Determining Half Lives Using Gamma Spectroscopy Lab Report

Melissa Githinji, GTHMEL001

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1 Abstract

The aim of this experiment is to investigate the reaction pathways of neutron activated ^{27}Al, to identify nuclei present, and explain observed features in the time-dependent gamma ray spectra emitted. Furthermore, the method is validated by experimentally determining half-lives of short-lived radioisotopes. Online resources such as Kaeri[2] and Nudat 2[1] are used to match measured gamma ray energies and isotope half-lives to expected values found through external study. The behaviour of the radioisotopes follow the exponential decay law and by applying weighted fitting, the decay can be characterised in some cases better than others. Results vary from 1.6 to 5.21 standard uncertainties from theory but maintain the correct order of magnitude.

2 Introduction and Background

Neutrons are uncharged, making them high interacting with the atomic nucleus, but difficult to detect since they don't interact with fields. Thus, to measure neutron reactions, we make an indirect measurement of a material irradiated with neutrons. The material investigated here is natural Aluminium, ^{27}Al. Aluminium undergoes neutron capture, $^{27}\mathrm{Al}(n,\gamma)^{28}\mathrm{Al}$, for neutrons with thermal and epithermal energies, which changes the element into its unstable radioisotope. This process, among other various reaction pathways, create unstable nuclei which will decay to stabalise the sample to have fewer decays over time.

Chiefly observed are:

The β^- decay of Magnesium 27:

$$^{27}_{12}\mathrm{Mg} \rightarrow {}^{27}_{13}\mathrm{Al} + {}^{0}_{-1}\mathrm{e}$$

Where ^{27}Mg has a half life of 9.458 minutes[2]. The ^{27}Al daughter nucleus can become excited to the first and second excited states. Therefore, during de-excitation 2 different valued gamma rays can be emitted: 843.76 keV[2] and 1014.52 keV[2] respectively.

The β^- decay of Aluminium 28:

$$^{28}_{13}\mathrm{Al} \rightarrow {}^{28}_{14}\mathrm{Si} + {}^{0}_{-1}\mathrm{e}$$

Where ^{28}Al has a half life of 2.245 ± 0.002 [3]. The gamma ray released during de-excitation of ^{28}Si from the second excited state is 1778.987 ± 0.015 keV [2].

β^- decay leaves the nucleus excited, giving rise to gamma emission. By measuring the gamma rays released with the production of the daughter nucleus in either case, the quantisation of energy levels means we can determine the event (decay) that took place.

A decay curve visualises the stabilisation of the sample by plotting a sum of the counts, within the energy interval of the emission by the radioisotope with a finite lifetime, to observe the exponential decrease in quantity. The decay has the functional form

$$N(t) = N_0 e^{-\lambda t} + B \tag{1}$$

Where N is the number of radioactive nuclei present in the sample (determined by number of counts) at time t (rather binned at a small time interval) and λ is the decay constant. B represents some background which the reaction experimentally settles at even after all the nuclei have decayed away. This background is subtracted and not used in the half life calculation since theoretically we assume the radio nuclei decays completely eventually. In this way, the half-life is found as:

$$t_{\frac{1}{2}} = \frac{\ln(2)}{\lambda} \tag{2}$$

3 Method

A 5cm x 5cm NaI(TI) scintillation detector was used in the setup of the apparatus with a 700 V power supply, and an amplifier set to a 50 coarse gain and 3 μ seconds shaping time. The USX acquisition software was used with a MCA to acquire the gamma data.

A calibration was taken of the system to benchmark the relationship between channels on the software and real energies detected. The well known pulse height spectrum was taken for ^{137}Cs, ^{22}Na, and ^{60}Co to perform a weighted linear fit of calibration using the centroid of the photopeaks of main features plotted with the expected energies of those photopeaks, using previous lab experience and Nudat 2[1]. The curve_fit() module in Scipy was used to perform the fit weighted using the uncertainty of the Gaussian fit of the centroid of the photopeaks in a self-written python script.

The americium-beryllium (AmBe) radioisotopic neutron source was used to irradiate 3 natural aluminium cylinders for the experiment. The energy of the neutrons emitted by the source range from thermal up to 11 MeV[3]. For lab safety, the AmBe source was stored in a water bath. The cylinders were stacked on top of the source one on top of another, with the cylinder closest to the source being in the bottom position, then the middle cylinder, and then the top one. The aluminium cylinders were left to activate for a minimum of 60 minutes to ensure sufficient interaction with the neutrons for clearer results with high decay counts.

