Nuclear Spectroscopy

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The emission spectrum of radioactive Co^{60} and Cs^{137} sources were measured using a Na-Tl scintillator and used to determine the absorption coefficients of lead and aluminum at peak energies. The photopeaks and Compton edges of each source were calculated from Gaussian fits and compared with theoretical expectations. All values obtained were found to agree with literature to within 3σ.

1 Introduction

Nuclear spectroscopy is the study of atomic scale emissions and absorptions. It has applications ranging from medicine to astronomy. In this experiment techniques from nuclear spectroscopy were employed to determine the electromagnetic absorption coefficients of lead and aluminum at various energies.

2 Apparatus

Two radioactive isotopes, Co^{60} and Cs^{137}, were used as radiation sources. These sources were placed in front of a Na-Tl scintillator attached to a photomultiplier tube (PMT) in series with a pre-amplifier connected to an amplifier connected to a multi-channel analyzer (MCA). As radiation stimulates the scintillator the resulting electrical signal is multiplied by the PMT and amplified at which point the the pulse-height distribution is binned by the MCA. This data is then saved using MAESTRO computer software for interpretation.

3 Procedure

First, the MCA was calibrated by measuring the primary photopeaks of each source and correlating those channels at which the peaks were measured with their known energy values. These data points were then fit to a linear equation giving energy as a function of channel number.

Next, radiation from each source was measured with and without shielding. The shielding consisted of blocks of lead and aluminum of thicknesses ranging from 6-31mm placed between the source and the scintillator. The corresponding distributions were used to calculate the absorption coefficients of lead and aluminum, as well as the energy resolution of the photopeaks and the location of the Compton edge.

4 Calculations

4.1 Fitting

Each Compton edge was fit using gnuplot to a Gaussian with a linear offset of the form $f(x) = a_0 exp[-\frac{(x-b)^2}{2c^2}] + \beta x + \gamma$. The two Co^{60}photopeaks were fit to a sum of gaussians with both a linear and quadratic offset of the form $g(x) = a_1 exp[-\frac{(x-b_1)^2}{2c_1^2}] + a_2 exp[-\frac{(x-b_2)^2}{2c_2^2}] + \alpha x^2 + \beta x + \gamma$ while the Cs^{137}photopeak was fit to just a single Gaussian with similar offsets.

4.2 Compton Edge

The values obtained were then compared to the theoretical energy of the Compton edge given by $E(1 - [1 + \frac{2E}{0.511 MeV}]^{-1})$ where E is the energy of the incident photon in MeV. The z-score of the comparison was then found from the difference in these two values divided by the error obtained from the fit.

4.3 Absorption Coefficients

The absorption coefficients of the lead and aluminum shielding were then obtained by integrating the total number of counts over the domain of each peak. The negative logarithm of the ratio of this value to the corresponding value with no shielding gives the dimensionless product of the absorption coefficient with the penetration depth, i.e $\mu x = -ln(\frac{P(n,x)}{P(n,0)})$ where $P(n,x)$ is the number of counts across a bin range of n and at a material depth x and where μ is the absorption coefficient of the material. It is trivial to show that this expression results from the familiar form of the intensity equation $I(x) = I(0)exp(-\mu x)$.

The corresponding data points $(x, \mu x)$ for each material were were then fit to individual linear regressions, the slope of which corresponds to the value of μ. These values were then compared to the interpolated NIST values of the same energy, and a z-score calculated from difference in these values divided by the error associated with the fit.

4.4 Fractional Energy Resolution

Finally the fractional energy resolution of the photopeaks with no shielding were obtained from the full-width-at-half-maximum of their associated Gaussian fits.

