

Introduction To Ionising Radiation

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Abstract

A set of experiments were performed using a Geiger-Müller tube, ^{90}Sr and ^{60}Co sources to demonstrate some of the fundamental principles of ionising radiation and its detection. The random nature of radioactive decay was represented by a Gaussian distribution and the inverse square law illustrated by a linear relationship between $1/C^{1/2}$, where C is the count rate, and source to detector distance, x . The attenuation of β -particles and γ -rays were investigated and a maximum endpoint energy for β -particles from the ^{90}Y daughter of the ^{90}Sr source found to be $E_{\beta}^{max}=1.86\pm 0.2\text{MeV}$. This compared well to a published value of 2.27MeV [2]. Some of the performance characteristics of the Geiger-Müller tube were analysed and the optimum operating voltage and dead-time of the tube were calculated to be 540V and $\tau=42\pm 2\mu\text{s}$ respectively. The published dead-time value of the detector was $\tau=100\mu\text{s}$ [3].

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1 Introduction

The interaction between ionising radiation and matter is of great importance, since it is widely used in industry and medicine (for both diagnosis and treatment) and forms a basis for many areas of scientific research. Ionising radiation generally occurs in the form of fast particles, such as α -particles, electrons and positrons, (β -particles) and electromagnetic photons, such as γ - and X -rays. In each case the radiation interacts with matter by creating electric fields strong enough to remove electrons from atomic shells. In the case of particles, this ionisation process is mainly due to the Coulomb interaction between the ion and the electrons of the absorber. In the case of photons, there are three interaction mechanisms. These are photoelectric absorption, Compton scattering and pair production [1]. In photoelectric absorption, the photon is absorbed by an atom and one of the electrons is released, creating an ion and free electron.

The key to radiation detection is being able to measure the electric charge using electronic circuits. By applying an electric field across the detector material, the charges can be separated, since the electrons move to the anode and positive ions move to the cathode. A suitable detector material will be an insulator under normal circumstances, but allow the charges to move in a radiation event. Suitable materials include gases and semiconductors [2]. One of the oldest instruments for detecting radiation is the Geiger-Müller (GM) tube, which was first developed in 1928. It is a gas filled detector, that has been manufactured in a wide variety of geometries that are suitable for detecting solid, liquid or gaseous samples of radioactive materials. Its simplicity, low cost and ease of operation have lead to its continued use today.

This set of experiments uses an MX168 Geiger-Müller tube [3] and a ^{90}Sr β -emitter to demonstrate some of the performance characteristics of GM detectors, such as pulse height fluctuations and dead-time. The random nature of radioactive decay is studied and some of the fundamental observations and laws concerning ionising radiation are validated, including the inverse square law and the attenuation of β -particles and γ -rays.

2 Background Theory

Radioactive decay is a process in which the particles or photons from a source are emitted isotropically with a decay rate that decreases with time according to an exponential law (equation 1). $N(t)$ is the number of undecayed nuclei at time, t , N_0 is the initial number of nuclei and λ is the decay constant.

$$N(t) = N_0 e^{-\lambda t} \quad (1)$$

Since radioactive decay is a random process, the pulses recorded by a detector for any given time interval will fluctuate. The magnitude of this fluctuation can be measured by calculating the mean, N , and standard deviation, ($\sigma = \sqrt{N}$) of a large number of readings. The distribution of the data should be approximately that of a Gaussian distribution, of the form of equation 2 [4], which is characteristic of this random nature.

$$P(x) = \frac{1}{\sqrt{2\pi\bar{x}}} \exp\left(-\frac{(x - \bar{x})^2}{2\bar{x}}\right) \quad (2)$$

The centroid of the Gaussian curve indicates the mean number of counts for a set of data and the spread, or fluctuation around the mean is given by the full width at half maximum (FWHM). This is related to the standard deviation by [5]:

$$FWHM = 2.35\sigma \quad (3)$$

Since increasing the length of time taken to collect readings will lead to a higher mean number of counts, N , the statistical uncertainty, \sqrt{N} , will be reduced. In reality, a compromise has to be made between the counting time used and the accuracy of the measurements.

