Calibration of the NaI(Tl) detector set-up used to study natural stone countertops

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Abstract

Thallium-doped Sodium Iodide detectors are capable of measuring the energy spectra of gamma particles (photons) emitted by radioactive nuclei with an energy resolution of a few percent. As the gamma particles emitted during the decay of specific radioactive elements have very well-defined energies, the measurement of specific energy gammas indicates what radioactive nuclei are decaying. The experimental set-up, however, requires a software calibration that converts the measured spectra versus "bin number" into the spectra versus the energy in MeV. This calibration for my measurements of the spectra from natural stone countertops is described in this note.

The basic set-up consists of a Thallium-doped Sodium Iodide detector read-out by a Photo-Multiplier Tube (PMT) and PMT "base," a preamplifier, an amplifier, and a Multi-Channel Analyzer (MCA). The MCA reads out the signal area over a linear scale called "bins". The bin number is related to the gamma energy monotonically. A software calibration is required to covert the MCA bin numbers into gamma energies in MeV. The gain of the set-up is a strong function of the high voltage applied to the PMT. The base for the PMT, which provides the voltages to the PMT's dynodes, includes "focussing." This provides the ability to slightly adjust the resistance of the various stages of the PMT to optimize the energy resolution. The overall high voltage applied to the PMT, the focussing, as well as the amount of pre-amplification and amplification, thus modify the spectra that are obtained both in gain and resolution. It is therefore important to study this parameter space in order to obtain the best possible resolution. This note describes how the MCA bin number to energy calibration is performed, which allows the subsequent optimization of the resolution of the system.

The calibration relies on a known "calibration source" that is a pure sample of a single radionuclide. I use ^{22}Na as the calibration source. This nucleus produces three sharp peaks at the known energies of 0.511, 1.27, and 0.511+1.27 = 1.78 MeV (see page 66 of Ref. [1]). The 0.511 MeV peak results from the decay of ^{22}Na to ^{22}Ne^{2+}, while the 1.27 MeV peak results from the decay of ^{22}Ne^{2+} to ^{22}Ne, which is stable. The peak at 1.78 MeV is the sum of these two steps in a single event. The half-life of ^{22}Na is 2.6 years.

In order to treat slow drifts in the energy scale with time (over hours), I typically alternate the collection of data from the ^{22}Na source with the collection of data from the stone sample of interest. The energy calibration parameters are typically constant to better than 1% once the PMT has been allowed to warm-up completely ($\sim$30 minutes). The calibration parameters are extracted from each ^{22}Na run and are then applied to the subsequent run of the stone sample of interest.

The raw spectra for four separate runs of the set-up are shown in Figure 1. The vertical axis is counts, and the horizontal axis is the MCA bin number. The blue and cyan histograms are from the ^{22}Na source, while the red and magenta histograms are from a granite sample. One can in fact see a slight drift in the energy scale by looking at the red and magenta histograms. This drift is automatically fixed during the MCA bin to energy calibration procedure using the ^{22}Na source.