5 Results

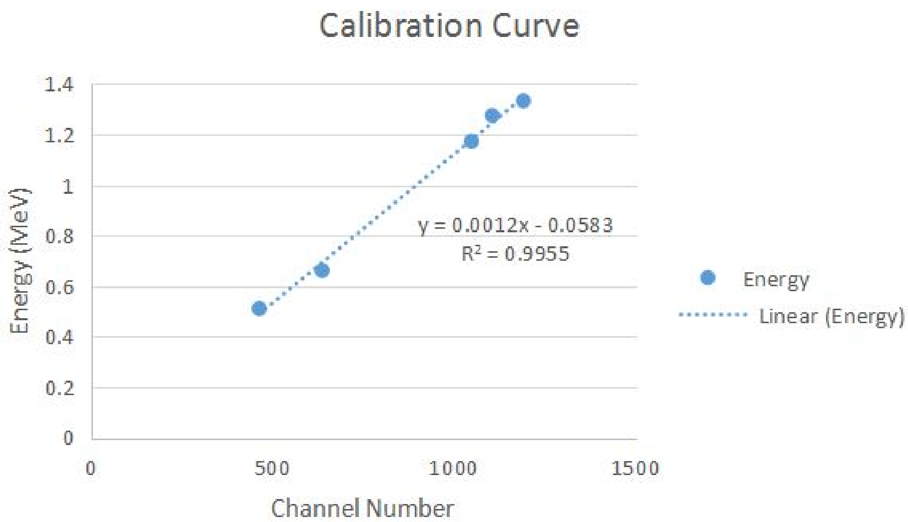

Figure 1: MCA calibration curve fit using a least squares fit.

The calibration curve was calculated as $y = 0.0012x - 0.0583$ where x is the channel number and y is the energy in MeV.