A consideration to be made when dealing with radioactive sources is the amount of dose that will be received by anyone working with the sources. The cheapest and easiest method for workers to reduce their exposure to ionising radiation is by exploitation of the inverse square law. This says that for a point source of radiation, at any distance, r , from the source, the radiation flux will spread equally over an imaginary sphere with an intensity of $N/4\pi r^2$. The amount of dose received will therefore be proportional to

$1/r^2$. This means that doubling the distance from source will reduce the dose by a factor of 4. The inverse square relationship can be expressed as equation 4 [5], where x is the distance from source to detector, C is the count rate, k is a constant and d is a correction factor for distance.

$$\left(\frac{k}{C}\right)^{1/2} = x + d \quad (4)$$

Another characteristic of ionising radiation is its attenuation through different absorbers. This is dependent on the type of radiation concerned. α -particles ($\frac{4}{2}He$ nuclei) can be stopped by a sheet of paper or a few centimetres of air, whereas β -particles (e^- , e^+) require a few millimetres of something more dense, such as aluminium. This is due to the fact that α -particles are heavier ions and much larger than β -particles, so although they only lose a small amount of energy per collision, they are much more likely to collide with the atoms or molecules of the medium through which it travels. The energy lost in each collision means that the particle will eventually be stopped in the material. Since β -particles are much smaller, collisions will be a lot less frequent. Although more energy per collision can be lost (due to conservation of energy and momentum), a denser material is required to increase the probability of a collision in the first place. The maximum range of β -particles in aluminium can be found, and used to calculate the maximum endpoint energy, E_{β}^{max} , for the particles using an approximate empirical expression that relates the two (equation 5) [5]:

$$R_{max} = 543E_{\beta}^{max} - 1.33mgcm^{-2} \quad (E_{\beta}^{max} \text{ in MeV}) \quad (5)$$

Since γ -rays are massless photons and not particles, it is much harder to stop them. They have a very long range and only several centimetres of lead can start to attenuate them.

One of the simplest and most sensitive instruments for radiation detection is the Geiger-Müller tube [2]. The GM tube is a gas filled detector based on the ionisation of gas atoms from the electron produced in an initial radiation event, to create electron-ion pairs. A potential between the anode and cathode in the tube creates an electric field in which the ions can move. The heavy, positive ions of the gas drift relatively slowly towards the cathode, but the lighter electrons accelerate towards the anode, gaining sufficient energy

to ionise further gas atoms within the tube. This leads to an avalanche of ions being created, and a self-propagating chain, which can directly record a pulse amplitude of several volts, without further processing. Once the ion discharge reaches a certain size, however, the collective effects of the individual avalanches and the presence of a quench gas limits the process, terminating the chain reaction. For a short time following each output pulse the detector therefore becomes insensitive to allow the ions to drift towards a normal electric field. This recovery time generally takes within the order of microseconds and is called the dead-time. This dead-time can be calculated by measuring the count rate of two radioactive sources together and separately, and using equation 6, where m_1 and m_2 are the count rates for the two separate sources, and m_{12} is the count rate for the sources together [5].

$$\tau = \frac{m_1 m_2 - [m_1 m_2 (m_{12} - m_1)(m_{12} - m_2)]^{1/2}}{m_1 m_2 m_{12}} \quad (6)$$

Since the process of creating ions within the tube is self-limiting, the amplitude of the current pulse produced by the GM detector is independent of the type or energy of the interacting radiation. This can be represented by differential and integral bias curves. Since the GM tube can be operated in two modes, a series of counts can be measured for various threshold voltages in each mode, and information about the pulse fluctuation observed. In integral mode, all pulses above a threshold value will be recorded by the analyser, but in differential mode only those pulses that are higher than the threshold but lower than a threshold plus window value will be recorded. By comparing the number of counts as a function of threshold voltage for each mode, it can be shown that all pulses made by the GM tube fall within a small range of threshold values, and are therefore of similar amplitude.

The sources used for this experiment are two ^{90}Sr and a ^{60}Co source with an activity of $\sim 10\text{kBq}$. ^{90}Sr decays via β -emission to ^{90}Y , which is also unstable and will therefore be a β -emitter itself, decaying to ^{90}Zr , a stable isotope. The radiation detected will therefore be a combination of β -particles from the parent and daughter. The ^{60}Co source decays via β -emission to an excited state of ^{60}Ni . As this state de-excites, a γ -ray is emitted, so the counts detected from this source will be due to both β -particles and γ -rays.

