BEOWULF: A BETA-GAMMA DETECTOR CALIBRATION GRAPHICAL USER INTERFACE

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ABSTRACT

Pacific Northwest National Laboratory (PNNL) has demonstrated significant advancement in using beta-gamma coincidence detectors to detect a wide range of radioxenon isotopes. To obtain accurate activities with the detector, it must be properly calibrated by measuring a series of calibration gas samples. The data are analyzed to create the calibration block used in the International Monitoring System (IMS) file format. Doing the calibration manually has proven to be tedious and prone to errors, requiring a high degree of expertise. The Beowulf graphical user interface (GUI) is a software application that encompasses several components of the calibration task and generates a calibration block, as well as, a detailed report describing the specific calibration process used. This additional document can be used as a quality assurance certificate to assist in auditing the calibration. This paper describes the capabilities of Beowulf and lays out a representative report generated by the ^{137}Cs calibration and quality assurance source.

OBJECTIVES

With the fielding of automated radioxenon systems throughout the IMS network, it has become important to have a standardized method for calibrating the sophisticated radioxenon beta-gamma coincidence nuclear detectors. Advanced and robust methods have been developed that allow the detector to be calibrated, however no advanced software has been developed that has proceduralized the process and made it both easier for experts and possible for non experts to quickly and confidently calibrate, verify, and certify a detector (Bowyer et al., 1996, 1998). Currently, much of the calibration of the detector uses typical desktop calculation tools (MS Excel) or other more robust but difficult to use tools such as ROOT (http://root.cern.ch/drupal/). To fill this gap, PNNL has demonstrated significant advancement in using beta-gamma coincidence detectors to detect a wide range of radioxenon isotopes. To obtain accurate activities with the detector it must be properly calibrated by measuring a series of calibration gas samples. The Beowulf GUI is a software application that encompasses several components of the calibration task and generates a calibration block, as well as a detailed report describing the specific calibration process used. This additional document can be used as a quality assurance and quality control (QA/QC) certificate to assist in auditing the calibration of nuclear detectors.

In order to fully calibrate a beta-gamma nuclear detector it is important to first set up the detector components to achieve the desired energy range and energy response. For older detector assemblies this requires gain matching of the photo-multiplier-tubes (PMT's) and the associated lower level discriminators (Reeder and Bowyer, 1998). For newer models of detectors, there is no need for PMT gain matching for a single detector component but gain matching between detectors is important to achieve consistent energy scales across all of the individual detector components (Cooper et al., 2007). Having properly adjusted the HV, which controls the gain of each PMT to the desired range, the detector assembly is then ready take a number of calibration spectra. These spectra are needed to calibrate the detector and generate the configuration parameters needed to convert the counts in a given spectra and region of interest (ROI) into concentrations for the radioxenon isotopes of interest (^{131m}Xe, ^{133m}Xe, ^{133}Xe, and ^{135}Xe).

The spectra needed are as follows: a detector background spectra,; a ^{133}Xe spectra, a ^{135}Xe spectra, a ^{131m}Xe spectra and a ^{222}Rn spectra. Missing from this list is a spectra for ^{133m}Xe, which decays into ^{133}Xe and is an interference. In addition this isotope of xenon is difficult to produce in significant quantities. The ^{131m}Xe is used as a surrogate because it closely matches the radiometric signature of ^{133m}Xe (i.e., a conversion electron (CE) in coincidence with a 31-keV x-ray). The ^{222}Rn spectrum is needed for subtraction of radon daughter interferences that may be present in samples collected. Furthermore, the radon daughter response (^{214}Pb and ^{214}Bi) provides additional gamma-ray energies, resolutions and additional beta energies used to populate the configuration files. Having the five calibration spectra it is then possible to calculate the gamma-ray energies and resolutions for all available x-rays and gamma-rays, the beta and CE energies and CE resolutions, the ROI sizes and locations, the interference terms from ^{214}Pb, and ^{133}Xe, and the detection efficiencies for each ROI.

