INITIAL BETA-GAMMA NUCLEAR DETECTOR BACKGROUND STUDY

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ABSTRACT

Detection of underground nuclear explosions and, more recently, nuclear reactor events is of great national interest. These measurements are most often made by determining the concentration of radioactive noble gases in the atmosphere. Currently there are several ground-based systems capable of making radioxenon gas measurements. The measurement is often close to the detection limit, so understanding the parameters and features that limit the measurement is very important.

A preliminary study of the radioxenon detection limit has been performed using a β-γ coincidence detector designed at Pacific Northwest National Laboratory (PNNL), the “Quad” detector. The initial study has concentrated on measuring the contribution to radioxenon energy regions of interest from internal and external radioactive backgrounds. By making several background measurements while varying the detector shielding thickness it is possible to identify whether the dominant backgrounds are internal or external to the detector. Once identified, internal background contributions can be potentially reduced by selecting alternative low-background materials, while external background can be reduced by increasing the active or passive shielding present. By reducing the background contributions, it is possible to improve the detection limit and therefore the likelihood of positively identifying a nuclear test.

OBJECTIVES

The current standard in nuclear explosion monitoring uses radioxenon measurements. Improvements to the detection limits for radioxenon systems are desirable as they improve the likelihood of positively identifying a nuclear test. Radioactive backgrounds are one potential limitation to detection limits in current systems, and so are examined in this work for a particular representative detector design.

Currently there are two nuclear detector technologies used in radioxenon systems. One technology uses a high purity germanium (HPGe) gamma-ray spectrometer and relies on the excellent energy resolution of HPGe to differentiate the radioxenon isotopes. The second technology, which is considered in this paper, depends on a gamma (γ) detector (usually sodium iodide (NaI)) coupled with a beta (β) detector (usually BC-404 plastic scintillator) to detect the β-γ signature (Bowyer 1998, Bowyer 1999, Bowyer 1999b, Bowyer 2002). This method provides a significant reduction in background due to the β-γ coincidence requirements. Figure 1 shows an example of the β-γ nuclear detector technology (Auer 2004, Cooper 2005, Cooper 2007). Typical gamma backgrounds and those backgrounds specific to β-γ nuclear detectors are discussed in the remainder of this paper.

Figure 1. An example of a β-γ nuclear detector with the components partially disassembled.

RESEARCH ACCOMPLISHED

Experimental setup

The background study uses a PNNL designed β-γ "Quad" detector (Cooper 2007), so-called because four individual β-γ detectors (see Figure 1) are housed together in a clover-like geometry (see Figure 1). The detector is surrounded by an inner shielding layer of 0.64 cm (¼ in.) of copper, followed by an outer layer of 2.5 cm (1 in.) of lead shielding. An energy calibration for both beta and gamma detector elements was performed using ^{152}Eu and ^{137}Cs pellet sources that were positioned centered between the four detectors. Compton scatter events in the beta detector scintillating plastic that were in coincidence with the remainder of the gamma energy being detected in the NaI detector were used to calibrate the beta energy scale. The initial background measurement, in which the detector had only the normal 2.5 cm of outer lead, was acquired over approximately a 24-hour period. The second background measurement acquired with a total of 10.2 cm (4 in.) of outer lead shielding and was taken over approximately a week.

Figure 2. An example of a Quad β-γ nuclear detector with the components partially disassembled.

The data was acquired using XIA (XIA 2010) electronics and the NYX software package (Schrom 2009, Cooper 2010) developed at PNNL. The data was taken with coincidence information, timestamps and energy for each event, and was post-processed to construct the γ-single, β-single and β-γ coincident spectra.