3 Experimental Procedure

3.1 GM Tube Operating Voltage

The ^{90}Sr source is placed a few centimetres from the end window of the GM tube. Starting with the HV control at zero volts, the voltage is increased until the starting potential is reached. This is the point at which the GM scaler starts to count. For a preset time of 30 seconds the count rate is measured, then the voltage is increased and readings repeated until a point is reached where the GM tube begins to discharge continuously. A plot of count rate against voltage is made and the midpoint of the plateau region found to obtain the GM tubes operating voltage.

The HV monitor box is set to the optimum operating voltage for the GM tube, in integral mode and the window control set to 0.25 units. With the threshold voltage set to its minimum value, the number of counts in a 30 second period is recorded. The threshold control is then increased in steps of 0.05V and readings repeated until pulses are no longer recorded. An integral bias curve is then plotted using the number of counts as a function of threshold voltage. This process is repeated in differential mode to create a differential bias curve.

3.2 GM Tube Dead-Time

The GM tube is set to its normal operating voltage in integral mode. For a preset time of 100 seconds readings are taken of the background count, each of the two ^{90}Sr sources and the two sources together. These values are then converted into a count rate, and the background rate is subtracted from each of the readings before using equation 6 to find the dead-time of the detector.

3.3 Counting Statistics

The GM tube is set to detect in integral mode with a threshold value of 0.15 units. For a preset time of 10 seconds a count rate is obtained for the ^{90}Sr source. This measurement is repeated 50 times and a histogram plotted to show the the relative frequency of counts falling into each interval. A Gaussian distribution with the form of equation 2 can be

plotted over the histogram, with the peak and FWHM of this distribution allowing a measurement of the mean and standard deviation to be made. This can then be compared to the values obtained from the original data.

3.4 Inverse Square Law

The count rate, C , for the ^{90}Sr source over different source to detector distances, x , is measured and a graph of $1/C^{1/2}$ against x is plotted to represent the inverse square law.

3.5 Radiation Attenuation

A count rate for the ^{90}Sr is obtained at a source to detector distance of around 10cm. An aluminium absorber foil, with a thickness measured in mgcm^{-2} is placed between the source and detector and count rate measured again. This is repeated for different foil thicknesses until the count rate falls to the background level. A graph of \log_{10} of count rate against absorber thickness is plotted and the maximum range of the β -particles is used to find the endpoint energy, E_{β}^{max} , for these particles in aluminium, using equation 5. This procedure is then repeated for the ^{60}Co source.

4 Results

4.1 Operating Voltage

Figure 1 shows the count rate for the ^{90}Sr source as a function of GM tube voltage. The starting potential was found to be 365V, and the optimum operating voltage was 520V. This was found by taking the central point on the plateau region. The gradient of the plateau in units of percentage change in count rate per volt is $0.07 \pm 0.03\%V^{-1}$. Figure 2 shows the integral and differential bias curves for the GM tube.