RESEARCH ACCOMPLISHED

The Beowulf GUI, displays the calibration spectra, allows the user to determine peak locations, the full-width-half-maximums (FWHM) for gamma, x-ray and CE peaks, the total number of counts in each peak, or beta distribution, and does a number of calculations that produce the calibration parameters needed to populate the detector configuration files. The program is laid out with tabs for each isotope needed for calibrating the detector plus a secondary tab for determining the gamma and beta efficiencies for each of the isotopes under consideration.

Xenon-133 Analysis Tab

Figure 1 shows a preliminary screen capture of the Beowulf GUI showing a ^{133}Xe spectra collected for calibration purposes. The top panel is where the actual calculations are performed for each isotope and it is in this panel that user can select which of datasets to analyze. The second panel (top-right) is the two-dimensional beta gamma histogram. This panel is used to determine the ROI's for each isotope and to verify the beta and gamma channel to energy conversions.

The four panels below these two are separated into the gamma-singles, and beta-gated gamma spectrum (middle panels 3 and 4) and the beta-singles and gamma gated beta spectra (the two bottom panels 5 and 6). It is worth pointing out that a singles spectrum has all of the counts that a single detector records without regard to the other detector. So for a gamma singles spectrum (panel 3) all of the gamma events recorded by the NaI(Tl) well detector are shown whether there was a coincident event in the plastic beta-cell detector or not. The spectra shown in this panel is the gamma singles spectrum for the isotope spectra (blue line) and the detector background spectrum (green line) along with the time adjusted background subtracted spectrum (red line). The fourth panel shows the beta-gated gamma spectrum where the line colors are blue is the coincidence ^{133}Xe spectrum, green is the coincidence background spectrum, and red is the background subtracted coincidence spectrum. From the background subtracted gamma singles and background subtracted beta-gated coincidence spectra it is possible to determine the beta efficiency for the 31-keV x-ray line (lower energy peak) and the 80-keV gamma line from ^{133}Xe. It is also possible to determine the locations of these two peaks in channel space and use them as part of the channel to energy conversion block in the final configuration files.

