Scintillation Counting

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1 Goal

We measure the nuclear spectra of three radioactive samples with known emission energies through the use of a scintillating crystal and create a calibration equation that relates each bin from the output of a multichannel analyzer to an energy value. The effects of Compton scattering within a scintillation crystal are investigated through measurements of the Compton edge and a mystery peak. Finally, we observe gamma emission from an unknown substance and use our calibration equation to identify the substance from a handbook containing the known spectral lines of various radioactive elements.

2 Introduction/Background

As quantum mechanical systems, it is natural to expect nuclei to emit a characteristic line spectra. Nuclear emissions are dominated by the strong force, which is many orders of magnitude more powerful than the long range force that binds electrons to nuclei. Consequently, gamma emissions from a nucleus create high energy spectral lines on the order of 500 keV, a drastic difference from the eV scale of electronic transitions. The transition energy of nuclear states can be measured by a scintillator, which is an inorganic crystal that interacts with incoming gamma rays through either the photoelectric effect or Compton scatting [2]. Electrons ejected via the photoelectric effect absorb the entirety of a gamma ray's energy, and in turn may excite other atomic electrons along a path. In the case of Compton scattering, the

scattering angle will differ between events, which causes scattered electrons to carry varying amounts of energy according to the equation

$$E'_{gamma} = \frac{E_{gamma}}{1 + \frac{E_{gamma}}{mc^2}(1 - \cos\theta)} \tag{1}$$

where E'_{gamma} is the final ray energy, E_{gamma} is the initial gamma energy, m is the electron mass, c is the speed of light, and θ is the scattering angle [1]. The final gamma energy will range according to the scattering angle up to a maximum value when the gamma is scattered by 180^o. Scattered gamma rays may again create a Compton scattering event or travel outside the crystal. Consequently, a scintillator displays multiple peaks of radiation intensity, but only the largest peaks correspond to full absorption in the photoelectric effect. These peaks are called photopeaks, and only the photopeaks reveal the true nuclear spectra.

High energy electrons traveling within the crystal can excite other atomic electrons, which promptly transition to a lowering energy state and release gamma rays. Some gammas can be collected by a photo multiplier tube (PMT), which amplifies incoming light via the photoelectric effect and a series of electrodes that cause an electron cascade. Due to the high electrode voltage, each electron collision will knock about three electrons from the electrode surface. Ultimately, the PMT passes the signal across a resistor, which crease a voltage pulse and allows a multi-channel-analyzer (MCA) to count the number of pulses in a range of voltage bins. Fast electrons produced via the photoelectric effect have the same energy as the nuclear emission, and these fast electrons excite many atomic electrons along their path, losing only about 2 MeV per collision and continuing until the original fast electron is has redeposited its excess energy into the crystal. This means the pulse height due to each radiated gamma is directly proportional to the energy of the gamma ray, and therefore each bin corresponds to energy in an approximately linear fashion.

3 Procedures and Data

We used an NaI scintillation detector and an MCA to measure the gamma ray spectrum of ^{137}Cs, ^{133}Ba, ^{60}Co, and another, unknown, radioactive element. As seen in Figure 1, the gamma source was placed directly beneath a scintillation crystal. Some scintillation photons from the crystal travel into

the photomultiplying tube where the incoming light is converted into an electric signal. The pulse voltage from the signal was observed on an oscilloscope and the pulse was also directed to an MCA to be counted and placed into a bin.