Background contributions

Contributions to the β-γ detector background can come from several sources. Due to the short range of alpha and beta particles, these are important as direct background sources primarily as surface contamination, on or near the beta detecting plastic, or as internal contamination in the NaI detector. Beta activity in bulk shielding can generate Bremsstrahlung photons, this is a common background source seen from lead refined in the modern era. X-ray emissions from materials near the beta and gamma detectors can contribute backgrounds, e.g., copper fluorescence x-rays. Cosmic-rays and secondary particles can give rise both to minimum-ionizing tracks in both plastic and NaI as well as high-energy neutron inelastic scattering reactions with subsequent gamma emission. Both thermal and high-energy neutrons can produce activation radioisotopes in the materials in and around the beta and gamma detectors. Thermal neutron interactions with hydrogen in the plastic of the beta detector can produce recoil ionization signals at lower energy as well as thermal neutron capture gammas that can be seen in the gamma detector. Gamma emitters in the exterior environment, as well as the materials of the detectors and shield can produce background signals in both the beta plastic (through Compton-scatter interactions) and the gamma NaI detector.

Under normal laboratory conditions, internal and external gamma emitters, along with cosmic-ray-induced backgrounds are usually the most significant background sources.

The main sources of environmental gamma backgrounds are the primordial $^{238, 235}$U, and ^{232}Th decay chains, along with ^{40}K decay (Bossew 2005). These background sources typically stay constant in a given location and detector configuration. The primordial uranium and thorium decay chains also include radon gas, which can be present at varying levels, depending on factors such as fluctuations in atmospheric pressure and local ventilation. Unless steps are taken to exclude radon gas from any empty volume around detector elements inside passive gamma shielding, its varying concentration can give rise to varying background levels. Radon backgrounds can be identified via characteristic-energy lines in the spectrum of the gamma detector. Figure 3 shows a HPGe spectrum for a typical gamma background. The relative peak heights will vary depending on the materials in the immediate vicinity of the detector.

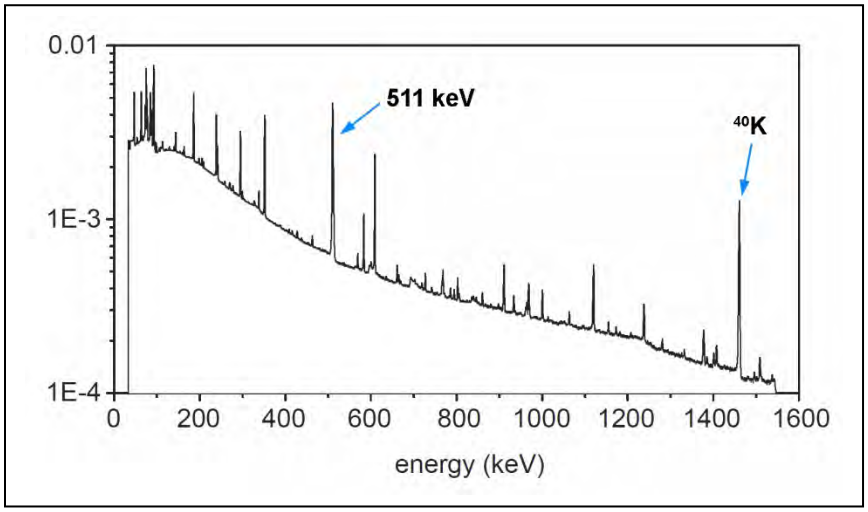

Figure 3. A typical gamma background spectrum seen with an HPGe detector. The HPGe has 10.2 cm of lead shielding.

Background measurement

The background measurements used the PNNL designed β-γ quad detector. They were carried out with two shield geometries: one using only 2.5 cm of lead and the other using 10.2 cm. The measurements were acquired over different time spans, and the resulting energy spectra have been normalized to a vertical scale of counts per keV per second. A comparison of normalized gamma background data is shown in Figure 4, where the three most intense γ-ray peaks have been identified (Browne 1986).

