Experiment 353: Radiation Detectors

Aim

To become familiarised with the semiconductor and scintillation detectors, two of the most often used radiation detectors.

To determine the range and straggling of α particles in air and the half life of ^{40}K.

References

1. Melissinos, A.C. "Experiments in Modern Physics" Chap.5, Academic Press
2. Evans, R.D. "The Atomic Nucleus" McGraw-Hill
3. ORTEC Application Note AN34 "Experiments in Nuclear Science"

Apparatus

Schematics of the two required circuits are shown in Figs. 1 and 3. It is important that you gain an understanding of the physics behind the different boxes in these diagrams.

Firstly, note that ORTEC Models 401A (feeds data to PC), 428 (detector bias supply), 419 (pulse generator), 575A (main amplifier) and 435 (active main amplifier) are all attached together in the control box.

The 575A main amplifier is connected with a "T" connector via UNI OUT to both the 401A port (MCA #1) and Channel 1 of the oscilloscope. Make sure you set the 575A switch to NEG.

The 142 preamplifier is a separate brown box sitting on a grey vacuum housing which contains the radioactive ^{241}Am and semiconductor detector. This is connected to a vacuum pump under the bench.

The 142 preamp is connected via

- TEST to OUTPUT ATTENUATED of the 419 pulse generator
- E to INPUT of the 575A main amplifier
- BIAS to OUTPUT of the 428 detector bias supply
- INPUT to the semiconductor detector and ^{241}Am source

A grey cable from 142 is also attached to the back of the control box.

The control box is connected to the PC with a USB cable, where you perform data collection and pulse height analysis using the "Gamma Acquisition" programme. This is briefly explained in the appendix.

The 435 active filter main amplifier is connected via NEG OUTPUT to OUTPUT of the scintillation detector preamp (a separate grey box). This preamp is connected via TEST INPUT to PREAMP POWER at the back of 435, and to ANODE of the 266 scintillation detector via DET. INPUT. Then 266 is connected via POS HV to the Brandenburg high voltage supply.

The current setup is now ready for the **Semiconductor Detector** section of the experiment. Once you have completed this, simply remove the "T" connector from UNI OUT of 575A and attach to OUTPUT of the 435 amplifier. Note that 435 (and everything subsequently attached to it) is used in the **Scintillation Detector** section.

Semiconductor Detector

Familiarise yourself with the basic theory of semiconductors with one of the above references.

A silicon surface barrier detector is supplied. This is made of partially depleted p-type silicon of resistivity 8 kΩ-cm, with a front Al electrode thickness of 40 μg/cm^2. It must be operated with a negative bias voltage not in excess of 100 V. Note that Output A of the 428 detector power supply has been modified to deliver a maximum of approximately 100 V. Two cables from the back of 428 should be connected to a multimeter to accurately measure the voltage supplied. Always adjust the detector voltage slowly.

Note that electrons are only collected from the semiconductor's depleted region. Since the depletion depth is a function of the bias voltage the effective detector thickness therefore depends on the applied voltage.

It is important not to touch the surface of the detector or the α source, nor to operate with wrong bias polarity.

(1) The source is ^{241}Am mounted near the bottom of the α box. The distance from the surface of the source to the surface of the detector is 5.24 cm.

If you would like to examine the source and detector, please consult a demonstrator. Do this as follows: with the vacuum box at atmospheric pressure and the bias supply turned off, carefully remove the plate to which the semiconductor detector is attached.

DO NOT TOUCH THE DETECTOR FACE OR THE SURFACE OF THE SOURCE.

After examination replace the lid, being sure that the O-ring is sealed properly.

(2) Ensure that the electronics are connected up as shown in Fig. 1.

Pump down the chamber to 0.2 Torr or better. (Which pressure gauge should you read off and why?)