Before data acquisition, multiple runs was setup on USX to collect data in 120, 30-second intervals, saved as .tsv files. A cylinder from the desired position was removed from the water bath, wiped dry, and swiftly moved to the experiment station. The detector was carefully placed inside the neutron activated cylinder and the multiple runs commenced. This process was carried out for all 3 cylinders in the water bath at the same experimental station (with the same calibration).

4 Data and Results

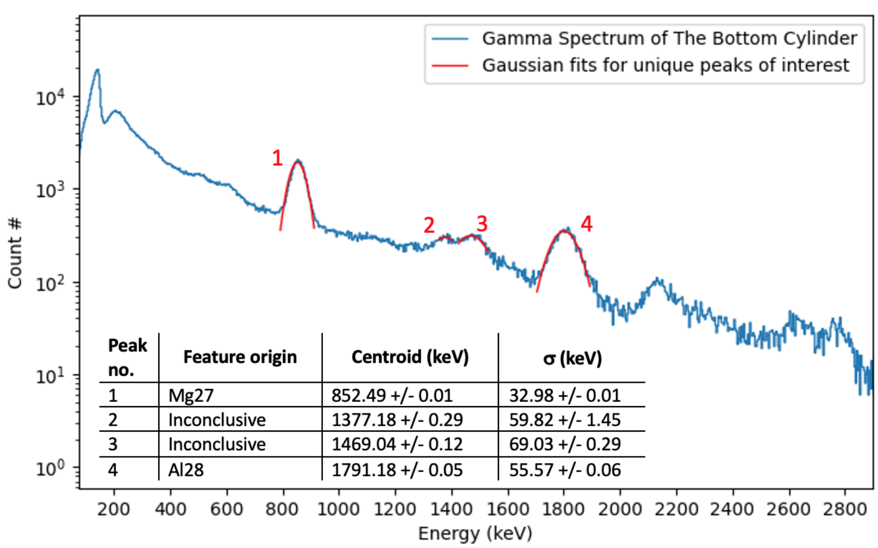
The data files were processed and plotted by a self-authored python script, PlotData.py, employing curve_fit to do Gaussian and exponential fitting and matplotlib to graphically plot results. The output for the calculations made in PlotData.py is in Appendix 1.

A total gamma spectrum was found by summing up the counts data for all 120 files at each channel.

$$\text{The calibration relation found was Energy} = (\text{channel}+6.858)/0.268 \text{ keV.} \tag{3}$$

The uncertainty for the energies of the total spectrum was calculated using standard propagation of uncertainty during the conversion calculation performed to obtain Figure 1. The calibration curve is given in Appendix 2.

Data for the top and middle cylinders was taken, however counts were low, and they both shared very different spectra to that of the bottom cylinder. The bottom cylinder was highly saturated with ^{28}Al while the middle and top cylinders lacked the wanted peaks for ^{28}Al and ^{27}Mg.



Peak no.	Feature origin	Centroid (keV)	σ (keV)
1	Mg27	852.49 +/- 0.01	32.98 +/- 0.01
2	Inconclusive	1377.18 +/- 0.29	59.82 +/- 1.45
3	Inconclusive	1469.04 +/- 0.12	69.03 +/- 0.29
4	Al28	1791.18 +/- 0.05	55.57 +/- 0.06

FIGURE 1

A staircase Histogram plot with a logarithmic scale of the Gamma Spectrum collected from the irradiated Aluminium 27 bottom cylinder. Peaks of interest are defined to have the top 4 total counts well into the Gamma energy range (¿400 keV), labelled 1 to 4. Data is shown over an hour of detection after 2 hours of saturation. The Histogram is binned with width 1 (1 keV) in accordance with the discrete channels 1,2,...,2047 of the MCA. A calibration conversion was applied using (3). The uncertainty in the weighted linear fit of calibration was added into the fitting of the Gaussian peaks. Below the spectrum is a table containing the output of PlotData.py with the results of the fitting process.

