K^{40} and Detector Efficiency - Revised

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Abstract

We found the activity of a 88.6g sample of KCl to be radioactive with an activity of $\sim 1111.44\frac{decay}{s}$. This activity is due to the K^{40} isotope. We used NaI scintillation detector to detect the emitted γ rays that result from the decay. The photopeak of which is known to be 1460keV. Our detector is about 16.6% efficient for this energy. Our NaI crystal was found to be situated about 33.5mm from the housing edge.

1 Introduction

So far we have been introduced to the probabilistic nature of nuclear decay and the equipment used to detect energies of emitted photons. In the previous lab, we found the correspondence between channel number and energy. In this lab, we find the detectors efficiency in detecting photons. By determining (approximately) the efficiency of our detector, we will be able to determine details of a sample's activity by the count's detected.

To determine the efficiency of the detector, we take into consideration three factors: the distance of the source from the detector, the detector size, and the energy of the photon. The efficiency happens to be different for different energies. This is possibly due to the elements the lattice crystal is made of and its doping. Different structures have different Densities of States, which describe how many states are available per energy interval.

After determining the efficiency and and geometric factors of our detector, we analyze a 2hr recording of a sample of salt substitute KCl to determine the activity of the K^40 isotope in our sample.

2 Theory

2.1 The Geometry Factor

The detector interacts with the emitted photons via a NaI crystal situated at some distance x from the detector housing. To determine how far situated it is in the housing, d, we vary a know sample of Cs^{137} and record it's counts at various distances from the detector. The counts detected should be proportional to the area of the detector cross section to the area of the sphere of radiation:

$$\frac{counts}{time} \propto \frac{\pi r^2}{4\pi(x+d)^2} \tag{1}$$

γ rays emitted by radioactive isotopes are proportional to the activity (A), called the Yield (Y). $\epsilon(E)$ is the efficiency of a particular energy. Equation 1 becomes,

$$\frac{counts}{time} = AY\frac{\pi r^2}{4\pi(x+d)^2}\epsilon(E) \tag{2}$$

2.2 KCl Activity

Earth was once an energetic soup of atomic and subatomic particles. As energy dissipated into the universe (Earth cooled down), atomic particles consolidated to form elements we see in the periodic table. These elements formed into their metastates, which decayed over time to turn into different elements. K^{40} is an isotope that decays either into Ar-40 or Ca-40. We'll be looking at the $K^{40} \rightarrow^{40} Ar$ decay. This decay undergoes a process called electron capture, where a proton captures an electron from the 1s shell. Subsequently, a higher orbit electron replaces that hole and γ ray of 1460keV is emitted.

After finding the constant d and the detection efficiency at 1460keV, we'll use the known Yield value of Y=.1069 to help us backtrack and find the K^{40} activity (in addition to some basic chemistry).

3 Materials and Methods

We use a NaI scintillation detector to gather emission data. We begin by finding the distance the NaI crystal is situated from the housing edge by collecting counts of a sample of Cs^{137} at varying distances: 5, 10, 15, 20, and 25 mm. Since we vary the distance only, Eqn 4 tells us that the counts is a function of $(x + d)$ only. We use the curve fitting program provided [1] to find d. Each recording was over a 120s duration.

Now to determine the detection efficiency equation, we take 120s (at 19mm) recordings of Cs^{137}, Na^{22}, Co^{60}, Bi^{207} and record the area under the photopeaks using the provided curve fitting proram[2]. The activity for each sample was labeled along with the dates of the recorded activity. We determine the activity at the time of the experiment using Rad Pro Calculator [3]. Using known Yield values for each sample, we solve for $\epsilon(E)$. With then plot $\epsilon(E) vs E$ and use excel to find a best fit curve.

We finally extract photopeak data from a 2hr KCl recording and use our equation to solve for the Activity. We compare our results to the theoretical value in Section 5.

4 Data

We use the inverse square program provided to process the following data to get $d = 33.521mm$. Our detector has a radius of 25.4mm. Refer to Figure 1 and Table 1.