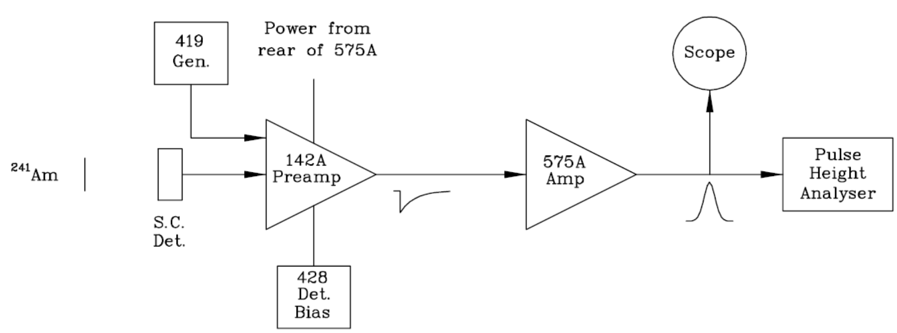


Figure 1: Experimental setup for the semiconductor detector.

(3) Use a conversion gain of 1024 channels in the PCA pulse height analyser (see Appendix).

Use a bias voltage of −100 V and remember to change this voltage slowly. On the 419 pulse generator, set the `Pulse Height` helipot to 10.00 and adjust the switches.

Adjust the gain of the 575A amplifier and the `Normalise` helipot so that the sharp pulser peak appears in the PHA spectrum at a higher channel than the Gaussian-shaped ^{241}Am peak. For your convenience, ensure that both peaks in the spectrum are centred between channels 850 and 950.

The corresponding pulses seen in the oscilloscope should point upwards. Check that the shape of the pulser pulses here is very similar to that of the ^{241}Am pulse.

Finally, by believing that the size of the output pulse of the pulse generator is proportional to the setting of the `Pulse Height` helipot, check the quality of the linearity of the preamp-amp-PHA system, and determine the spectrum channel corresponding to zero input volts.

(4) Study the pulse height (units are in channel number, or its corresponding energy) and energy resolution (the full-width-at-half-maximum, FWHM, of a peak) of the spectrum from the ^{241}Am source as a function of bias voltage from $0 \to -100$V, paying particular attention to the range $0 \to -20$ V. Comment on your results.

(5) Study the range in air of ^{241}Am particles by letting air into the vacuum box. The following should be recorded for each value of pressure from roughly 0 Torr to atmospheric pressure:

(a) pulse height

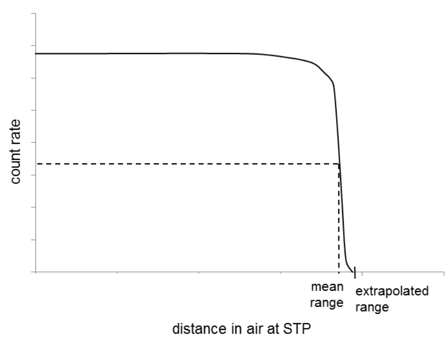
(b) energy resolution

(c) number of counts per second by integrating over the peak on pulse height analyser (determined from Integral).

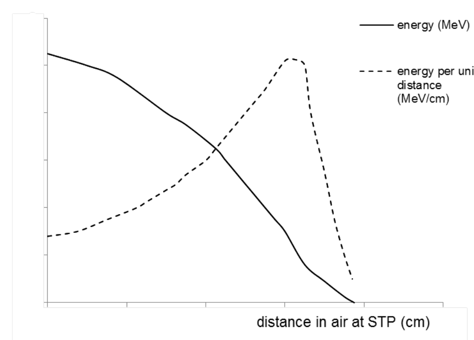
You should pay more attention to measurements for pressures of ∼450 Torr and above.

(6) From these results plot count rate against equivalent distance in air at STP and hence determine the mean range and the extrapolated range of the α particles. Use the ideal gas law.

Then use the energy measurements to plot α particle energy as a function of distance in air at STP. From the slope of this graph plot a curve of energy loss per unit path length.



(a)



(b)

Figure 2: (a) Example of the number of counts from an α source reaching the detector as function of distance in air at STP. (b) Example of α particle energy when it reaches detector as a function of distance. Dotted curve is derivative of solid curve, i.e. energy loss per unit path length, $\mathrm{d}E/\mathrm{d}x$.