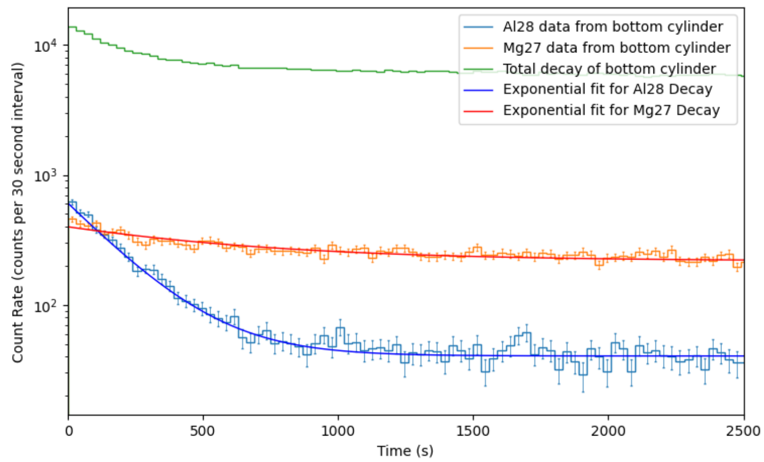


FIGURE 2

The same data from Figure 1 is shown in this staircase Histogram plot of the decay curves for ^{28}Al and ^{27}Mg. Due to the multiple runs that were taken using USX, counts are summed in 30 second bins on the x-axis and put through equation (1) to plot N(t) on the y-axis with a logarithmic scale. The uncertainty in the points is given as $\sqrt{N}$ and is shown using error bars for each time interval.

Table 1: Showing the output of PlotData.py after the fitting process weighted with $\sqrt{N}$, giving experimental values for the functional form of the decay curves shown in Figure 2.

	Magnesium 27	Aluminium 28
N_0 (#)	180.4 ± 8.7	566.0 ± 15.1
λ (constant)	$1.517 \pm 0.133 \times 10^{-3}$	$4.919 \pm 0.137 \times 10^{-3}$

The decay curves required different data processing to investigate the total counts associated with specific energies of interest since ^{28}Al and ^{27}Mg have different half-lives. All of the counts associated with a certain energy interval were summed for each of the 120 datasets and plotted in 30 second intervals (as a function of time) to represent the decay of the hour acquisition period. After exponential fitting, the determined fitting parameters given in table 1 are used to calculate the half-lives.

Using equation (2), the half lives of ^{28}Al and ^{27}Mg are calculate as follows:

$$t_{\frac{1}{2},{}^{28}\mathrm{Al}} = \frac{\ln(2)}{(0.004919)(60)} = 2.349 \text{ minutes}$$

$$u(t_{\frac{1}{2},{}^{28}\mathrm{Al}}) = 2.349 \times \frac{0.000137}{0.004919} = 0.065 \text{ minutes}$$

$$t_{\frac{1}{2},{}^{28}\mathrm{Al}} = 2.349 \pm 0.065 \text{ minutes}$$

$$t_{\frac{1}{2},{}^{27}\mathrm{Mg}} = \frac{\ln(2)}{(0.001517)(60)} = 7.615 \text{ minutes}$$

$$u(t_{\frac{1}{2},{}^{27}\mathrm{Mg}}) = 7.615 \times \frac{0.000133}{0.001517} = 0.668 \text{ minutes}$$

$$t_{\frac{1}{2},{}^{27}\mathrm{Mg}} = 7.615 \pm 0.668 \text{ minutes}$$

The uncertainty provided for the measured gamma radiation photopeaks from Figure 1 is related to the quality of the fit and not for the value itself. Therefore the uncertainty is more accurately given as $\frac{\sigma}{\sqrt{N_0}}$, where N_0 approximately represents all of the ^{28}Al at t=0 of measurement.
Therefore the energy associated with the β^- decay of ^{28}Al present in the source is the combined standard uncertainty with the relatively inconsequential uncertainty of the fit:

$= \frac{55.57}{\sqrt{566}} =$ 2.34 keV

$\therefore$ Gamma peak of Aluminium 28 is 1791.18 $\pm$ 2.34 keV

Similarly the Gamma peak of Magnesium 27 is 852.49 $\pm$ 2.46 keV

5 Analysis

The half-life of ^{28}Al found experimentally is 1.6 standard uncertainties (6.24 seconds) from reality, with the associated gamma ray only within 5.21 standard uncertainties of the value theoretically expected. The half-life of the β^- decay of ^{27}Mg found experimentally is 2.7 standard uncertainties (1.80 minutes) from reality, with the associated gamma ray 3.5 standard uncertainties from the value theoretically expected.

The quality of the results varies, however in the case of both quantities, the values found were larger than expected. The half-life values were of better quality than the gamma rays, which was 12 keV off in the case of aluminium. It is suspected that there is some calibration factor which was not caught by the calibration. The apparatus used for the aluminium cylinders lacked the shielding used for the calibrated radioisotopes, thus the capacity for unwanted interactions is higher. Results are in the correct order of magnitude for the 2 most abundant reactions expected and precise data was given for the clear, well-formed peaks.