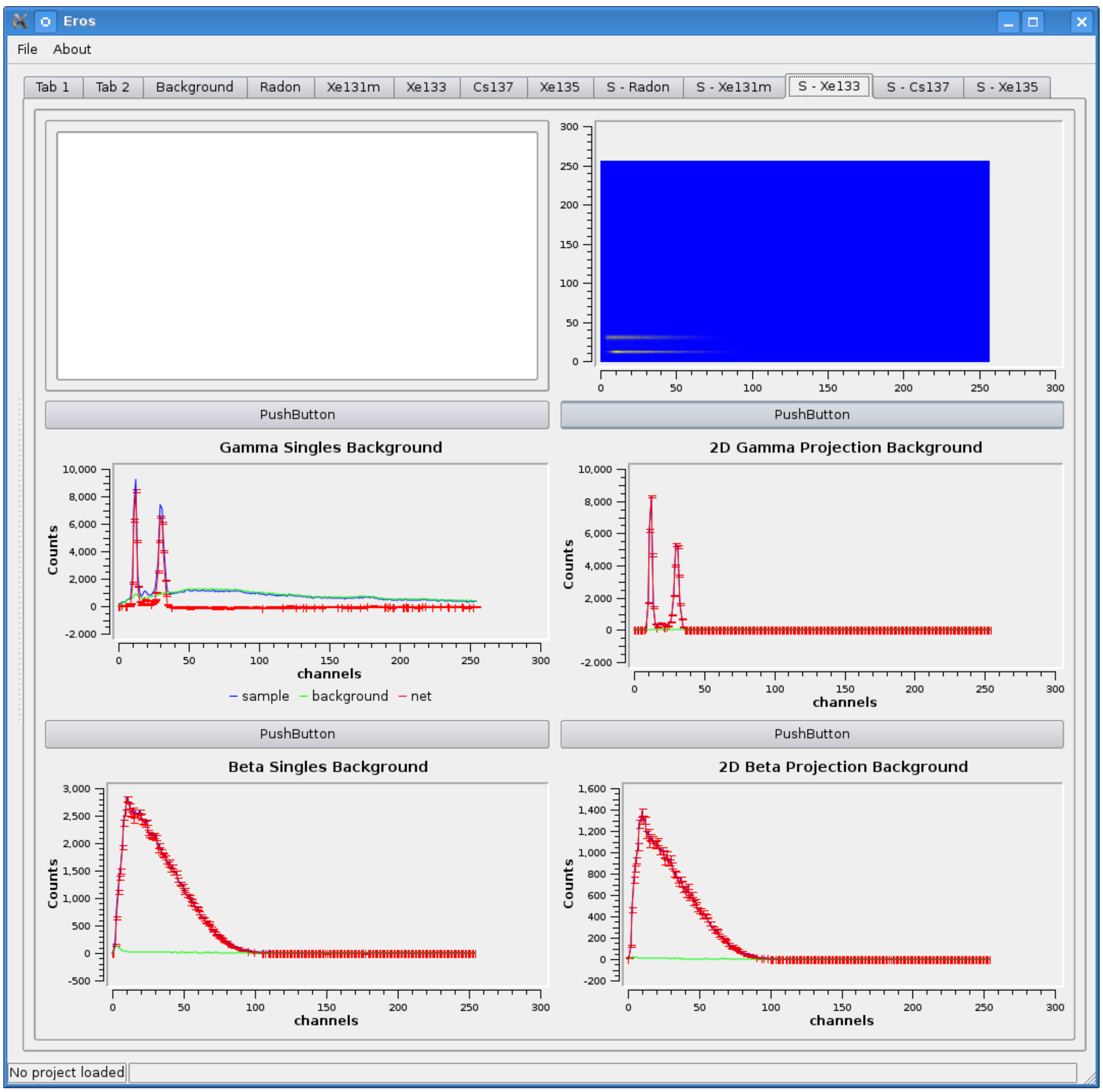

Figure 1. A screen capture of the Beowulf GUI with the ^{133}Xe calibration spectrum shown.

The two bottom panels show the beta-singles and gamma-gated coincidence beta spectra for ^{133}Xe and the detector background. The color coding for the different spectra is the same as mentioned earlier. Like the gamma spectra these spectra along with the decay branching ratios for the different gamma and x-ray lines allow the GUI operator to determine the gamma efficiency for the 31-keV x-ray and 80-keV gamma. While not as easy to see as the x-ray and gamma it is also possible to determine the beta end point energies for the x-ray and gamma distributions.

Radon Analysis Tab

Figure 2 shows the Radon tab with several radon calibration spectra from the same calibration file plus the detector background file. What is actually seen in the panels is not ^{222}Rn but instead the decay products ^{214}Pb and ^{214}Bi, which have strong beta-gamma coincidence signatures that interfere with the xenon isotope signatures. The gamma singles and beta-gated gamma spectra show this interference best and indicate that it causes problems across the entire energy range of the detector. The interference of the radon is determined by determining the ratio of counts associated with radon in each ROI and dividing these counts by the counts in ROI 1 (the fifth peak from the right in

