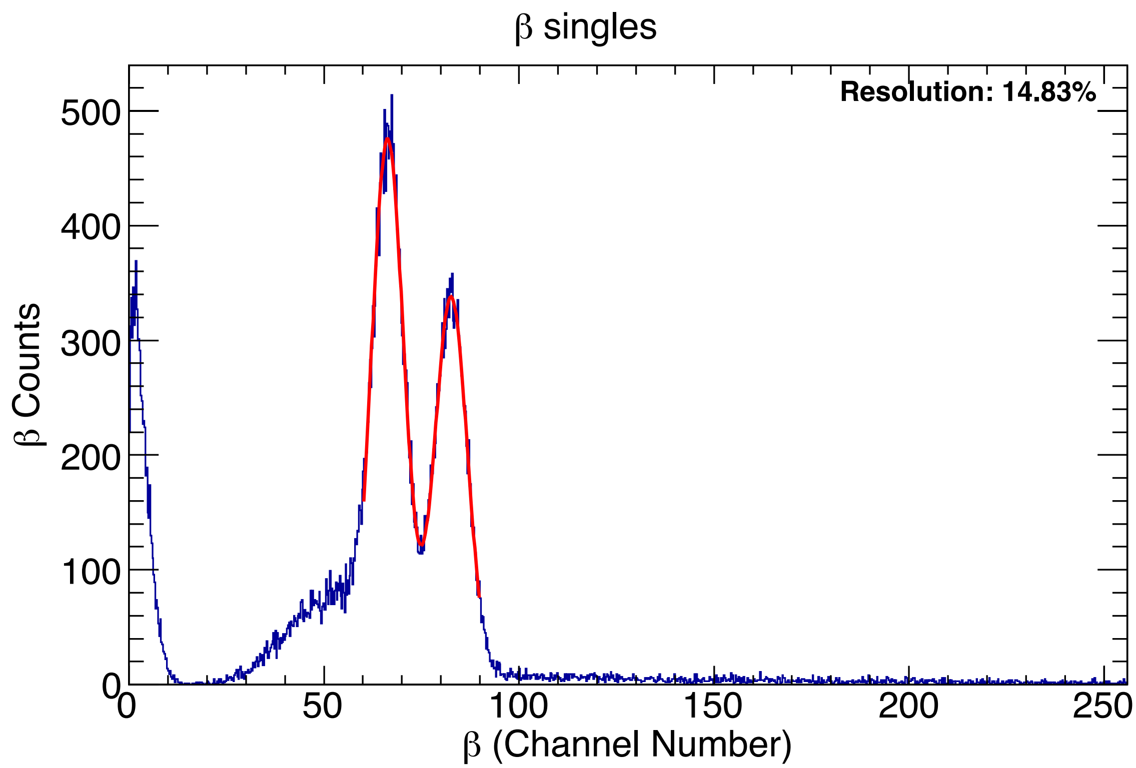

Figure 5: Beta singles spectrum for ^{131m}Xe. The energy resolution is not enough to completely separate the ^{131m}Xe conversion electron peaks.

3.2 Beta Efficiency

While the underground system detection limits could not be determined in the aboveground setup, the preliminary beta efficiency for ^{131m}Xe were determined with the NaI gamma detectors. Due to the limited shielding used for initial testing of the PIPSBox, the calculation of the efficiency was performed using background-subtracted spectra. **Figure 6** shows the overlay of the coincident gamma spectrum with that of the gamma singles from the ^{131m}Xe calibration spike, along with that of the background data. By taking the ratio of gamma spectra, we obtain a beta efficiency of ~32%. This value is approximately two-thirds of that measured by CEA with the original PIPSBox detector (44%), and one-third of plastic scintillator beta cells (100%). CEA states that approximately 30% of the ^{131m}Xe events are detected with energy below the conversion electron peak due to electron backscattering[4]. The beta efficiency of the PNNL tested PIPSBox is expected to increase to approximately 40-45% with the optimization of the detector settings in order to lower the threshold and detect the electron backscatter events. Further refinement of detector settings should yield higher efficiency, since the lower energy tail of the ^{131m}Xe spectrum is absent from the current data. PNNL is currently working on the refinement process. The final beta efficiency used for each isotope will also depend on the bounds of each region-of-interest (ROI).