Note: It may not be possible to plot these graphs in their entirety with your data. Figs. 2 (a) and (b) are just provided to give you a point of reference.

(7) The energy distribution of α particles is approximately Gaussian after passage through an absorber. This is known as energy straggling and results in a spectrum of the form:

$$N = N_o \exp\left(-\frac{\Delta E^2}{2\sigma^2}\right)$$

According to the Bohr straggling theory:

$$\begin{aligned}\sigma^2 &= \frac{z^2 e^4 Z N}{4\pi\varepsilon_o^2 A}\,\Delta x \\ &= \frac{156.6 z^2 Z}{A}\,\Delta x \text{ in } (\mathrm{keV})^2 \text{ where } \Delta x \text{ is in mg/cm}^2\end{aligned}$$

Take the FWHM for a number of values of the air pressure and determine σ using the relationship:

$$\text{FWHM} = 2.37\sigma$$

Plot a graph of σ^2 against x. From this determine the energy range over which the Bohr theory is valid. Comment on why this simple theory is not valid at low energies. Remember that the effect of instrumental energy resolution must be removed by using the expression

$$\sigma^2_{\text{total}} = \sigma^2_{\text{instr}} + \sigma^2_{\text{strag}}$$

σ_{instr} is best determined from the measured α line width under vacuum (0 Torr).

Scintillation Detector

This consists of a cylindrical crystal of NaI(Tl) 50.8 mm in diameter and 50.8 mm long permanently attached to a 10 dynode photomultiplier tube. The dynode voltages are supplied from a resistor chain mounted inside the plug-on housing. The Brandenburg high voltage power supply must be used with **positive** polarity.

(8) Connect up the electronics as shown in Fig. 3. (Refer to the **Apparatus** section if unsure.) Using the ^{60}Co source, check the pulses with the oscilloscope and adjust the 435 preamplifier gain so that no "limiting" occurs up to about 1600 V on the phototube. (Limiting is denoted by a flat-topped pulse).

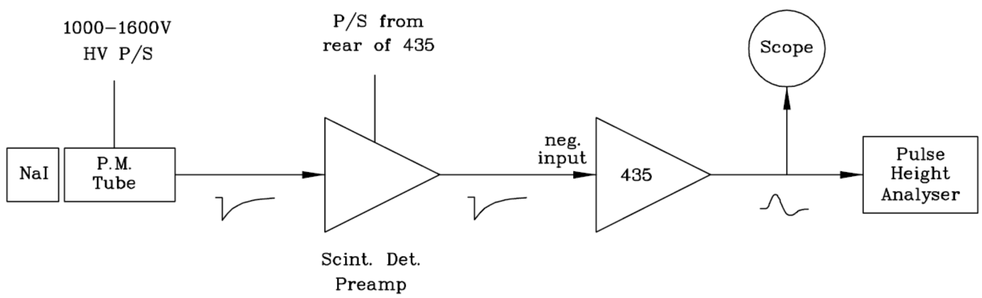


Figure 3: Experimental setup for the scintillation detector.

(9) Plot pulse height versus applied voltage in the range 1000 V to about 1600 V. Comment.

At the time of writing (May, 2013), the controls on the Brandenburg power supply do not accurately give the applied voltage. You should read the voltage off the scale if this is still the case.

(10) From a consideration of Compton and photo-electric interactions in the sodium iodide explain the shape of the energy spectrum observed for the ^{60}Co source. Determine the energy resolution and compare with the semiconductor detector. Comment on the difference.

(11) Natural potassium contains a small fraction of radioactive ^{40}K which has a very long half-life. The stainless steel block contains 18.97 g of KCl. Using the abundance of ^{40}K given below, determine the number of ^{40}K atoms in the sample. Since $\mathrm{d}N/\mathrm{d}t = -\lambda N$, the half-life may be determined if $\mathrm{d}N/\mathrm{d}t$ can be measured absolutely.