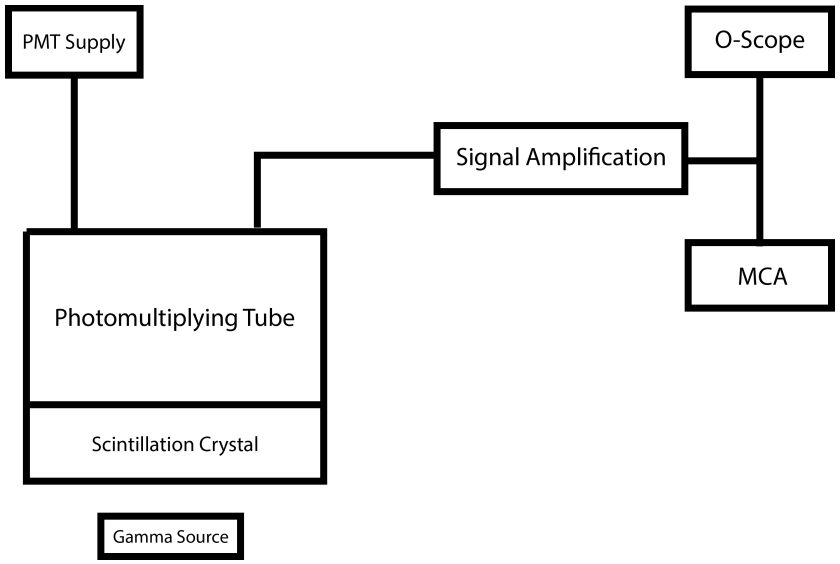

Figure 1: Experimental arrangement. The source feeds into the crystal, then through the PMT, and then is further amplified for the MCA to count.

First, we verified that our MCA readings showed approximately linear dependence upon the input pulse voltage by measuring the centroid MCA value for 10 μs pulses varying in magnitude. As expected, the centroid MCA value rises proportionally with pulse voltage, and we used this fact to help identify the proper photopeaks of interest in further measurements.

In order to measure the gamma spectrum of ^{137}Cs, ^{133}Ba, ^{60}Co, we placed the source under the scintillator, inside an enclosed chamber. The scintillator interfaced with a computer USB port and the Amptek Pocket MCA software displays a plot of intensity vs channel number. We measured the photopeak centroid values found in Table 3 by selecting a symmetric region around the peak and then recording the centroid value reported by the MCA software. With a symmetric region of interest, we also recorded the full width half max from software calculations.

The leftmost peak in Figure 2 is what we call the the mystery peak as it is present at 203 $\pm$ 4 keV in all our measurements. The rightmost edge is

Table 1: This table shows the MCA reported photopeak channel number, the measured energy resulting from converting channel number to energy, and the accepted energy for all known transitions.

Source	Peak Channel	E_{meas} (keV)	E_{acc} (keV)
^{137}Cs	417	671 ± 4	662
^{133}Ba	225	357 ± 4	356
^{133}Ba	189	301 ± 4	303
^{133}Ba	55	88 ± 4	81
^{60}Co	809	1338 ± 4	1333
^{60}Co	714	1172 ± 4	1173
Unknown	786	1298 ± 4	
Unknown	323	518 ± 4	
Unknown	123	196 ± 4	

clearly the photopeak and nearby in the center lies the Compton edge, which we calculate to be at 462 keV. From the right data column of Figure 2, we recorded the FWHM for each of our photopeaks, which is seen in Table 2.

Table 2: Measurements of the full width at half max of the photopeak for each radiation source.

Source	FWHM (Channels)	FWHM (keV)
^{137}Cs	23	37
^{133}Ba	17	27
^{133}Ba	14	22
^{133}Ba	6	10
^{60}Co	32	56
^{60}Co	31	53
Unknown	31	54
Unknown	23	38
Unknown	23	36

4 Analysis and Discussion

In total, we measured the channel number of all identifiable photopeaks for each of our samples. From this data and the accepted value of the energy

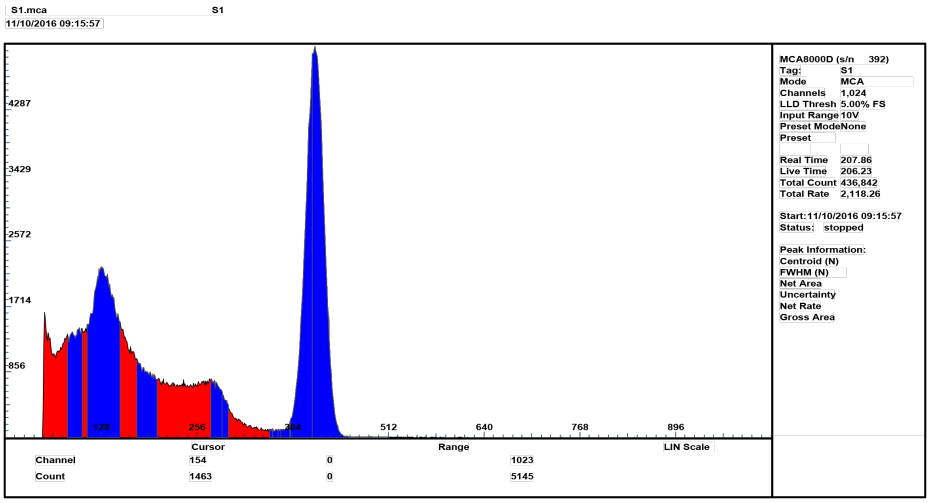

Figure 2: Cesium-137 nuclear spectra as measured by our scintillation crystal and reported on computer software.