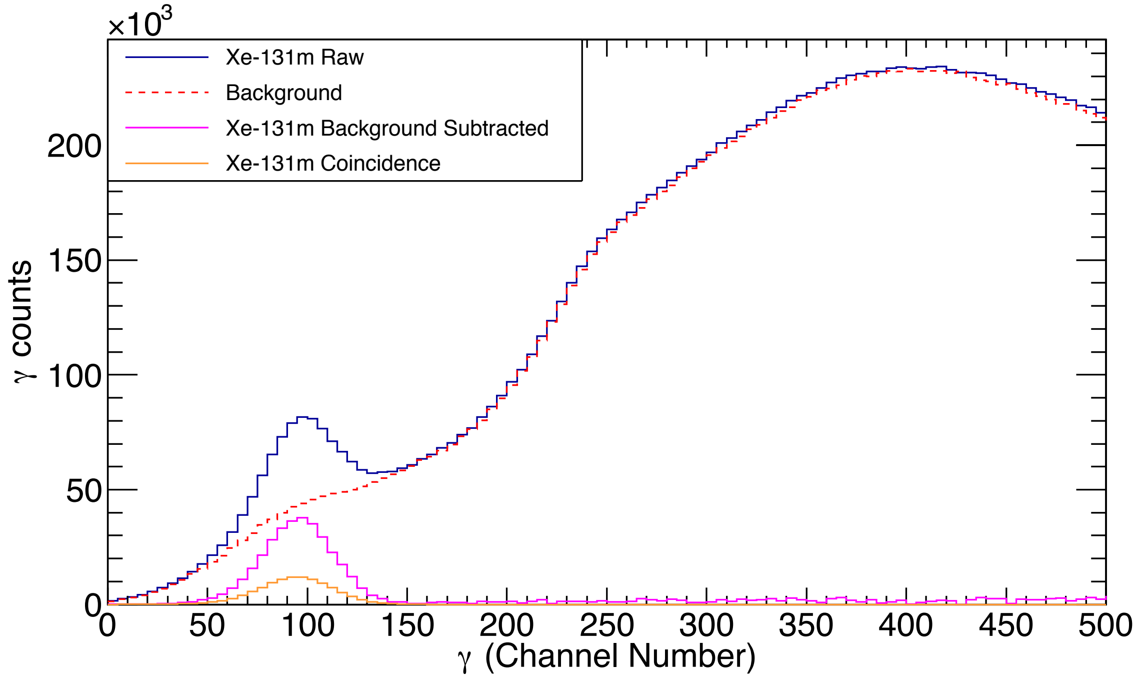

Figure 6: Beta efficiency for the PIPSBox was measured to be 32%, less than the published value of 44%.

3.3 Memory Effect

The ROI for ^{131m}Xe was calculated from the 3σ Gaussian fit of the ^{131m}Xe peak in both the gamma and beta direction. After the ^{131m}Xe calibration measurement, **Figure 7**, the memory effect was measured after two xenon potential cleanup methods. The first memory effect measurement was performed with a pump and flush routine of flushing the PIPSBox with 300 Torr of stable xenon, then pumping it down with a roughing pump. A 24-hour measurement was performed with xenon within the PIPSBox during counting, **Figure 8**. This procedure yielded a memory effect measurement of 0.3%. The xenon was subsequently pumped out of the PIPSBox with a turbo pump for 80 minutes. The memory effect was further reduced to 0.1% with the turbo pump evacuation. Given a memory effect of 0.1% or lower, it may be reasonable to either shorten or remove the gas background run, which would allow for the sample measurement time to be increased up to 24 hours.