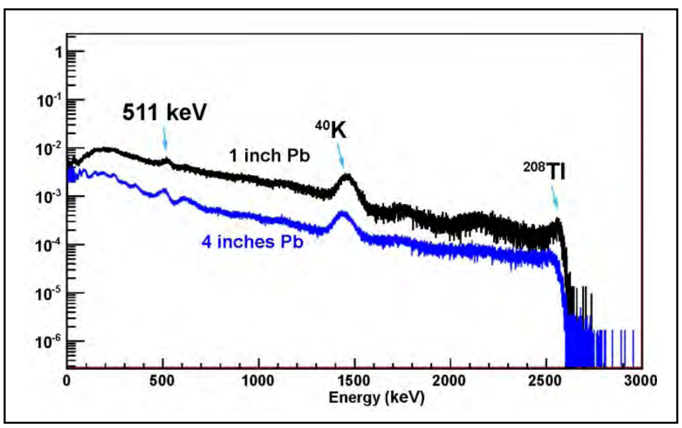

Figure 4. Normalized gamma background spectra generated from the NaI well detector of a β-γ nuclear detector with different thicknesses of lead shielding. The black spectrum has 2.5 cm of lead, while the spectrum in blue has 10.2 cm of lead shielding. The vertical scale is in counts per 3 keV per second.

Although, the gamma spectra are excellent indications of what background sources are present, they do not directly represent the background observed in β-γ coincidence. Figure 5 is an example of the β-γ spectrum generated from the quad detector with 2.5 cm of lead shielding. There are several features observed in this spectrum. First, there two diagonal lines that are circled. These lines represent Compton scatter events that interact in both the NaI and the BC-404 scintillators and deposit the full gamma energy between the two detectors as given by the following: $E_{Total} = E_\gamma + E_\beta$. The events that Compton scatter into both β and γ detectors, while not depositing the full energy, may contribute to the background in a particular region of interest (ROI) relevant for radioxenon. Of note is the higher-background region in the lower left corner of the β-γ spectrum. This region is of the most interest as it is where the radioxenon signatures are found. The higher background there is due to partial energy deposition in both the γ and β detectors and is enhanced by gamma backscatter.

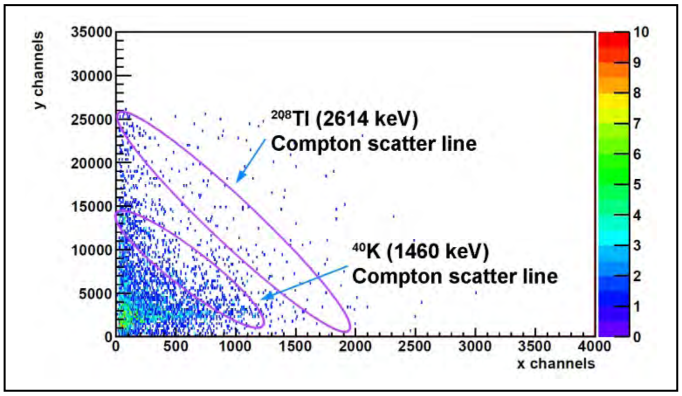

Figure 5. A β-γ coincidence plot of the ambient background radiation with 2.5 cm of Pb shielding.

Once additional shielding (10.2 cm) has been added, the β-γ background changes, as can be seen in Figure 6. The Compton scatter constant-energy line from ^{208}Tl disappears, but the Compton scatter constant-energy line from ^{40}K remains visible. This suggests a portion of the background is due to ^{40}K radioactivity in internal materials and may be reduced by selection of lower- background materials. The most important portion of the spectrum for β-γ radioxenon measurements is marked with a green box in Figure 6. An expanded view of this is shown in Figure 7.