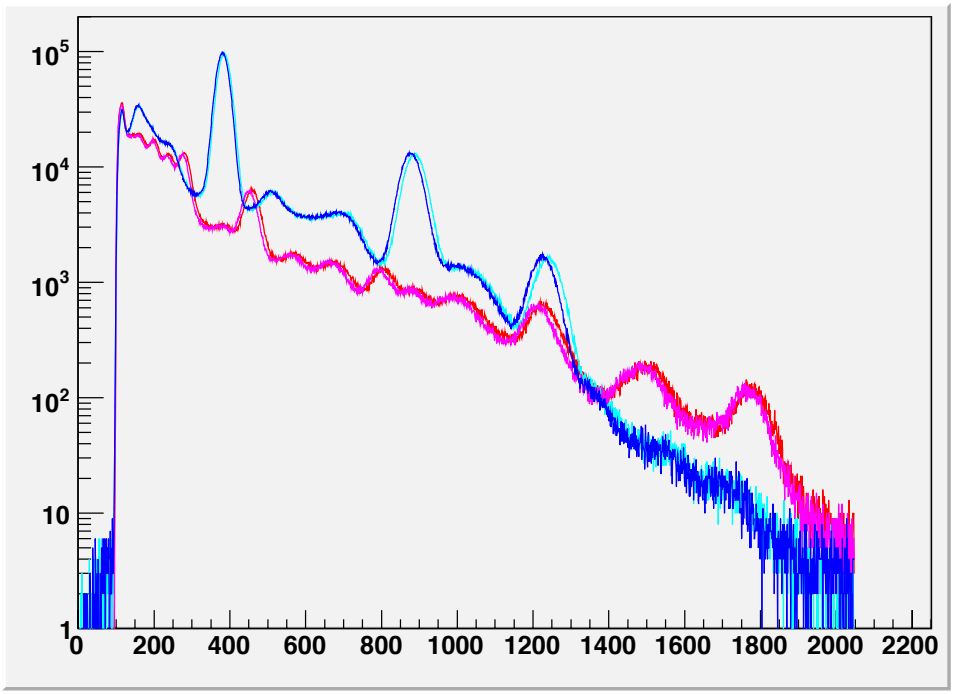

Figure 1: *The raw spectra from two runs with a ^{22}Na source (blue and cyan) and from a section of a granite countertop (red and magenta). The vertical axis is counts, and the horizontal axis is the MCA bin number.*

The MCA bin to energy calibration proceeds as follows. The locations of the three ^{22}Na peaks along the MCA bin number axis have to be determined in the presence of the "backgrounds" from the Compton edges and the other contributions to the shape of the full spectrum, which is shown in Figure 2. The vertical axis is logarithmic. The red lines are exponential functions (seen as straight lines due to the logarithmic Y-axis) that are fit to the spectra on both sides of each peak.

These three exponentials are then subtracted from the raw spectrum, which produces the 3 "pure" peaks shown in Figure 3. Each of these peaks is then fit with a Gaussian function, and the positions of the centroids in units of MCA bin numbers are thus extracted. According to Figure 3, the mean values are 381.2, 879, and 1228 MCA bins, respectively, in this example. The resolution of each peak for this example is 4.3%, 2.9%, and 2.3%, respectively. I will return to a discussion of the optimization of the resolution below.

These three peaks are identified with energies of 0.511, 1.27, and 1.78 MeV, respectively. The MCA bin number to energy calibration then simply involves the linear fit of these three energies versus the corresponding centroid MCA bin numbers obtained from Figure 3. This linear fit is shown in Figure 4.

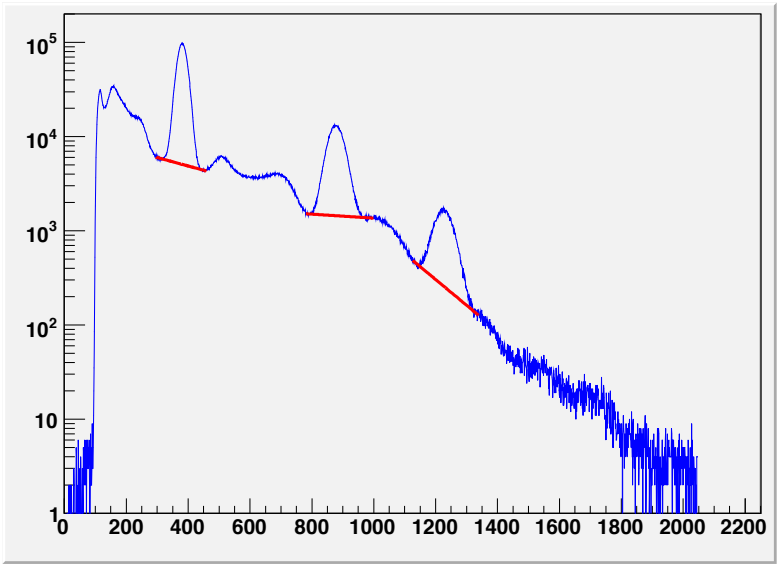

Figure 2: *A raw spectrum the ^{22}Na source. The vertical axis is counts, and the horizontal axis is the MCA bin number. The red lines are exponential fits to the "background" around each of the three peaks.*