Time [s]	x [mm]	Counts	Counts/s
123	5	83628.422	679.906
120	10	67265.425	560.545
120	15	54669.023	455.575
120	20	44008.408	366.737
120	25	34566.593	288.055

Table 1: Varying Sample Distance

Eqn 4 becomes

[1] https://blackboard.cpp.edu/bbcswebdav/pid-3838865-dt-content-rid-15637088_2/xid-15637088_2
[2] https://blackboard.cpp.edu/bbcswebdav/pid-3838865-dt-content-rid-15637089_2/xid-15637089_2
[3] urlhttp://www.radprocalculator.com/Decay.aspx

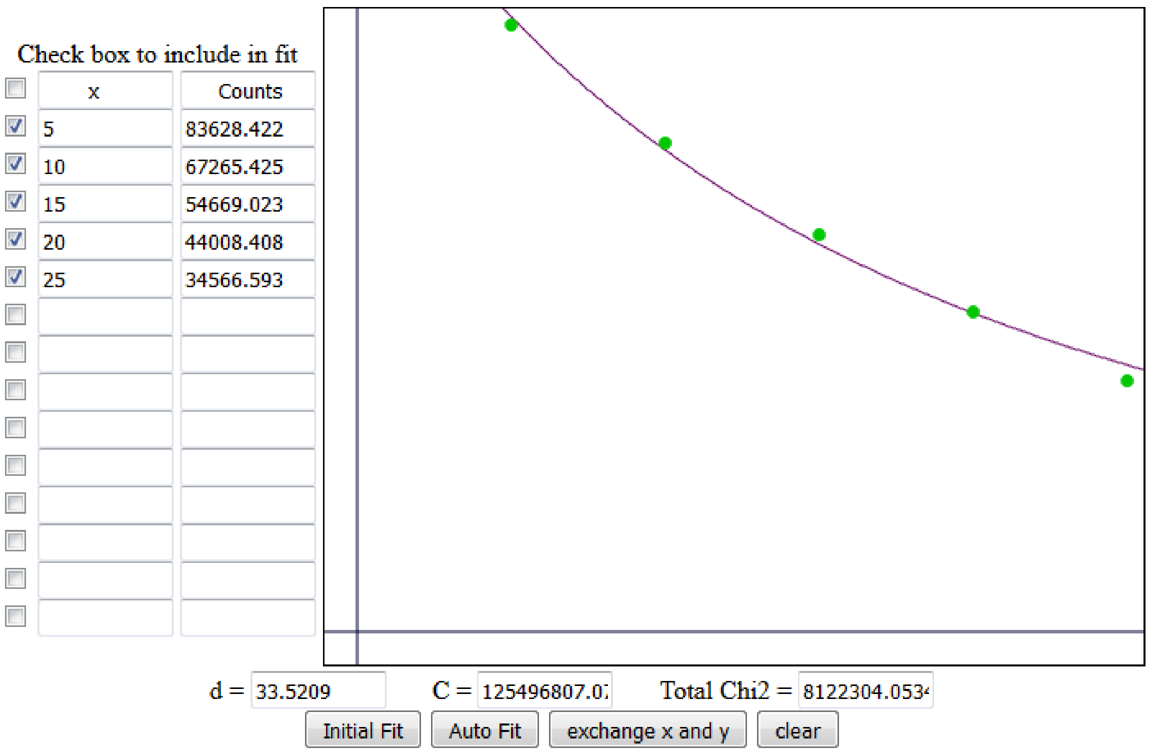

Figure 1: Inverse Square Curve Fitting

$$\frac{counts}{time} = AY\frac{25.4^2}{4(x+d)^2}\epsilon(E) \tag{3}$$

$$\approx AY\frac{161.3}{(x+33.521)^2}\epsilon(E) \tag{4}$$

4.1 Detector Efficiency

Equation 4 gives us the relationship we need to determine the detectors efficiency. We took ∼120s recordings of Cs^{137}, Na^{22}, Co^{60}, Bi^{207} at the same distance of $19mm$. Plugging in $(x+d) = (19+33.521)$, equation 4 becomes

$$\frac{counts}{time} \approx AY\frac{161.3}{2758.5}\epsilon(E) \tag{5}$$

$$\approx AY(0.0585)\epsilon(E) \tag{6}$$

4.2 Getting Current Activity

From the above equation, we see that we need to calculate the current activities [4] based on the dates and activities labeled.

