

Nuclear Spectroscopy

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Three samples, Na-22, Cs-137, and an unknown one, were observed with gamma-ray spectroscopy. By measuring the photopeaks and comparing them to known values, we determined the makeup of the unknown sample to be Cs-137 and Zn-65. Analysis was done involving the detector's resolution energy dependence; photon interactions with matter, such as Compton scattering, pair production, and annihilation, were also studied.

Nuclear spectroscopy is used to analyze samples' emissions, both in frequency and energy. In this lab, we are focussing on γ ray emissions and some of the features that show up in the measured energy spectrum. Five separate experiments were followed, as described in the lab manual.

EQUIPMENT

A sodium iodide crystal and photomultiplier tube (PMT) were used to obtain results and were recorded on a PC via an A/D converter. Several radioactive substances were provided, of which sodium 22 (Na-22), cesium 137 (Cs-137), and an unknown sample were used.

PROCEDURE

Each sample was placed in the top tray level (closest to the detector) with a lead block underneath it. After initially turning on the detector, increasingly higher gains were tested until the entire spectrum was being detected (and recorded). The settings used throughout the measurements are listed in Table (I). Data was recorded for extended amounts of time, as shown in Table (II), in order to produce the clearest data.

Setting	Value
PMT Voltage	640 V
Conversion Gain	1024
Course Gain	8
Fine Gain	1.702

TABLE I: The settings used for all measurements.

Source	Time (m)
Na-22	124.8
Cs-137	372.2
Unknown	132.2

TABLE II: Measurement times used for each radioactive source.

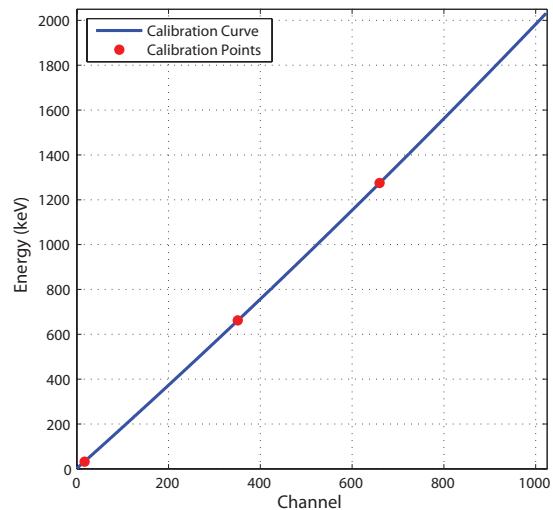


FIG. 1: The energy calibration used to convert the data from channels to energy.

I. ENERGY CALIBRATION

When data is recorded, the x-axis is given in “channels”. Whenever a pulse is measured by the PMT, a current is produced which is measured and stored digitally as a number from 0 to 1023 (10 bits); these are the different channels. This scale is mostly linear with energy, but is better approximated by a quadratic.

In order to complete the calibration, three spectroscopic features whose energies are known need to be identified. By plotting these known energies against the measured channels, a quadratic fit can be performed; Figure(1) shows these data points along with the fit. In order to get the most accurate calibration, low, medium, and high energy features were chosen so that extrapolation would be minimized. The features used were E, F, and I, as shown in Figures (2) and (3). The quadratic fit obtained resulted in Equation (1), which can be used for converting channels (the variable x) to energy.

$$E = (0.0001549)x^2 + (1.826)x + (1.721) \quad (1)$$

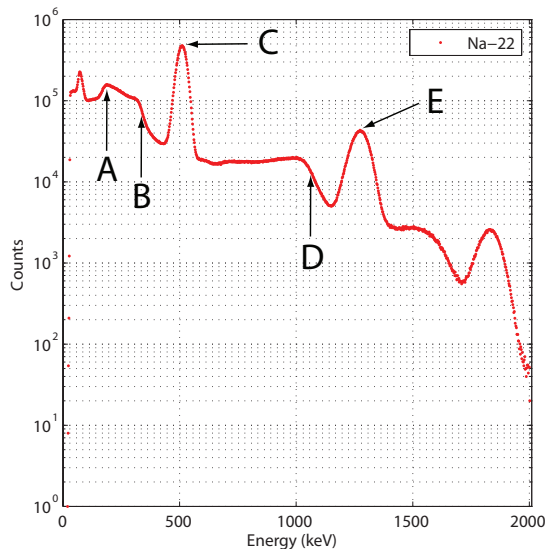


FIG. 2: Measurements obtained for Na-22 using the calibration from Figure (1). The letters refer to features of the spectrum mentioned in the text; information about them can be found in Table (III).