Use the 1μCi ^{60}Co source provided to determine the detector efficiency for ^{40}K γ-rays as a function of γ energy. Devise an approximate method of correcting for the efficiency.

The decay scheme for ^{40}K is shown in Fig. 4. The positrons do not reach the detector but are annihilated in the source resulting in 0.511 MeV γ-rays which could be detected. The β^- particles have a continuous energy distribution up to a maximum of 1.35 MeV. Most of this is absorbed in the source. The few that emerge and penetrate the 0.05 mm Al scintillator casing will produce a broad spectrum difficult to differentiate from the background.

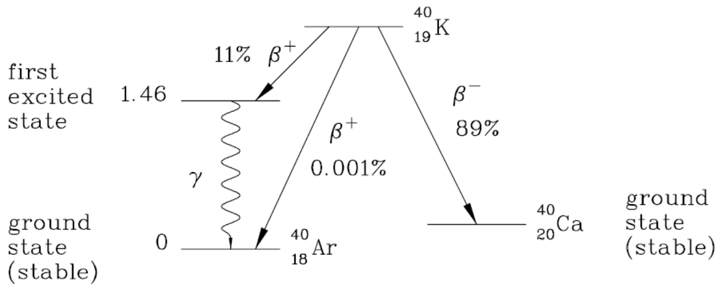


Figure 4: Decay scheme for ^{40}K.

Of all the decays of ^{40}K, 11% produce the 1.46 MeV excited state of ^{40}Ar which decays almost immediately by γ emission to the ground state. These γ-rays produce an easily recognisable photo-electric peak just above the two ^{60}Co peaks. Use the counts in this peak (suitably corrected for detector efficiency) to determine $\mathrm{d}N/\mathrm{d}t$ and hence the half-life of ^{40}K.

Note: Take the percent abundance of ^{40}K in natural potassium as 0.0118%.

(12) Potassium is fairly uniformly distributed throughout the Earth's surface. (It is a necessary trace element for plant and animal growth.) One therefore expects some ^{40}K to be present in the concrete walls of the laboratory. Take measurements with and without the lead shield around the scintillator and determine the approximate γ-ray flux from this source. How does this compare with the cosmic ray background at sea level and the radiation received from a chest x-ray?

Questions

1. The preamplifier used for the semiconductor detector is charge sensitive, i.e. it gives an output pulse height which is proportional to the charge of the input pulse rather than its peak voltage. Why is it desirable to use such a preamplifier with the semiconductor detector?

2. To be used as an energy spectrometer, the semiconductor detector must completely absorb the particles. Explain why this is necessary and determine the maximum energy of α particles for which our detector is suitable as a spectrometer.

3. Say we used a voltage-sensitive amplifier of infinite input impedance to measure the ^{241}Am α particles. Determine the magnitude of the resulting voltage pulse.

4. In procedure (7) a method of determining σ_{instr} is suggested. Calculate approximately the natural α line width and hence justify this procedure. What are the main factors contributing towards σ_{instr}?

5. Explain why a magnet placed near the scintillation detector will change the gain.

6. If, on the average, each dynode releases 2.4 secondary electrons for each incident electron, calculate the overall gain of the 10-dynode tube used.