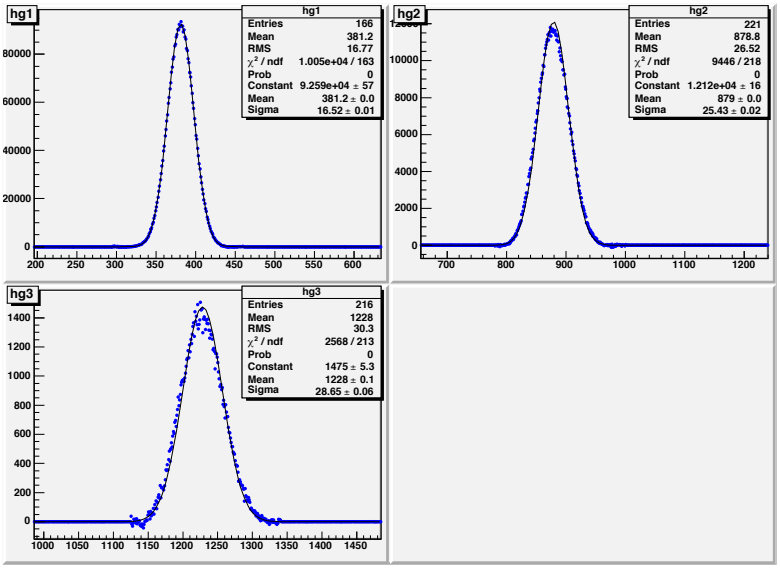

Figure 3: *The three peaks from the ^{22}Na source following the subtraction of the background around each peak using the exponential fits shown in Figure 2. The vertical axis is counts, and the horizontal axis is the MCA bin number.*

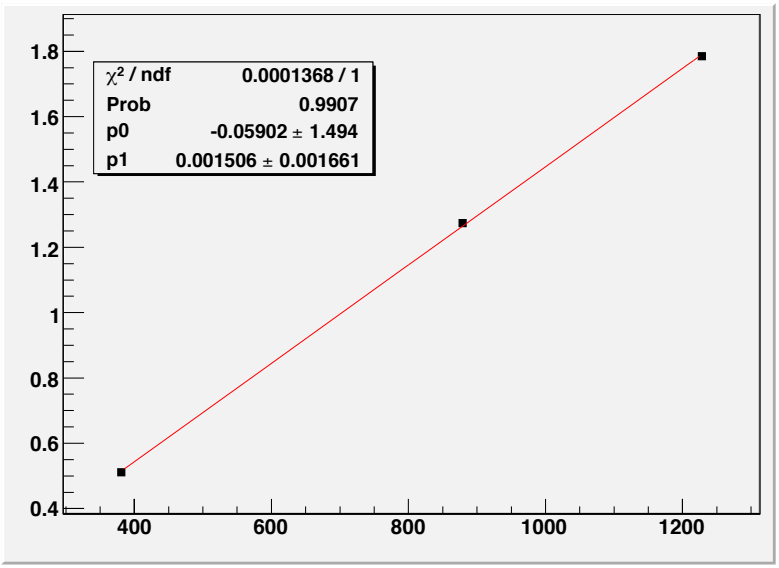

Figure 4: *The MCA bin number to energy calibration. The vertical axis is energy in MeV, and the horizontal axis is the MCA bin number.*

The calibration parameters obtained for this example are thus

$$E = B * (1.506 \times 10^{-3} \pm 1.661 \times 10^{-3}) - (5.902 \times 10^{-2} \pm 1.494), \quad (1)$$

where E is the energy in MeV and B is the MCA bin number. The fit quality χ^2 parameter is 1.368×10^{-4} for one degree of freedom.

The spectra shown in Figure 1 are thus converted from MCA bins to energy using this calibration function. The result is shown in Figure 5. The calibrated spectrum from the ^{22}Na source is shown as the blue histogram, while that from a stone sample is the red histogram.

The spectrum from the stone sample is shown alone in Figure 6. The text in this figure indicates the energies expected from a combination of uranium ore, ^{40}K, and ^{232}Th. The majority of the peaks in this figure result from the decay of ^{214}Bi that is a progeny of ^{238}U via ^{226}Ra. The countertop thus contains a significant amount of Uranium ore (see page 537 of Ref. [1]). There is also an admixture of ^{232}Th (indicated by the 2.615 MeV peak from the decay of ^{208}Tl - see page 535 of Ref. [1]) and ^{40}K (indicated by the 1.46 MeV peak - see page 85 of Ref. [1]). The observed mixture of Uranium, Thorium, and Potassium radionuclei in granite is consistent with all of the published literature (see Ref. [2] and references therein).

The energy resolution in this example was 4.3% at 0.511 MeV, 2.9% at 1.27 MeV, and 2.3% at 1.78 MeV. A subsequent exploration of the parameter space of this set-up (high voltage, focussing, and amplification values) was performed. These parameters were varied over wide ranges while keeping the positions of the three ^{22}Na peaks constant. The resolution of the set-up depends very weakly on the specific choices of these parameters ($\pm 0.1\%$).