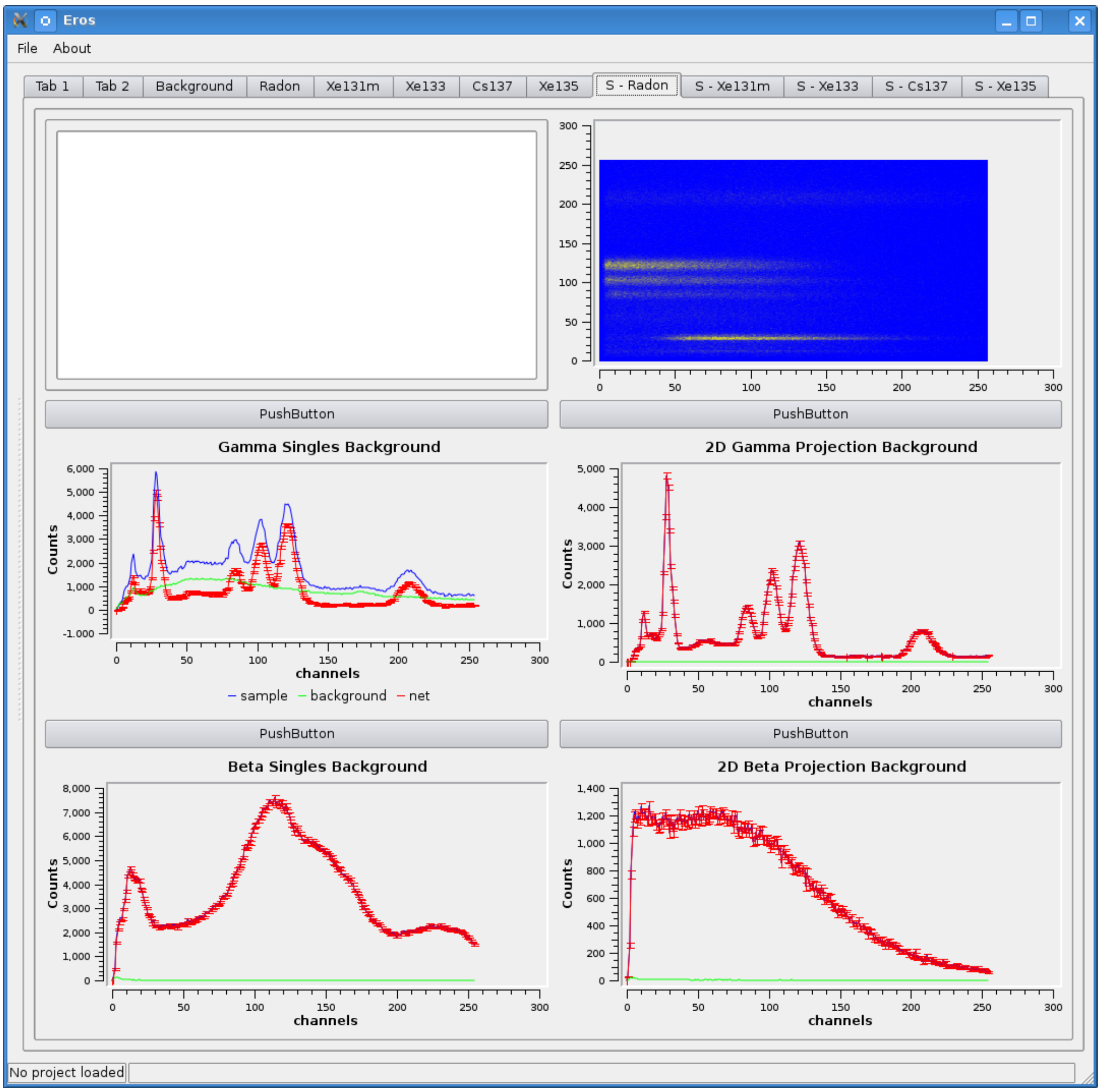

Figure 2. Radon-222 calibration spectra used for gamma and beta energies and radon interference ratio terms used in the radioxenon concentration calculations.

the beta-gated gamma-singles spectrum, panel 4). This ROI is only populated by the radon daughter ^{214}Pb and gives a direct measure of the radon interference throughout the entire two-dimensional spectra.

The spectra shown on the radon tab can also be used to further define the gamma channel to energy conversion and the beta channel to energy conversion, as well as the energy resolution for each of the 5 gamma peaks and one x-ray peak. It is interesting to note that the beta singles spectrum has several alpha decays present as well as the beta spectra for the ^{214}Pb and ^{214}Bi.

Cesium-137 QA/QC Analysis Tab

A tab has been defined to address the QA/QC spectra taken using a ^{137}Cs source that has mono energetic gamma-ray at 661.7-keV. This set of spectra allows the testing on the nuclear detector in the absence of other radiometric