[4] at time of experiment

Sample	Date	Activity Labeled	Activity Current
Cs	2/1/1985	1.12 μCi	0.5232 μCi
Co	2/1/1989	12.27 μCi	0.2702 μCi
Na	12/13/2000	8.46 μCi	0.0904 μCi
Bi	5/1/1980	1.32 μCi	0.5756 μCi

Table 2: Activity Table

4.3 Counts Detected

We then recorded the counts of Cs^{137}, Na^{22}, Co^{60}, and Bi^{207} at a distance of approximately 19mm over a 120 second interval. The sampling width was kept constant at 57 channels centered about the peak. Refer to the attached images but note that even with the same data, the curve fitting values change after reuploading.

Sample	[s]	[mm]	Peak Channel	Counts	Counts/s
Bi^{207}	120	19	288.4193	64260.501	535.504
Bi^{207}	120	19	517.6039	24070.620	200.588
Co^{60}	120	19	567.2837	13114.807	109.290
Co^{60}	120	19	630.7313	12149.534	101.246
Cs^{137}	120	19	44156.470	44008.408	366.737
Na^{22}	120	19	260.5838	24789.688	206.581
Na^{22}	120	19	612.4203	5211.086	43.426

Table 3: Counts

We use equation 6 to tabulate $\epsilon(E)$ with data from the previous two tables. Excel's best fit curve is used to determine $\epsilon(E)$, Fig 2.

Sample	$\frac{cts}{s}$	Yield	Energy [keV]	Activity [μCi]	$\frac{decay}{s}$	$AY(.0585)[\times 10^2\ \frac{decay}{s}]$	$\epsilon(E)$
Bi^{207}	535.504	0.977	570.4051	0.5756	21297.1391	12.172	44.0%
Bi^{207}	200.588	0.745	1071.0290	0.5756	21297.1391	9.2818	21.6%
Co^{60}	109.290	1.0	1173.2370	0.2702	9997.4000	5.8485	18.7%
Co^{60}	101.246	1.0	1332.5010	0.2702	9997.4000	5.8485	17.3%
Cs^{137}	366.736	0.85	662.0000	0.5232	19357.0057	9.6253	38.1%
Na^{22}	206.580	1.8	511.0000	0.0904	3344.8000	3.5221	58.6%
Na^{22}	43.425	1.0	1275.0000	0.0904	3344.8000	1.9567	22.2%

Table 4: Efficiency

5 K^{40} Activity

For K^{40}, the photopeak energy is known to be 1460keV. $\epsilon(1460\,keV) = 665.61(1460)^{-1.144} = 0.1597 \approx 16\%$. We were given a recording for KCl over 2 hours and a background radiation recording for 2 hours. The peak center was centered at channel 688 with window 57 units wide. The area under that curve was 14710 counts,