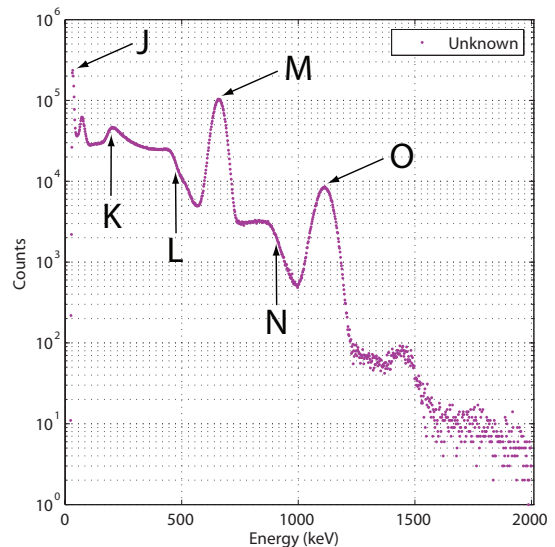


FIG. 4: Measurements obtained for the unknown sample using the calibration from Figure (1). The letters refer to features of the spectrum mentioned in the text; information about them can be found in Table (III).

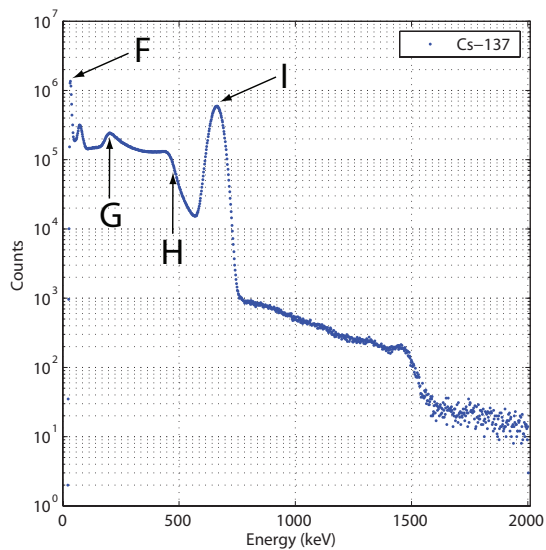


FIG. 3: Measurements obtained for Cs-137 using the calibration from Figure (1). The letters refer to features of the spectrum mentioned in the text; information about them can be found in Table (III).

II. DETERMINING THE UNKNOWN SAMPLE

After using the energy calibration just described, the various features in Figure (4) were measured and compared to emissions from known isotopes. As shown in Figure (5), the unknown spectrum is almost identical to

Source	Feature	Description	Center (keV)	FWHM (keV)
Na-22	A	Backscatter	189 ± 15	
	B	Compton Edge	342 ± 15	
	C	Photopeak	510.2848	50.9979
	D	Compton Edge	1070 ± 15	
	E	Photopeak	1274.3	95.7154
Cs-137	F	Photopeak	32.1828	9.2338
	G	Backscatter	201 ± 15	
	H	Compton Edge	480 ± 15	
	I	Photopeak	661.5258	60.6608
Unknown	J	Photopeak	32.2150	9.0749
	K	Backscatter	204 ± 15	
	L	Compton Edge	480 ± 15	
	M	Photopeak	659.0941	59.9981
	N	Compton Edge	910 ± 15	
	O	Photopeak	1111.9	85.4504

TABLE III: A summary of the data for all spectroscopic features. The letters correspond to those shown in Figures (2), (3), and (4)

that of Cs-137 except for features N and O (the vertical difference between the two is due to one being measured longer than the other). This can also be seen quantitatively in Table (III) where features F-I of Cs-137 correspond to features J-M of the unknown sample.

It was then found that Zn-65 has a peak at 1115.52 keV, which is quite close to Feature O at 1111.9 keV. With this accounting for all the peaks, it was determined that the unknown sample is comprised of Cs-137 and Zn-65.

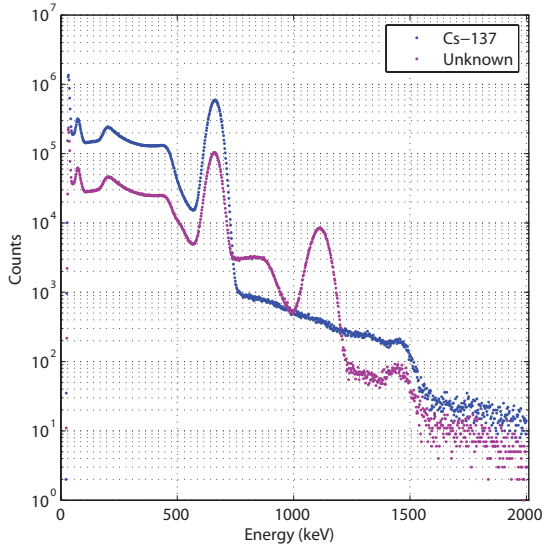


FIG. 5: The same data as shown in Figures (3) and (4), overlaid to show the similarities.

III. DETECTOR ENERGY RESOLUTION

As one can see from the data, the peaks have a finite width. Thus, if the detector's resolution is not high enough, two closely spaced peaks may appear as a single peak. It has been shown for sodium iodide detectors that the square of the ratio between a peak's width (FWHM) and energy is related linearly to inverse energy. In equation form, we get:

$$\left(\frac{\Delta E}{E}\right)^2 = m\left(\frac{1}{E}\right) + b \quad (2)$$

After plugging in data obtained from photopeaks C, E, I, and O, and fitting it to a line, we find the constants to be:

$$m = 3.7869 \text{ keV} \quad (3)$$

$$b = 1.5138 \times 10^{-4} \quad (4)$$

A plot of these data points with the linear fit is shown in Figure (6).