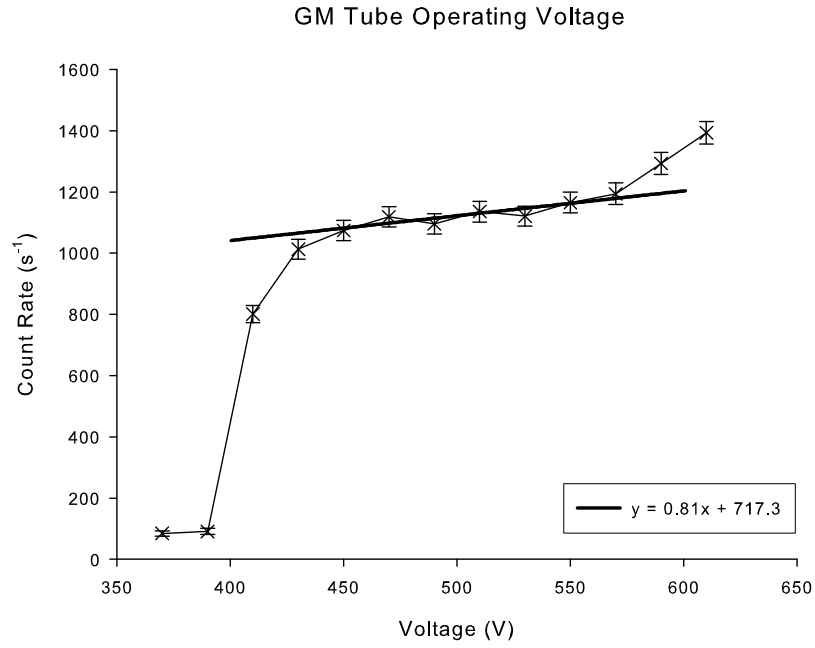


Figure 1: GM tube operating voltage plateau

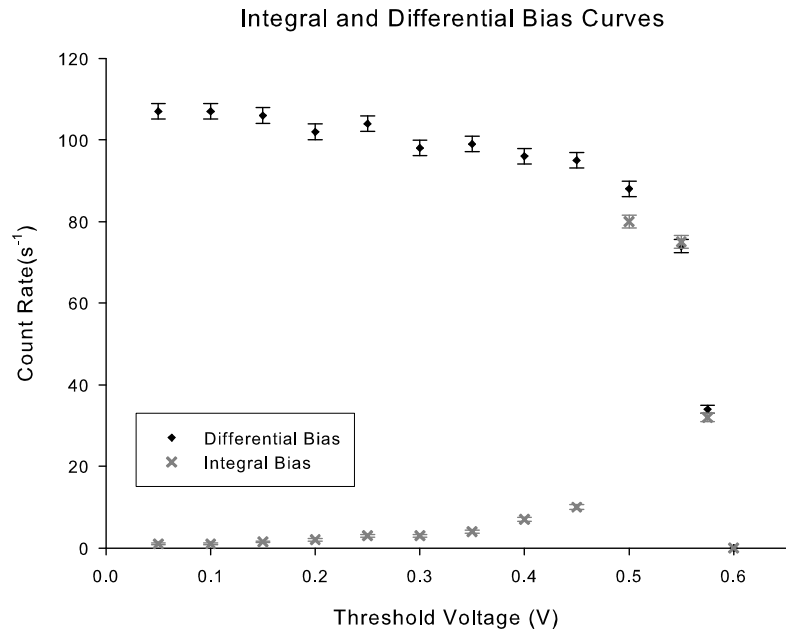


Figure 2: GM tube integral and differential bias curves

4.2 Dead-Time

The dead-time of the detector was found by using the count rate values and equation 6 for the two sources together and separately. These rates were $m_1 = 1076$ counts/sec and

$m_2 = 1084$ counts/sec for the separate sources, $m_{12} = 2066$ counts/sec for the two sources together and a background rate of 1.6 counts/sec. This lead to a dead time of $42 \pm 2 \mu s$.

4.3 Counting Statistics

Figure 3 shows the histogram for the frequency of counts in each interval for the ^{90}Sr source. A Gaussian distribution was fitted to the histogram data, with the form of equation 2. The peak of this distribution, x , was found to be 1013.2 counts, while the FWHM was 97.3. The standard deviation, σ , was then found from equation 3 as 41.4 counts. The mean and standard deviation from the raw data were found to be $\bar{x}=1019.6$ counts and $\sigma=31.9$ counts.