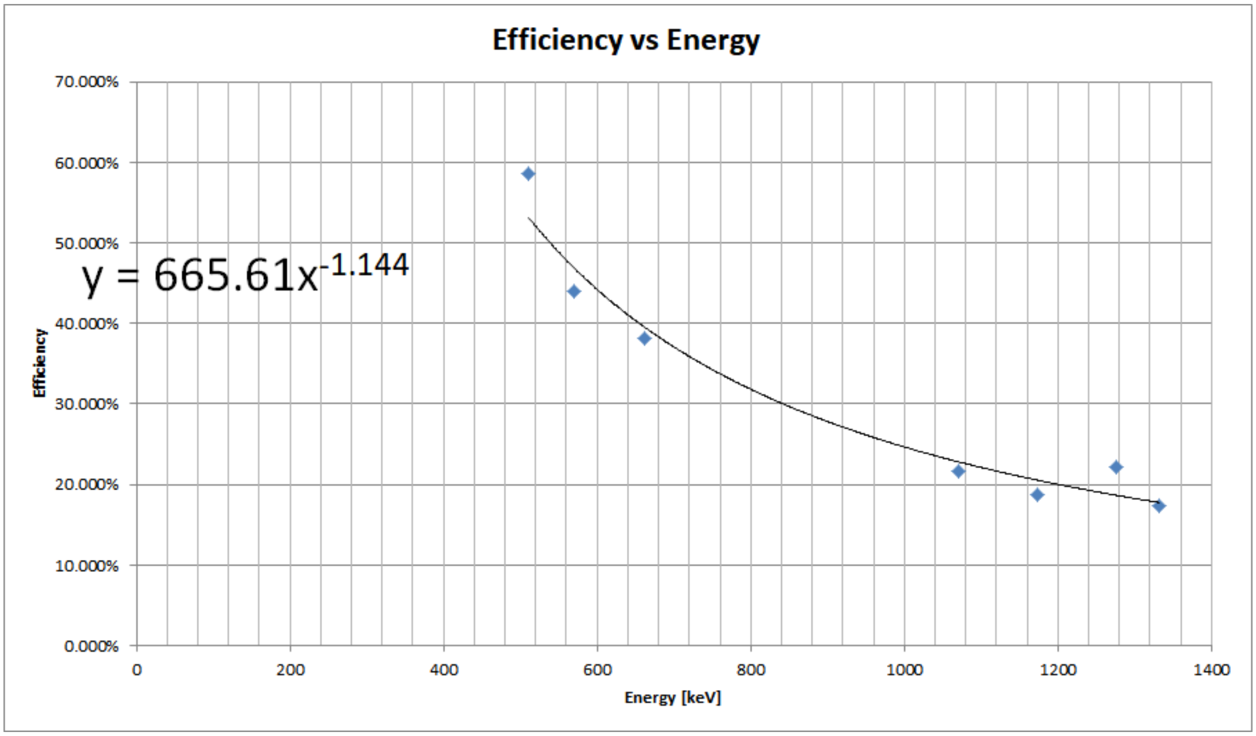

Figure 2: Best Fit Efficiency

with background at 6743 counts[5]. We have 7967 counts $\rightarrow \sim 1.11\frac{cts}{s}$.

$$\frac{counts}{time} \approx AY(0.0585)\epsilon(E) \tag{7}$$
$$1.11 = A \times .1069 \times .0585 \times .1597 \tag{8}$$
$$A \approx 1111.44\frac{decay}{s} \tag{9}$$
$$\approx 0.03\mu Ci \tag{10}$$

$$\sqrt{n} = \sqrt{7967}\frac{cts}{2hr}$$
$$0.0124\frac{cts}{s} = \Delta A \times .1069 \times .0585 \times .1597$$
$$\Delta A = 12.41\frac{decay}{s}$$

6 Theoretical Activity

Our salt substitute consisted of 88.6g of KCl ($74.55\frac{g}{mol}$). We determine the number of K atoms by calculating the number of KCl molecules in our sample. The molecule-mole ratio is 1:1.

$$88.6g \times \frac{1\ mol}{74.55g} \times 6.022 \times 10^{23}\frac{molecules}{mol} = 7.1643 \times 10^{23}\ molecules$$

[5]The figures are attached to the back of this report.

Knowing the number of K atoms in our sample, we multiply by the Natural Abundance (.0117%) to tell us how many K^{40} there are.

$$7.1643 \times 10^{23} \times .000117 = 8.382 \times 10^{19} K^{40}$$

Then the decay constant tells us the rate at which the above decays

$$8.382 \times 10^{19} \times 1.761 \times 10^{-17} \frac{decay}{s} = 1476 \frac{decay}{s}$$

7 Conclusion

Our experiments result is within 24% of the theoretical value. $\frac{\Delta Counts}{Theoretical\ Counts}$. Based on Fig 1, the geometry factor can't be improved by much because every data point falls on the best fit line. The error is due to the efficiency factor. Fig 2 shows us that the detection efficiency decreases significantly as the photon energy increases. But the data points don't fall on the line. So we are extrapolating an equation that is a rough estimation. Based on the theoretical activity, $\epsilon(1460) \approx 9.23\%$. The y-axis calibration is very involved and there is plenty of room for error, especially when measuring the sample distance from the detector.