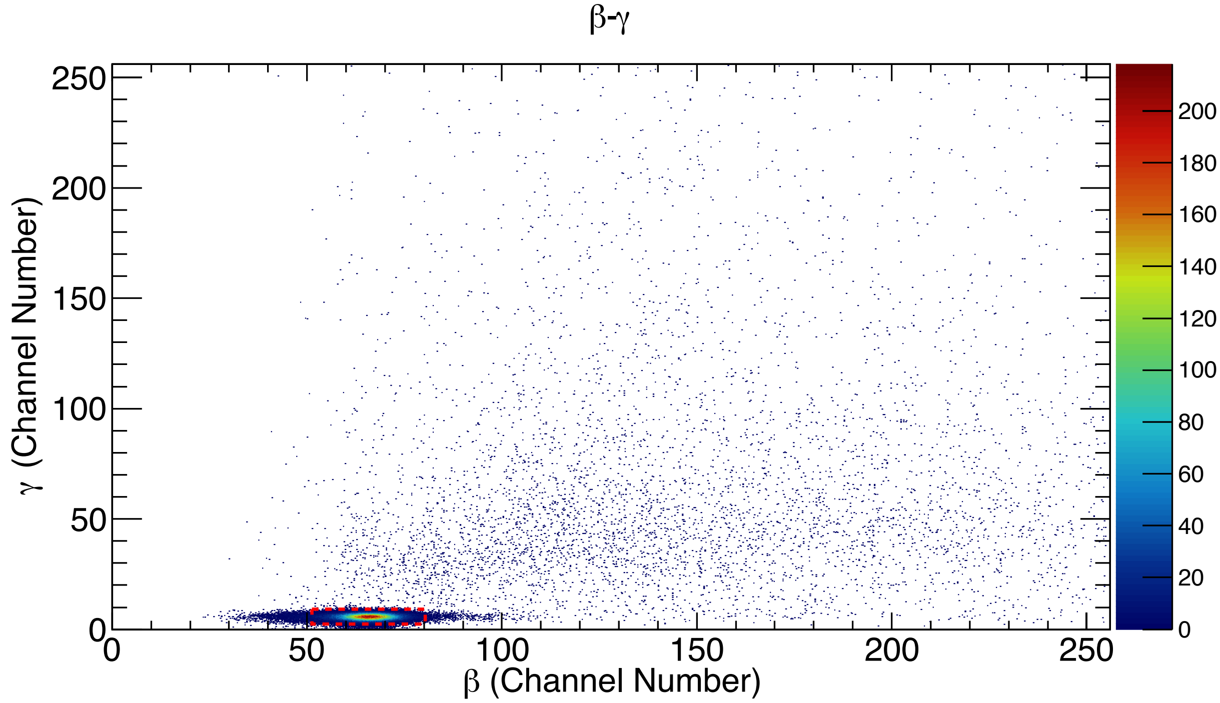

Figure 7: Beta-gamma spectrum for ^{131m}Xe, with a 3-sigma ROI drawn around the peak.