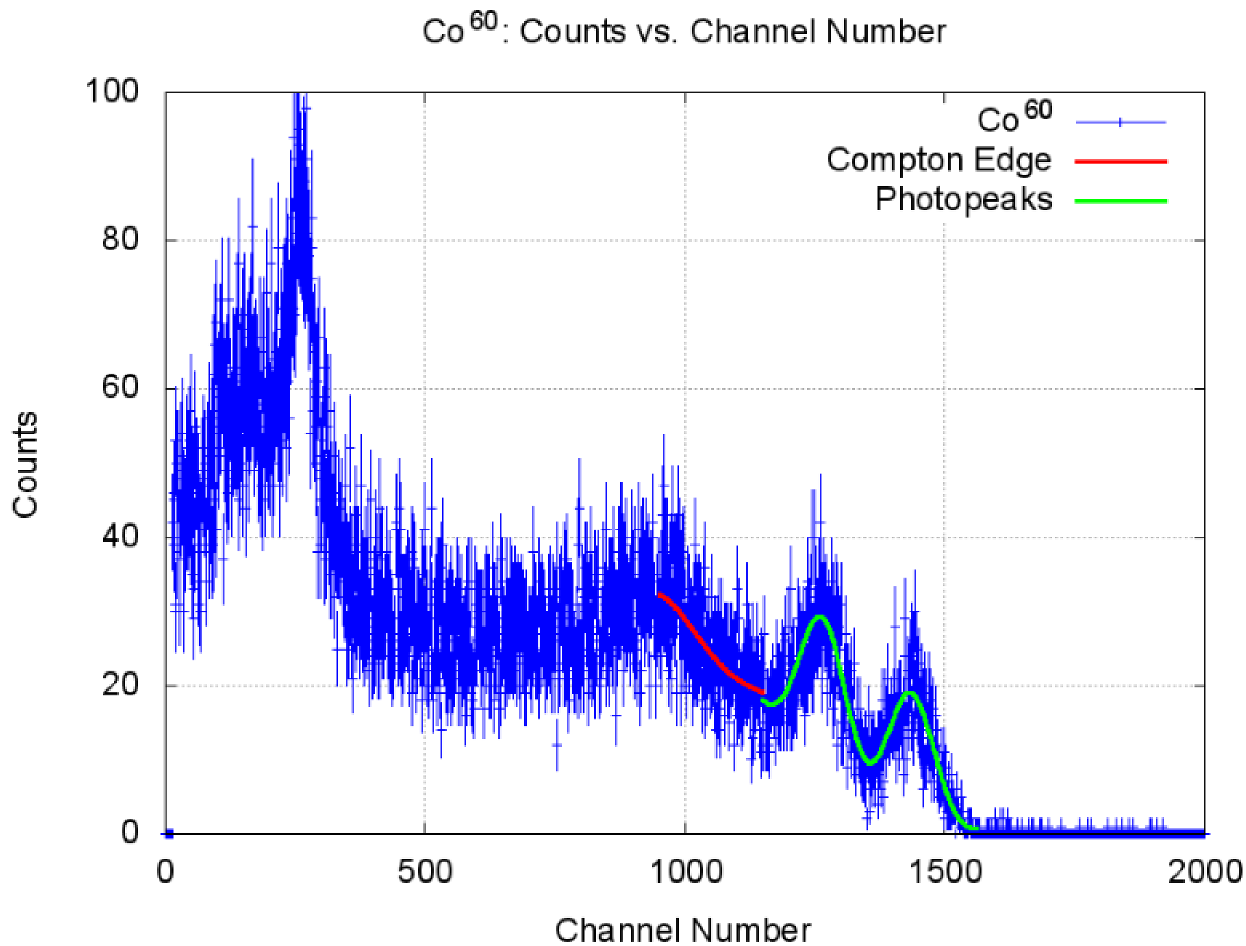

Figure 2: Gaussian fits to Co^{60}. The Compton edge (red) and photopeaks (green) are shown alongside counts with error bars (blue).

The compton edge for Co^{60}was calculated from the fit as $(1.287 \pm 0.182) MeV$ corresponding to a z-score of 1.8σ as compared to the theoretical value $0.976 MeV$.

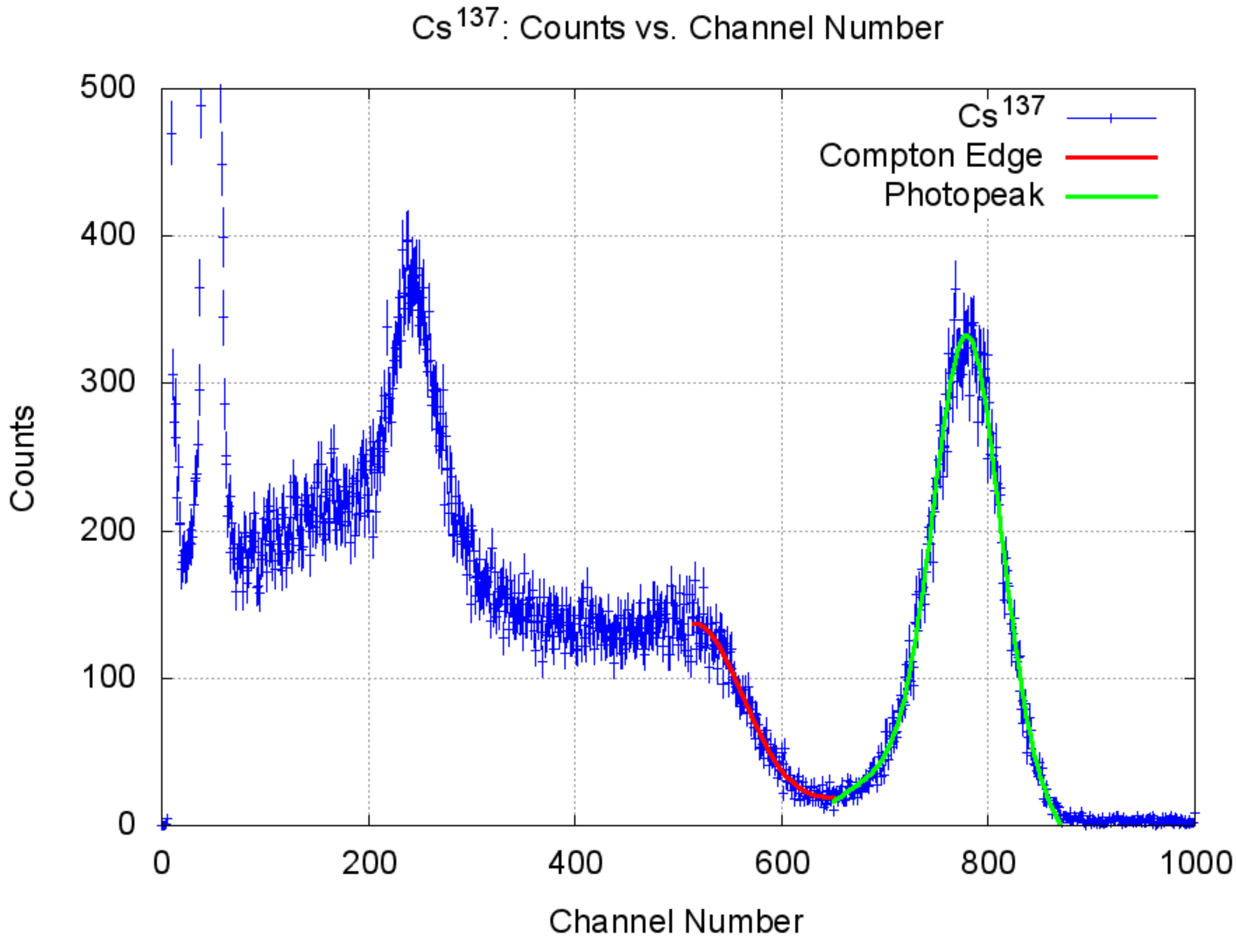

Figure 3: Gaussian fits to Cs^{137}. Compton edge (red) and photopeak (green) alongside counts with error (blue).