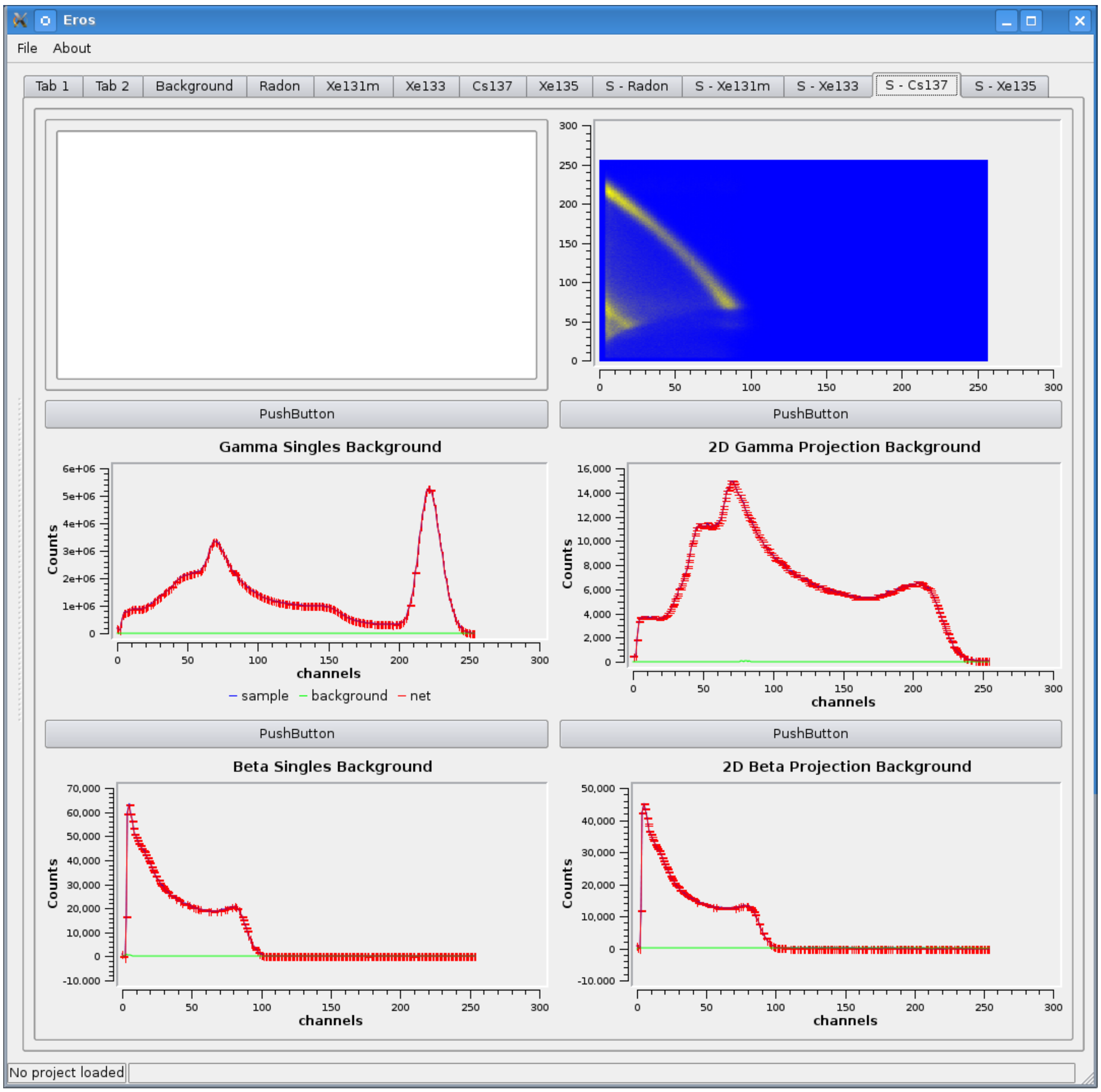

Figure 3. Screen capture of the QA/QC 137Cs Compton scatter spectra used to check the beta energy scale, the beta resolution and the gamma and beta energy calibrations and efficiencies.

signatures from the xenon and radon daughter isotopes and because it is sealed source pellet it can be easily and automatically insert and removed from the detector on a daily basis. One of the key features of the detector response is the Compton scatter energy line (Reeder et al., 2001). Figure 3 is a screen capture of the QA/QC ^{137}Cs tab and it clearly shows the Compton scatter line in the two-dimensional plot (panel 2). This line is a constant energy line where the energy has been shared between the gamma detector (Compton scattered gamma) and the beta detector (Compton scattered electron). Because the gamma and beta energy along this line is constant it is possible to use the calibrated gamma axis to determine the calibration of the beta axis. This is done by taking a slice from left to right across the gamma axis and projecting the subsequent beta response onto the beta axis. This provides an average gamma energy and the location of the beta peak is at 661.7-keV minus the gamma-energy. The beta resolution can also be determined by finding the FWHM of the project beta peak.