IV. COMPTON SCATTERING

Compton scattering occurs when a photon with energy $E_{\gamma,i}$ collides with a stationary electron, transferring some of its own energy upon it. Thus, $E_{\gamma,i} = E_{\gamma,f} + E_e$ by the

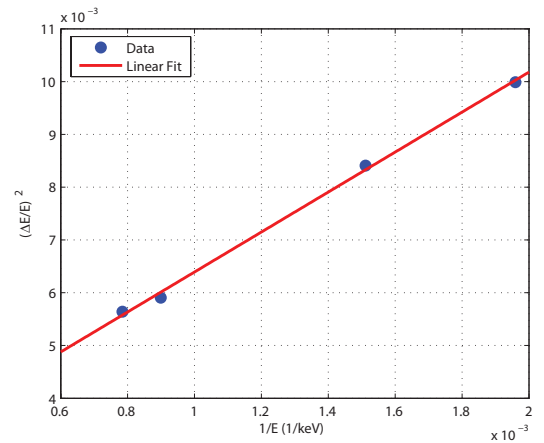


FIG. 6: A plot demonstrating the relation in Equation (2)

conservation of energy, where $E_{\gamma,f}$ is the photon's energy after the collision and E_e is the electron's energy. The relation normally stated is given by Equation (5), which relates the photon's initial and final energies based on the angle it scatters.

$$\frac{1}{E_{\gamma,f}} - \frac{1}{E_{\gamma,i}} = \frac{1 - \cos(\theta)}{m_e c^2} \quad (5)$$

Considering this effect, one may realize that some photons from the radioactive source may undergo Compton scattering and not have all their energy be detected. Upon inspecting Equation (5), one finds that $E_{\gamma,i} - E_{\gamma,f}$, or E_e , is maximum for $\theta = 180^\circ$. Thus, there should be detections of these excited electrons at all energies up to the maximum, given by Equation (6).

$$E_{e,max} = \frac{2E_{\gamma,i}^2}{2E_{\gamma,i} + m_e c^2} \quad (6)$$

This "Compton edge" appears to the left of each photopeak as a rising edge and is identified in Table (III). One might also notice that some peaks are described as "backscatter". This is related to Compton scattering in that photons which undergo 180° Compton scattering, or backscattering, outside of the detector may subsequently be detected, resulting in a peak. One finds, then, that the backscatter energy plus the Compton edge energy should add up to the original gamma energy (which is a photopeak).

It may also be noticed from the equations that knowledge of some of these energies can result in the determination of the rest mass energy of the electron. Solving in terms of $E_{\gamma,i}$ (photopeak energy) and $E_{\gamma,f}$ (backscatter energy), we get Equation (7).

$$m_e c^2 = \frac{2E_{\gamma,i} \cdot E_{\gamma,f}}{E_{\gamma,i} - E_{\gamma,f}} \quad (7)$$

V. PAIR PRODUCTION AND ANNIHILATION

If a photon is more energetic than two times the electron rest mass energy, it may interact with matter by producing an electron and positron (pair production). Alternately, when a positron meets an electron, they will annihilate each other and produce two photons, each with energy equal to the electron's rest mass energy.

If pair production occurs, the positron that is emitted may very well undergo annihilation almost immediately. The detector will measure the energy from the electron (produced from the original pair production) and may measure the photons produced from the annihilation. If one of these photons escapes without detection, then the measured energy will equal [the energy of the original photon] - [the energy of the escaped photon]. Because the escaping photon has an energy of 511 keV, there will be measurable peaks at both 1022 keV and 511 keV below the main photopeak (assuming it is at high enough energy). These are known as escape peaks and correspond to the situations where either one or both photons escape detection after annihilation.

From the data, it appears that neither this high energy photopeak nor its two related escape peaks are observed at energies below 2000 keV in the samples we tested. There does appear to be a small peak in Figure (3) at around 1450 keV; however, since there is no peak (escape

peak or photopeak) 511 keV above or below it, we must dismiss it as something else.

CONCLUSION

After measuring the samples and performing a three-point energy calibration, specific features could be identified. With this ability, it was determined that the unknown source included Cs-137 and Zn-65. Upon investigating the resolution of the detector, it was shown that the square of the ratio between a peak's width and energy decreased with increasing energy. Analysis was also done to identify Compton edges and backscatter peaks and how they could be utilized to measure the rest mass energy of the electron. Finally, pair production and annihilation were discussed, but it was determined that either higher energies needed to be measured or other samples used.

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- [1] Peterson, Randolph S. Experimental γ Ray Spectroscopy and Investigations of Environmental Radioactivity. Sewanee, TN: Spectrum Techniques, 1996.