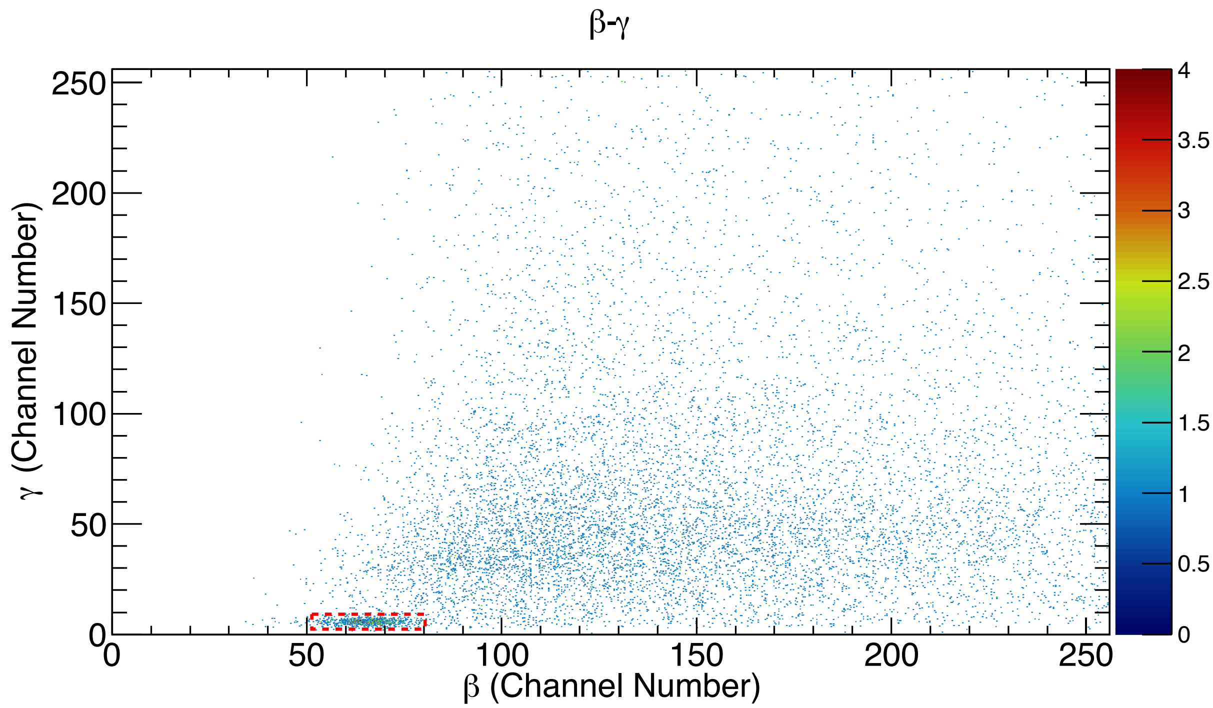

Figure 8: Memory effect ^{131m}Xe spectrum showing a 0.3% memory effect after a pump and flush following the calibration measurement.

4.0 Figure-of-Merit Comparison

Using the previously developed FOM[1], the performance of the currently tested PIPSBox can be compared to plastic scintillator beta cells. The FOM used for the comparison is:

$$\frac{100(Efficiency\ [\%])^{-1}(Res.\ [keV]*0.0025+0.025)(Res.\ [keV]*0.003+0.01)}{\sqrt{\frac{Count\ Time}{12\ [hrs]}}}$$

Table 1 gives the FOM for the PIPSBox with a beta efficiency of 32%, an energy resolution of 18 keV, and minimal memory effect.

Table 1. *FOM calculated for detector setups and parameters of interest. A lower FOM indicates a better performing detector.*

Detector	Efficiency	Resolution	Memory Effect	Count Time	FOM
Plastic Beta Cell	100%	30 keV	Yes	12 hours	0.2
Coated Plastic Beta Cell	100%	40 keV	No	24 hours	0.18
Coated Plastic Beta Cell	100%	40 keV	Minimal	12 hours	0.255
PIPSBox (CEA)	50%	10 keV	Minimal	24 hours	0.128
PIPSBox (PNNL)	32%	18 keV	Minimal	24 hours	0.296
Si PIN Beta Cell	67%	10 keV	Yes	12 hours	0.134
Optimal Si Beta Cell	100%	10 keV	No	24 hours	0.064

Unless the decrease in detector backgrounds expected for a silicon detector beta cell can offset the loss in detection efficiency, it appears that the overall minimal detectable concentration (MDC) of the PNNL PIPSBox may be slightly worse than that of current plastic scintillator beta cells. It is clear that for both the PIPSBox and any future silicon detector, an emphasis must be placed on maintaining high detection efficiencies in order to utilize the full benefit of the enhanced isotopic discrimination possible with the improved energy resolution of the silicon.

5.0 Conclusions and Future Work

The PIPSBox shows significant improvement in energy resolution (18 keV vs 30 keV) and memory effect (0.1% vs 5%) compared to a plastic scintillator beta cell, but suffers from poor detection efficiency (32% vs 100%). While the use of silicon will aid in isotope discrimination, there is room for substantial improvement in detection efficiency, and thus radioxenon sensitivity. As the PIPSBox is further tested with the HPGe detectors in the underground laboratory, the background will be reduced giving a better idea of the ultimate sensitivity for the system, both the minimum detectable activity and the isotope discrimination. In the future, effort will need to be placed on the initial design of a silicon detector in order to ensure that the detection efficiency is high enough to leverage the full capabilities of silicon with the improvements in energy resolution and memory effect.

6.0 References

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