In the future, the vertical axis of these spectra will be scaled from total counts to counts per minute. This allows an integration of the normalized spectra to obtain an overall radiation rate per minute. Such a measurement of the decay rate will be superior to that obtained from broad-spectrum Geiger-Mueller (GM) detectors given the differing

response of GM detectors to different decay particles as well as the different energy-dependence of the GM detection efficiencies for these particles.

The energy-calibrated and time-normalized spectra can also subsequently be unfolded to extract the relative amounts of the three parent radionuclides in secular equilibrium [3]. This procedure is described in detail in Ref. [1]. The results from this unfolding will be described in a subsequent note when available.

References

[1] "Scintillation Spectrometry, Gamma-ray Spectrum Catalog", R.L. Heath, RDO-16880, 2nd edition - Vol. 1, Feb. 1997. `http://www.inl.gov/gammaray/catalogs/pdf/naicat.pdf`

[2] W.J. Llope, "Radiation and Radon from Natural Stone," May 7, 2008. `http://wjllope.rice.edu/SaxumSubluceo/LLOPE_StoneRadRn.pdf`

[3] `http://en.wikipedia.org/wiki/Secular_equilibrium`

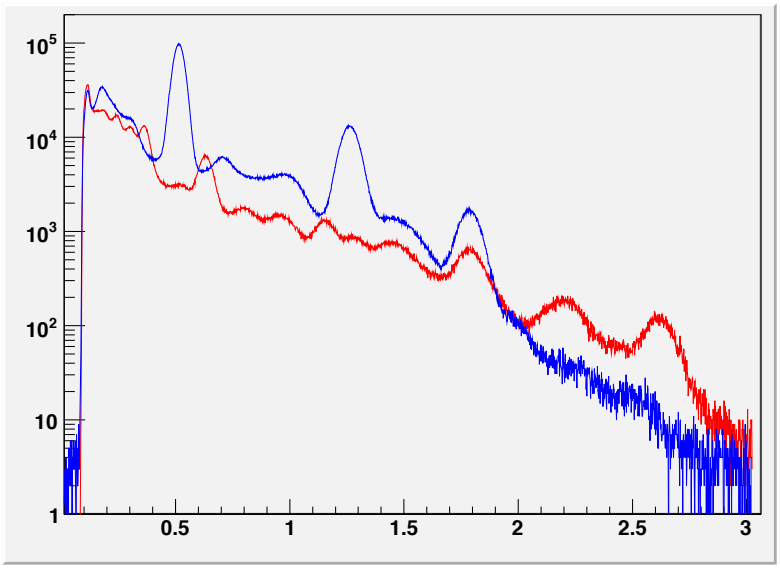

Figure 5: *The gamma spectrum from the ^{22}Na source (blue) and a stone sample (red) following the MCA bin to energy calibration. The vertical axis is counts, and the horizontal axis is the energy in MeV.*

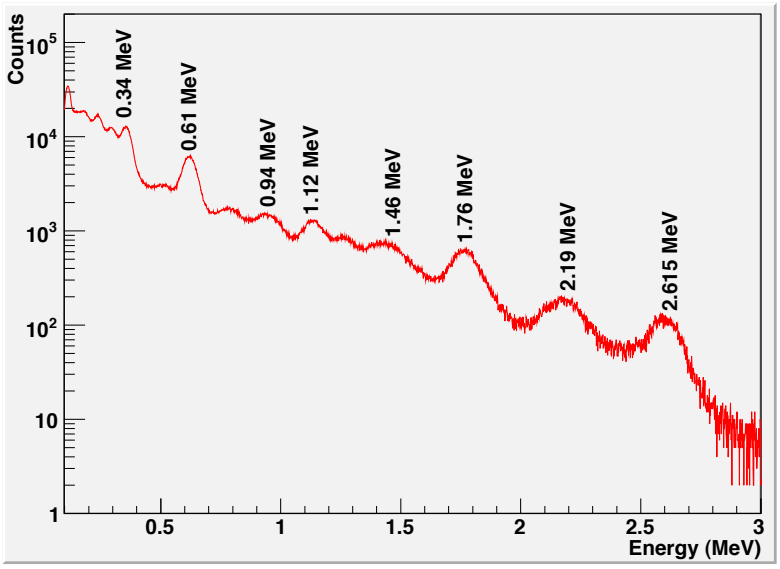

Figure 6: *The spectrum from a stone sample following the MCA bin to energy calibration and including the expected positions of the peaks from specific naturally occurring radionuclides.*