associated with each decay, we fit a second order polynomial to compute the energy corresponding to each channel number,

$$E = a + bN + cN^2 \tag{2}$$

where a, b, and c are fit parameters and N is the channel number. The results of this fit are seen in Figure 3. Then, we determined that the uncertainty in our fit to be $\delta E = 4$ keV by averaging $\Delta E = |E_{calc} - E_{meas}|$ for all peaks. Note that in this fit, $a = -2 \pm 7$ keV, so $\pm$ 7 keV may also be a reasonable estimate of the uncertainty, we will choose to use $\pm$ 4 keV.

From the calibration of Equation 2, we find the measured energy of the ^{137}Cs photopeak to be 668 $\pm$ 4 keV, which is within two standard deviations from the accepted value of 662 keV. Then we determined the full width at half max of the ^{137}Cs peak, which is seen in Table 2, to be 37 keV. Additionally, we converted our remaining data to find that Cesium's Compton edge lies at 462 $\pm$ 4 keV and the mystery peak is at 203 $\pm$ 4 keV. Compton scattering creates many electrons of energy $E_{elec} \ll E_\gamma$, but the maximum value of E_{elec} occurs when the gamma is scattered by 180^o. Therefore, the expected energy of the Compton edge is

$$E_{edge} = E_{elec\,max} = E_{gamma} - E'_{gamma} \tag{3}$$

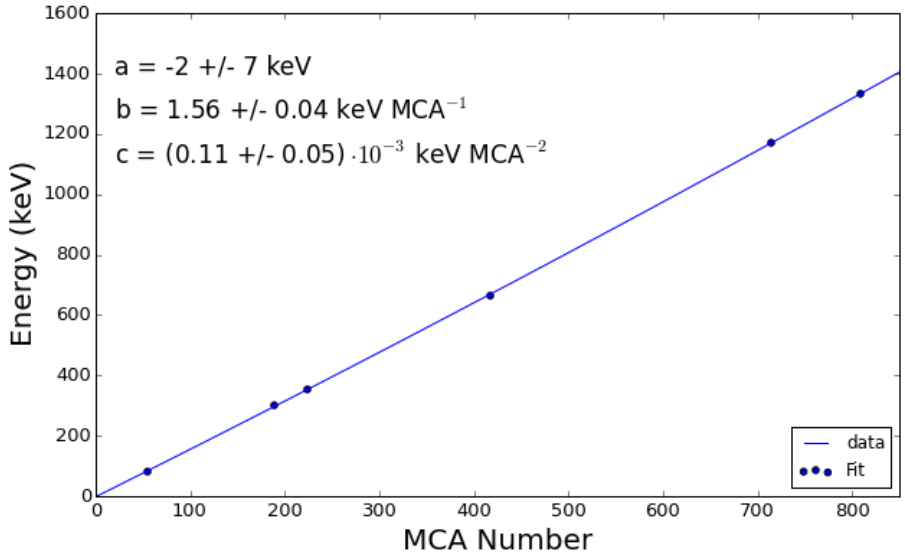

Figure 3: Second degree polynomial fit for the calibration relation of emission energy and MCA channel number.

where E_{gamma} is the accepted value of the gamma energy and E_{gamma}' is the final energy of gamma after scattering off the electron by 180^o, which is calculated from Equation 1. From Equation 3 we calculated the expected Compton edge to be at 478 keV, so while Equation 3 provides a satisfactory estimate of the Compton edge, we see it fails to consider all the complexities of a real Scintillation crystal.

The mystery peak, which we measured to lie at 205 keV is a also a product of Compton scattering, and so this peak corresponds to a scattering angle of 49^o. It is unlikely that this scattering angle is somehow the cause of the mystery peak. Instead, we believe the peak is a result of gamma rays returning into the crystal after traveling outside.