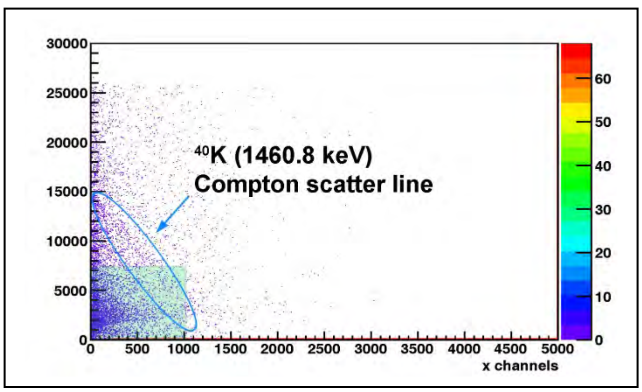

Figure 6. A β-γ coincidence plot of the ambient background radiation with 10.2 cm of Pb shielding.

Results

The expanded view, shown in Figure 7 is representative of the energy span for a radioxenon β-γ system. The red boxes displayed in Figure 7 are the seven ROIs (ROI-1: ^{214}Pb, ROI-2: ^{135}Xe, ROI-3: ^{133}Xe, ROI-4: ^{133}Xe, ROI-5: ^{131m}Xe, ROI-6: ^{133m}Xe) used in radioxenon analysis. As can be seen, the highest background region falls on top of the radioxenon ROIs (ROI-1 and 2). The use of 10.2 cm of lead shielding as opposed to only 2.5 cm significantly reduced the backgrounds in these regions. The reduction in background by the additional lead shielding can be seen in Table 1. This reduction, although significant, does not completely address possible background reductions.

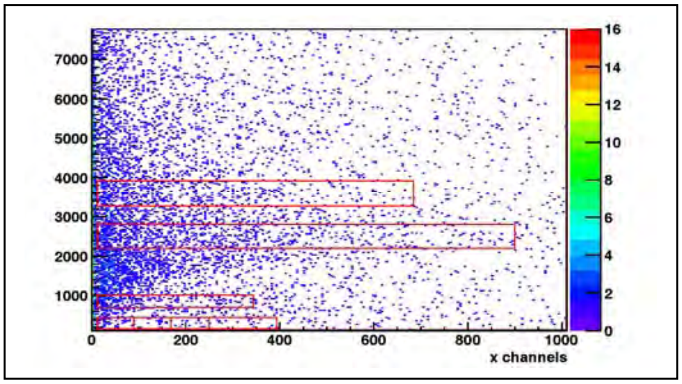

Figure 7. A coincident β-γ spectrum typical for the region of interest analysis used in radioxenon measurements.

Table 1. A listing of the activity attributed to background in the total spectra and several key ROIs.

	Activity for 2.5 cm Pb (Bq)	**Activity for 10.2 cm Pb (Bq)**	**Improvement factor $\left(\frac{1\ inch}{4\ inch}\right)$**
Total γ	21.099	0.9251	22.81
Total β-γ	0.05438	0.00248	21.97
^{135}Xe	0.00527	0.00018	29.13
^{133}Xe (ROI-3)	0.00182	0.00017	10.76
^{133}Xe (ROI-4)	0.00201	0.00015	13.85

The other potential method for reducing the overall background is to improve the radiopurity of internal detector and shielding components. This is perhaps just as important as adding additional shielding. As can be seen in Figure 4 the largest peaks at full energy are marked as from ^{40}K and ^{208}Tl. Once additional shielding is added the ^{208}Tl peak nearly disappears while the ^{40}K peaks remain nearly as strong. This suggests that a large percentage of the ^{40}K peak is due to potassium internal to the detector and shield. By careful selection of low-background materials, the internal background may be significantly reduced.

CONCLUSIONS AND RECOMMENDATIONS

A preliminary background study of the PNNL designed β-γ coincidence nuclear detector has been performed. The findings suggest a combination of background reduction techniques may yield an improvement to the detection limits for radioxenon.

The easiest method to reduce the background is by simply adding more shielding. This will have limitations due to size and weight considerations for particular implementations and locations. However, the increase in shielding will have significant benefits in reducing the overall detector background and improving the detection limits.

The second method relies on reducing internal detector background by the careful selection of low-background materials. This requires additional effort to determine which detector components currently contribute the highest background rates and to develop alternative replacement materials.

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