Appendix - Gamma Acquisition & Analysis

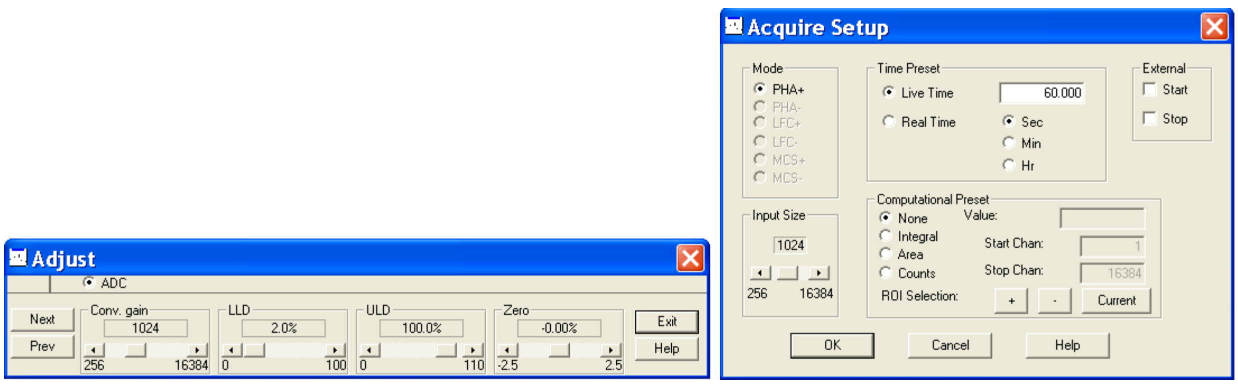
This is a quick guide to the "Gamma Acquisition" software. For a more thorough introduction, please see other lab handouts which use the same programme, such as Expt 252: Relativistic Electrons.

Open 'Gamma Acquisition and Analysis' on the Windows desktop.

To collect data, you must open a detector data source:

- select File – Open Datasource ... from the menu
- click the Source:Detector radio button
- select MP2_MCA1, then click Open.

Set the MCA to 1024 channels by going to MCA – Adjust and change Conv. gain to 1024. Then go to MCA – Acquire Setup and also set Input size to 1024. Time Preset allows you to collect data for a specific time duration.



(a) (b)

Figure 5: Settings

You can now use the buttons under Acquire in the main window to collect data.

The PHA spectrum shows a dot for each channel (in this case, 1024 of them) along the x-axis. Channel number corresponds to the pulse height (energy) produced by the preamplifier whenever a radioactive particle is detected, and the y-axis shows the number of counts of that channel. This is essentially a histogram.

After data collection, move the] and [markers to highlight in red the region of interest (ROI). The | is your "cursor", which tells you about a specific channel number. This is displayed in the strip above the spectrum.

Click Next or Prev to display various collections of information. Of particular interest is Marker Info, where Integral is the total number of counts in your ROI.

If you decide to use energy instead of the corresponding channel number for plotting graphs, etc., it is a good idea to calibrate the energy scale. Otherwise the energy values from the previous experimenter's calibration may not be accurate for your measurements. This calibration depends on the amplifier gains used, which must be kept constant once calibration is done.

Say your calibration source emits two γ-rays of known energies. You identify the channel numbers of these γ-rays on the spectrum, and plot a calibration line on a graph of known energy vs channel number at Calibrate - Energy Only Calibration. This process needs to be repeated at the beginning of every lab session and whenever you change the amplifier gains.

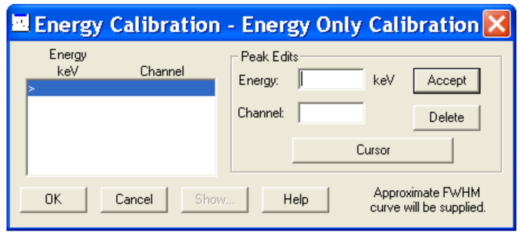


Figure 6: Calibration

You can save your data as *.CNF files (used by this programme) or *.TKA files (used by MATLAB).

List of Equipment

1. 1μCi ^{60}Co source
2. ^{40}K source in brass block
3. ^{241}Am source and semiconductor detector in vacuum housing
4. Pressure gauges
5. Rotary vacuum pump
6. Brandenburg Model 2475R high voltage supply for scintillation detector
7. Scintillation detector
8. Scintillation detector preamplifier
9. ORTEC Model 401A Multiport II
10. ORTEC Model 428 detector bias supply for semiconductor detector
11. ORTEC Model 419 precision pulse generator
12. ORTEC Model 575A main amplifier
13. ORTEC Model 435 (active filter) main amplifier
14. ORTEC Model 142 preamplifier for semiconductor detector
15. PC with Nucleus PCAII-8000 PHA card
16. Multimeter

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September, 2003.

This version: R. Au-Yeung, 10 May 2013.