These data are also used to determine changes in the gamma and beta energy calibration (panels 3 and 5) and also to track the beta and gamma efficiency. The 661.7-keV gamma is clearly seen in panel 3 with the pure Compton scatter spectrum shown in panel 4. Panels 5 and 6 look very similar because the beta detector responds to the Compton scattered electrons and has very little detection efficiency for the full 661.7-keV gamma peak. The only difference between the two is the gamma gating requirement for the beta-gamma coincidence spectrum (Panel 6).

Auto-Report Feature

An additional capability of the Beowulf GUI is the automatic generation of calibration reports. This feature allows the technician to generate a detailed report for each of the calibration tabs. The ^{137}Cs QA/QC report is shown below and includes both a description of the process and the actual values and parameters obtained. It is envisioned that a report file will be auto-generated for each of the calibration processes used to fully characterize the nuclear detector.

Calibration for
"IFX01-xy1-2008/11/06-00:06:44"

Auto-calibration v0.2 for beta-gamma, Pixie4 Quad-detector setup

Fri Jul 10 14:18:14 2009

Run with parameters:

Commandline parameter	Value
sampleFileName	Cell4-cs137_110608.pbg
betaGain	1
betaOffset	0
numBetaBins	256
betaEnergyLow	0
betaEnergyHigh	1000
gammaGain	1
gammaOffset	0
numGammaBins	256
gammaEnergyLow	0
gammaEnergyHigh	730
gammaCutLowEnergy	200
gammaCutHighEnergy	500
gammaCutN	5
iStart	10

1 Introduction

The process of putting a count into a histogram from a Pixie4 capture card goes through a couple of steps. The steps are:

1. Convert ADC value to energy
2. Convert Energy to bin number

The conversion of ADC to energy is done through the following equation:

1

$$E(ADC) = A * ADC^2 + B * ADC + C \quad (1)$$

where: (2)
ADC Value from Pixie4 (3)
A Nonlinear term (4)
B Linear term (5)
C Offset term (6)

The conversion to bin number depends on the number of bins and the energy span represented by the histogram. Nominally, the bin number can be figured out by:

$$BIN(E) = \frac{E - E_{low}}{E_{high} - E_{low}} * N_{bins} \quad (7)$$

One additional step happens because counts are not allowed to be divided. A weighted probability, based on the portion of the "count" that covers the bin number, is used with a random process to determine what bin number the actual count gets added to. For the remainder of this calibration, this fact will be ignored.

The point of this auto-calibration code is to determine, and possibly adjust, the A, B, and C coefficients in equation 1.

There are three items mentioned above that are confusing, but need to be kept strait:

ADC Native number from Pixie4 with range from $0 - 2^{16} - 1$

Bin Number The bin number in the histogram. Normally 256 bins, but can be set with command option

Energy Real energy in keV. Usually between 0-1000keV

Channel is NOT used anywhere as it is a confusing, ill-defined term.

1.1 Strategy

The first assumption this code makes is that the file being analyzed is a ^{137}Cs spectrum and that γ singles and coincidence $\beta - \gamma$ data are available.

The second assumption is that this code requires the user (or external agent), to pass in the current A, B, and C coefficients.

These assumptions allow the following process to happen:

2

- Find two points in the γ singles spectrum
- Find an energy calibration for this spectra.

From this point forward, we assume that the γ axis is calibrated and that the calibration is identical for singles and coincidence axises.

Using the known calibration of the γ axis, cuts can be made on the $\beta - \gamma$ coincidence data. The γ ray emmitted by ^{137}Cs at 661.67keV is detected in the coincidence counter because some fraction of its energy is deposited in the β cell when it Compton scatters and the remaining energy is deposited in the γ detector. Since the γ energy is known, the β energy can be solved for by subtracting the γ energy from 661.66keV.