The compton edge for $Cs^{137}$was calculated from the fit as $(0.602 \pm 0.122) MeV$ corresponding to a z-score of 1.0σ as compared to the theoretical value $0.477 MeV$.

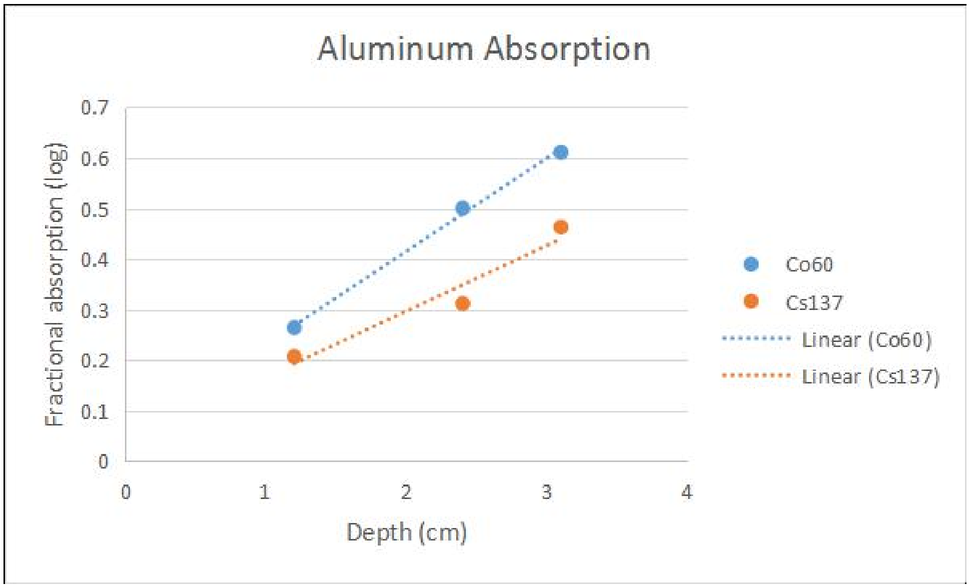

Figure 4: Fractional absorption of incident radiation in aluminum as a function of penetration depth.

The absorption coefficient for aluminum in response to the Co^{60}emission peak at $1.33 MeV$ was calculated from the fit as $(0.068 \pm 0.011)\frac{cm^2}{g}$ corresponding to a z-score of 1.0σ as compared to the NIST value of $0.057\frac{cm^2}{g}$.

Similarly its absorption in response to the Cs^{137}peak at $0.662 MeV$ was found to be $(0.048 \pm 0.010)\frac{cm^2}{g}$ corresponding to a z-score of -2.7σ as compared to the NIST value of $0.075\frac{cm^2}{g}$.