Electrons that fully absorb a gamma ray will create a number, N, scintillation photons per photoelectric event. Then, the energy of a photopeak is proportional to this number N, and therefore counting statistics predicts the photopeak energy to fluctuate proportional to $\sqrt{N}$. Fluctuations in the photopeak energy give the peak a width, which we can characterize by the full width at half max. The resolution of our scintillator is determined by

the ratio

$$R = FWHM/E \tag{4}$$

where FWHM is the full width at half max and E is the peak energy. A plot of the resolution at each of data point is seen in Figure 4. According to counting statistics, we expect the resolution to behave according to

$$R = aE^x \tag{5}$$

where E is the peak energy, and a, x are fitting parameters. From the curve fit seen in Figure 4, we found $a = 0.56 \pm 0.07$ and $x = -0.35 \pm 0.02$. The true resolution behavior is fairly close to the expected relationship of $R = E^{1/2}$, which follows from Equation 4 and the fact that counting statistics dictates that the FWHM increases as $E^{1/2}$.

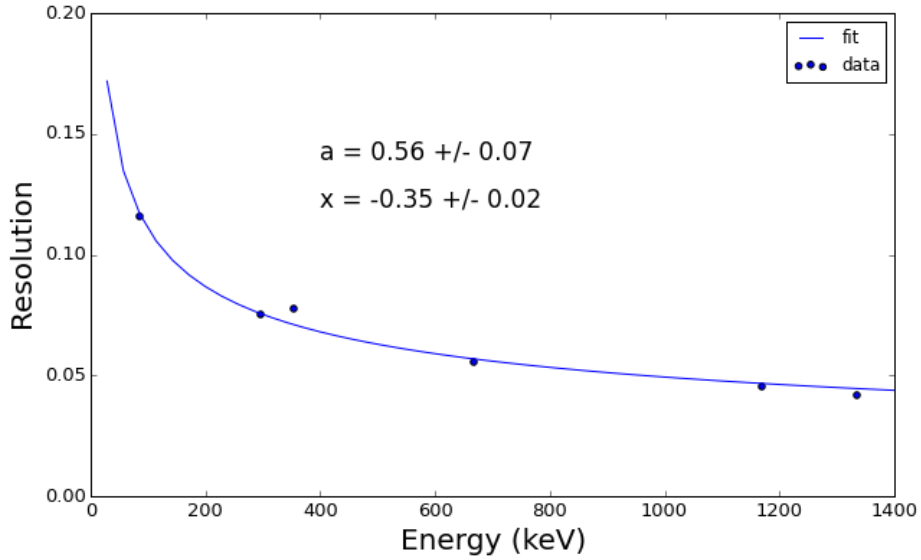

Figure 4: Nonlinear fit of Equation 5 for the resolution of our measurement device at as a function of gamma energy. Where the values on the energy axis are from the channel number calibration.

Although we reported three different photopeaks with our unknown sample, we believe that the only true peak is the one we measured at 1298 ± 4

keV. The radioactive samples in our lab do not have short lifetimes and only a few documented sources of reasonable lifetime share a line at 1298 ± 4 keV, which was our largest peak. Then, in order to match our measurements with a proper entry in an appendix it was necessary to discard the peaks at 518 ± 4 keV and 196 ± 4 keV as they were not present in any other listings. Then we determined that our unknown sample is likely to be ^{22}Na, which emits a single line at 1274 keV and has a half life of 2.6 years. With our uncertainty estimate of ± 4 keV, this identification has a statistically significant energy discrepancy. A large discrepancy may be worrying, but of the other available options, this was the only reasonable choice.

5 Conclusion

We have shown that nuclear emissions have discrete line spectra that can be detected by a scintillation crystal. The energy of a gamma ray from the nucleus is deposited into a the crystal via the photoelectric effect or internal Compton scattering. By amplifying the crystal scintillation, we determined the gamma emission energy of three sources. Then we built a calibration equation from the photopeak data for all known samples and used that calibration to identify an unknown source, with a measured emission line at 1298 ± 4 keV, to be ^{22}Na, which has an accepted transition energy of 1274 keV.

References

[1] Randy Harris. *Modern Physics*. Pearson, 1998.

[2] Adrian C. Melissinos. *Experiments in Modern Physics*. Academic Press, 2003.