1. Find 200.5keV in γ Compton backsatter peak.
2. Find 661.67keV in γ singles.
3. Get γ ADC to energy function
4. Get γ energy to bin number function (needed for finding β energy)
5. Get γ bin number to energy function (needed for finding β energy)
6. Divide $\beta - \gamma$ coincidence spectrum into regions based on γ values.
7. For each cut region, project data onto β axis. This will have a Gaussian appearance.
8. Find the centroid, β bin number, of the Gaussian and the corresponding β energy by subtracting from the corresponding γ energy.
9. Using all of the found energy centroids and corresponding ADC values, do a nonlinear fit to get a β ADC to energy function. The 2^{nd} order fit is for informational purposes only.
10. Using all of the found energy centroids and corresponding ADC values, do a linear fit to get a β ADC to energy function. This is the one that gets used.

2 Gamma (γ)

$$energy(BIN) = A * BIN^2 + B * BIN + C \tag{8}$$

Basing calibration point on ^{137}Cs energy 200.5keV

3

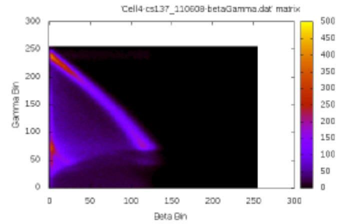

Figure 1: Beta Gamma coincidence

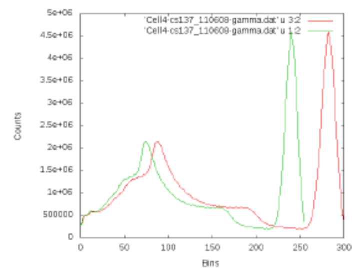

Figure 2: Gamma singles

^{137}CsCompton peak The compton energy peak energy is found with the following equation, taken from Knoll 3^{rd} ed., p310

$$h\nu'|_{\theta-\pi} = \frac{h\nu}{1 + \frac{2h\nu}{m_0c^2}} \tag{9}$$

4

where:

$h\nu'$	energy of scattered gamma ray
$h\nu$	total energy
m_0c^2	rest mass energy of electron

$$h\nu'|_{\theta-\pi} = \frac{661.\bar{6}\text{keV}}{1 + \frac{2\times 661.\bar{6}\text{keV}}{511\text{keV}}} = 184.32\text{keV} \tag{10}$$

One	Two
found at bin number	75.0366
estimated ADC	213.971

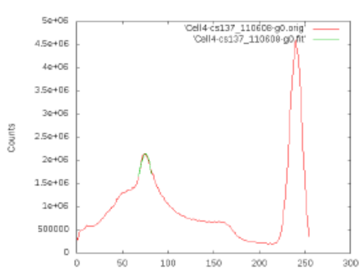

Figure 3: Fitting the 200.5keV ^{137}Cs gamma singles peak

Fit settings:

Parameter	Value
scale	$1.58048e+06 \pm 589.213$
centroid	75.0366 ± 0.00461983
sigma	12.0097 ± 0.0142535
fwhm	28.2808 ± 0.0335645
resolution	0.376893 ± 0.00044791

Basing calibration point on ^{137}Cs energy 661.67keV

One	Two
found at bin number	239.901
estimated ADC	684.093

5

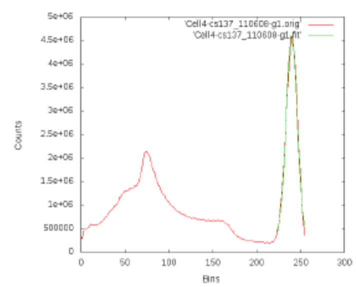

Figure 4: Fitting the 661.67keV ^{137}Cs gamma singles peak

Fit settings:

Parameter	Value
scale	$4.25016e+06 \pm 710.059$
centroid	239.901 ± 0.000920846
sigma	8.6731 ± 0.00109744
fwhm	20.4236 ± 0.00258426
resolution	$0.0851334 \pm 1.07772e-05$

$$Energy(ADC) = 0 * ADC^2 + 0.980959 * ADC + -9.39729 \tag{11}$$

$$Bin(Energy) = 0 * Energy^2 + 0.357492 * Energy + 3.35945 \tag{12}$$

$$Energy(bin) = 0 * bin^2 + 2.79727 * Energy + -9.39729 \tag{13}$$

3 Beta (β)

Beta: energy(BIN) = $A * BIN^2 + B * BIN + C$ Fit settings:

Fitting ^{137}Cs coinc spectrum between gamma 200keV and 500keV

Fitting ^{137}Cs coinc spectrum between gamma bin number 74 and bin number 182

6

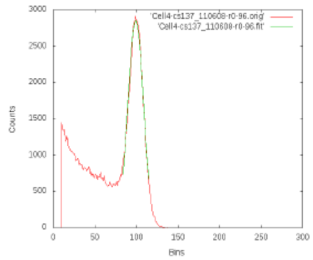

Figure 7: Coincidence β projection based on γ cuts. β centroid 99.2524β energy 371.76

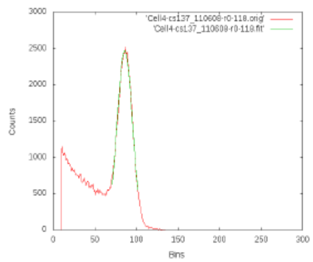

Figure 8: Coincidence β projection based on γ cuts. β centroid 86.1604β energy 310.22

Fit settings (2nd order, information only):

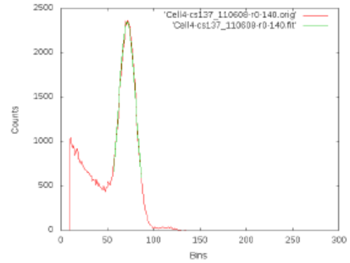

Figure 9: Coincidence β projection based on γ cuts. β centroid 71.6991β energy 248.68

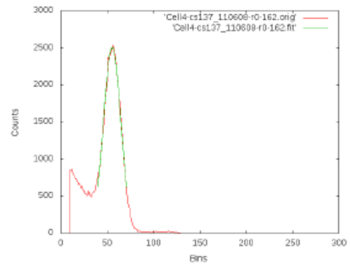

Figure 10: Coincidence β projection based on γ cuts. β centroid 55.4477β energy 187.14

$$energy(ADC) = 0.00109213 * ADC^2 + 0.420484 * ADC + 44.9614 \quad (14)$$

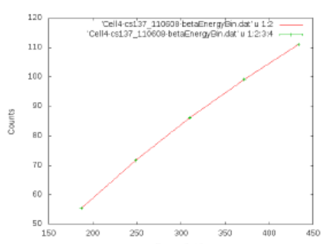

Figure 11: Energy vs. found centroids

$$\chi = 0.292567 \quad (15)$$

Fit settings (1st order):

$$energy(ADC) = 0 * ADC^2 + 1.13033 * ADC + -63.8948 \quad (16)$$

$$\chi = 145.89 \quad (17)$$

4 Results

Brief summary of analysis

Parameter	Value
Date analyzed	Fri Jul 10 14:18:14 2009
Acquired on	Thu Nov 6 00:06:44 2008
Real time	74692 seconds
Live time	36616.3 seconds (49.0231%)
Dead time	38075.7 seconds (50.9769%)

Beta: energy(ADC) $= A * ADC^2 + B * ADC + C$

Settings	Current	New	Relative change
A	0.00000	0	N/A
B	1	1.13033	N/A
C	0	-63.8948	N/A

Gamma: energy(ADC) $= A * ADC^2 + B * ADC + C$

Settings	Current	New	Relative change
A	0.00000	0	N/A
B	1	0.980959	N/A
C	0	-9.39729	N/A

CONCLUSIONS AND RECOMMENDATIONS

The calibration of the beta-gamma nuclear detector requires a large set of calibration spectra that are used to generate an extensive calibration configuration file. The configuration file is used by the radioxenon concentration calculations to convert sample files, gas background files, and detector background files into accurate radioxenon concentrations. The development of a sophisticated GUI that can determine these calibration configuration parameters can greatly reduce the time required to calibrate the beta-gamma detectors and makes it possible for a well trained technician to do the work rather than a subject matter expert with several years of experience.

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