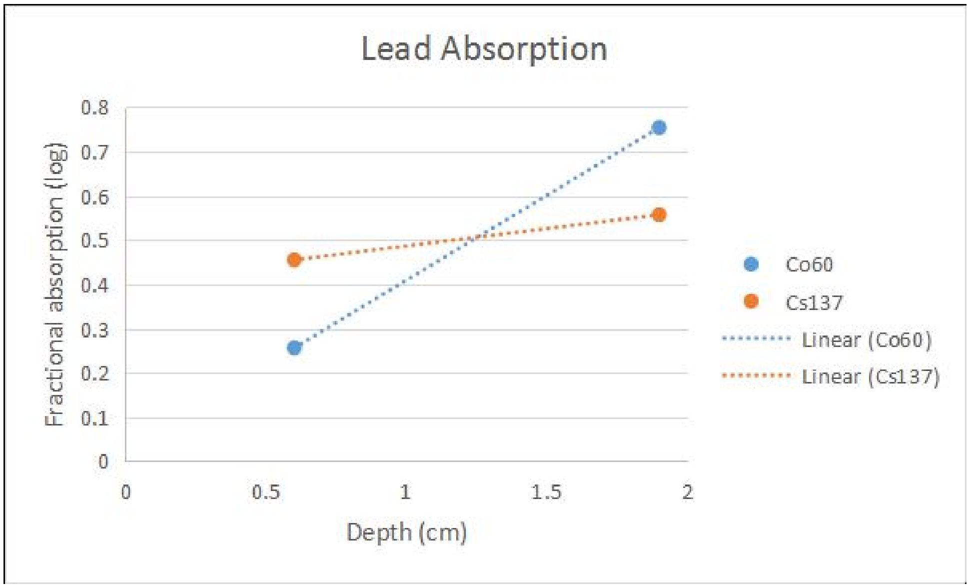

Figure 5: Fractional absorption of incident radiation in lead as a function of penetration depth.

The absorption coefficient for lead in response to the Co^{60}emission peak at $1.33MeV$ was calculated from the fit as $(0.034 \pm 0.014)\frac{cm^2}{g}$ corresponding to a z-score of -2.1σ as compared to the NIST value of $0.063\frac{cm^2}{g}$.

Similarly its absorption in response to the Cs^{137}peak at $0.662MeV$ was found to be $(0.007 \pm 0.010)\frac{cm^2}{g}$ corresponding to a z-score of -2.9σ as compared to the NIST value of $0.036\frac{cm^2}{g}$.

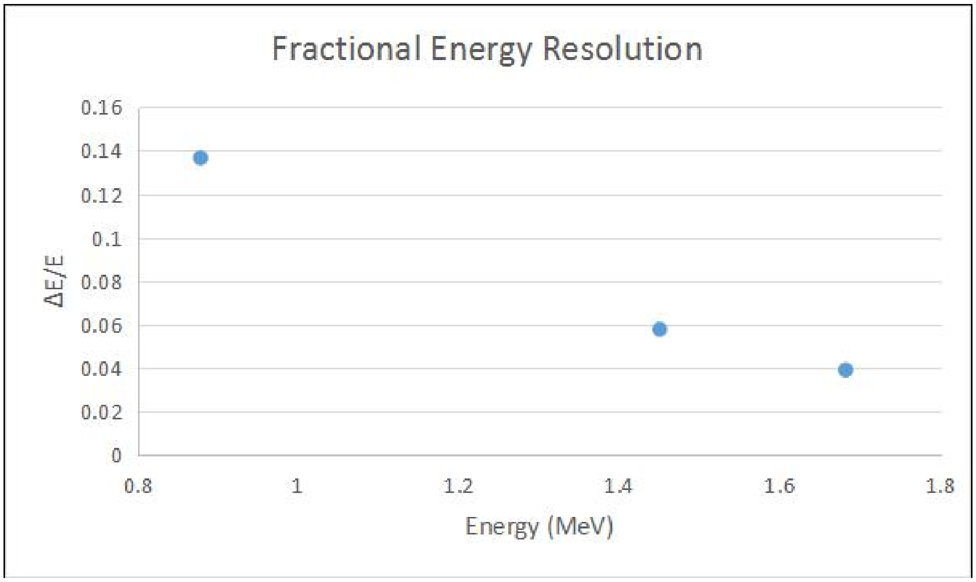

Figure 6: Fractional energy resolution as a function of energy. Each point corresponds to a photopeak with no shielding.

The fractional energy resolution was found to decrease with increasing energy. In general the energy resolution of inorganic crystals can be expected to outperform organic scintillators at the expense of time resolution.

6 Conclusion

In summary the Compton edge and photopeaks of Co^{60} and Cs^{137} were measured using a Na-Tl scintillator. The absorption coefficients for lead and aluminum were calculated using shields of various thicknesses and found to contain systematic biases most probably resulting from incomplete background subtraction. Finally the fractional energy resolution of each photopeak measurement was measured and shown to decrease with increasing energy. All values obtained were found to agree with literature to within a maximum uncertainty of magnitude 3σ.

References

[1] "NIST: X-Ray Mass Attenuation Coefficients - Table 3." Web. 10 Dec. 2016. http://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html

[2] Rapach, Theodore A., and Melanie A. Pelcher. "Gamma Ray Spectroscopy." University of Rochester, Web. 10 Dec. 2016. http://www.pas.rochester.edu/~advlab/reports/pelcher_rapach_gammaspec.pdf