The double hump feature given by peaks 2 and 3 are evidently not a full Gaussian shape, however a high-count reaction did take place. The β^- decay of ^{28}Na and the β^- decay of ^{24}Na release gamma radiation at 1473.5 keV [2] and 1368.625 keV [1] respectively- additionally at relative intensities of 37% and 99.9940% respectively. The half-lives for these radioisotopes, however, are not appropriate as ^{28}Na has 30μ seconds and ^{24}Na has 15 hours. One of the reaction pathways of this experiment is $^{27}\mathrm{Al}(n, \alpha)^{24}\mathrm{Na}$, which motivates the existence of Sodium. Furthermore, with lower counts at high energy, the transition for second to first excited state of ^{24}Mg can be seen to be close to the 2754 keV[1] in Figure 1, which is more evidence for this reaction pathway. Resolution at higher energies was much lower through. Due to the misaligned calculations for half-life conducted outside of this report, these results remain inconclusive.

6 Conclusions

The process of neutron activation with the AmBe source was good and yielded a high enough number of decays for gamma photopeaks. The standard deviations of the Aluminium and Magnesium peaks are large, making the results broad and further from the theoretical delta functions expected from higher resolution detectors. Additionally, shielding of the cylinders during detection is recommended. The experiment produced data with good quality fits which followed the exponential decay law.

7 References

[1] **Nudat 2**National Nuclear Data Center, Brookhaven National Laboratory (2024).

[2] **KAERI Nuclear Data Centre**M. Shamsuzzoha Basunia, Nuclear Data Sheet (2013) [Accessed March 2024].

[3] Hutton, T., Neutron activation of ^{27}Al, PHY3004W laboratory, University of Cape Town (2024).

8 Appendix 1

Peak 1: Magnesium 27 Decay, 1st Excited Al27
Amplitude: 1924.1992574475096 +/- 0.3200454939014301
Centroid: 852.4916830445369 +/- 0.006381204622112058 keV
Standard deviation: 32.98462352334905 +/- 0.007195529865057824 keV

Peak 2: Isotope of Sodium: Possibly Na 24 producing Mg 24 through Beta- decay
Amplitude: 300.973211434628 +/- 0.4380441248684089
Centroid: 1377.1836045974387 +/- 0.2857943988982306 keV
Standard deviation: 59.8162349916704 +/- 1.4534136351260272 keV

Peak 3: Isotope of Sodium: Possibly Na 28 producing Mg 28 through Beta- decay
Amplitude: 312.2427999558618 +/- 0.29115112607245924
Centroid: 1469.040730371082 +/- 0.12480306141004316 keV
Standard deviation: 69.03199872878938 +/- 0.2878755331374584 keV

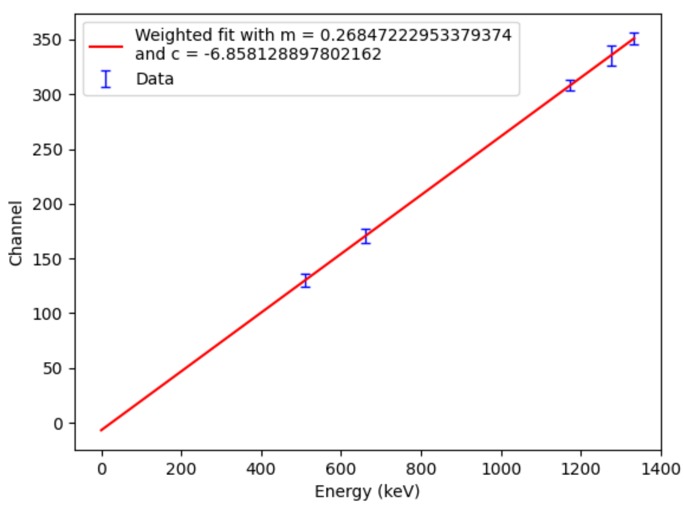
Peak 3: Aluminium 28 Decay
Amplitude: 347.18223415179176 +/- 0.2514617736930889
Centroid: 1791.1793008760626 +/- 0.047801044747047695 keV
Standard deviation: 55.57178266611113 +/- 0.05746862627540157 keV

Decay Curve

Decay Curve of Aluminium
Half life = 2.348460383225392 minutes
N0: 566.0482885055746 +/- 15.098717633228294
Lambda: 0.00491916026851013 +/- 0.00013746400325082575
Background energy: 40.50385963027735 +/- 0.8076010642453932

Decay Curve of Magnesium
Half life = 7.580384461213638 minutes
N0: 181.22555103397477 +/- 8.14815228927041
Lambda: 0.0015239930202013586 +/- 0.0001247815878849562
Background energy: 217.66050328980546 +/- 2.5541461980458116

9 Appendix 2



Graph showing the calibration curve for the experiment