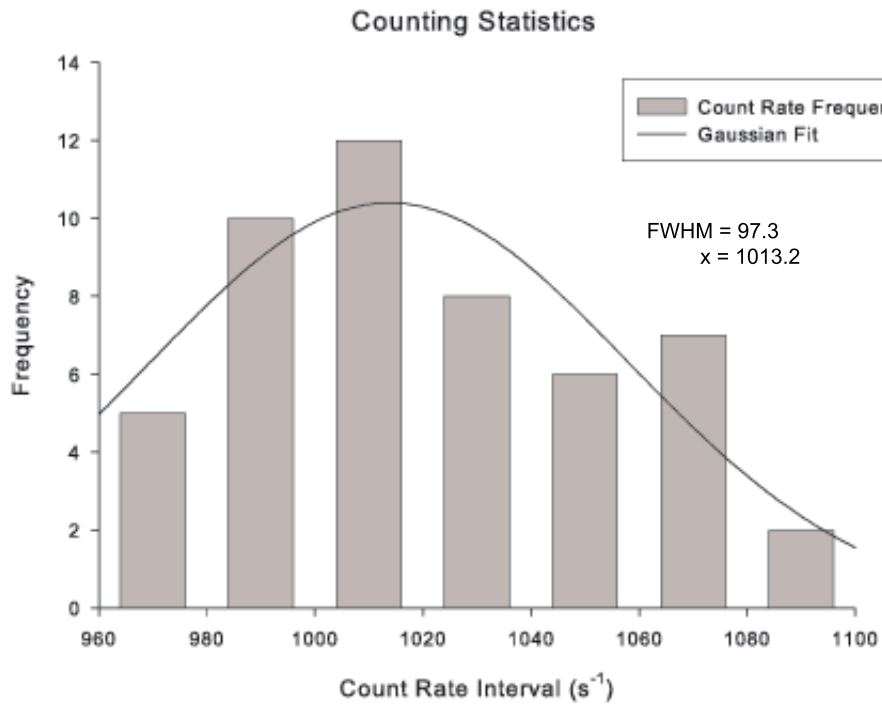


Figure 3: Counting statistic histogram

4.4 Inverse Square Law

The inverse square law is shown in figure 4. $1/C^{1/2}$ was plotted against source to detector distance, x , and compared to equation 4. The gradient of the line, $1/k^{1/2} = 2.5 \times 10^{-3} \pm 1.0 \times 10^{-4}$ and y-intercept, $d/k^{1/2} = 4.9 \times 10^{-3} \pm 4.0 \times 10^{-4}$. $k^{1/2}$ and d are therefore found to be $400 \pm 16 \text{ cm s}^{-1/2}$ and $1.96 \pm 0.24 \text{ cm}$ respectively.

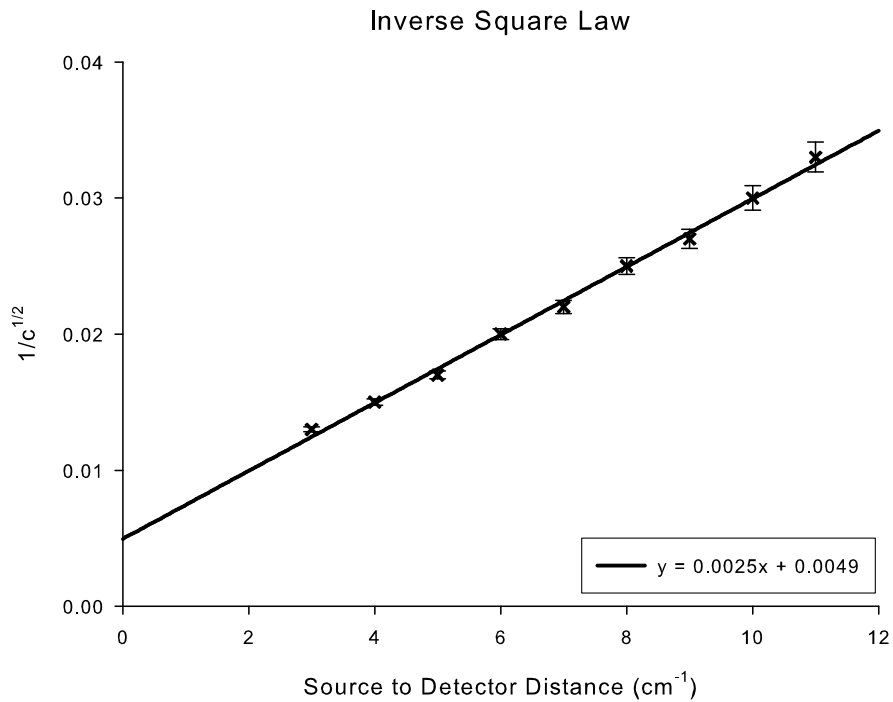


Figure 4: Inverse square law

4.5 Radiation Attenuation

The \log_{10} of count rate against aluminium absorber thickness is plotted in figure 5 for the ^{90}Sr and ^{60}Co sources. The β -particles from the ^{90}Y daughter of ^{90}Sr are attenuated at $R_{\text{max}} = 1008 \pm 40 \text{ mg cm}^{-2}$, therefore the endpoint energy, $E_{\beta}^{\text{max}} = 1.86 \pm 0.2 \text{ MeV}$, found from equation 5.

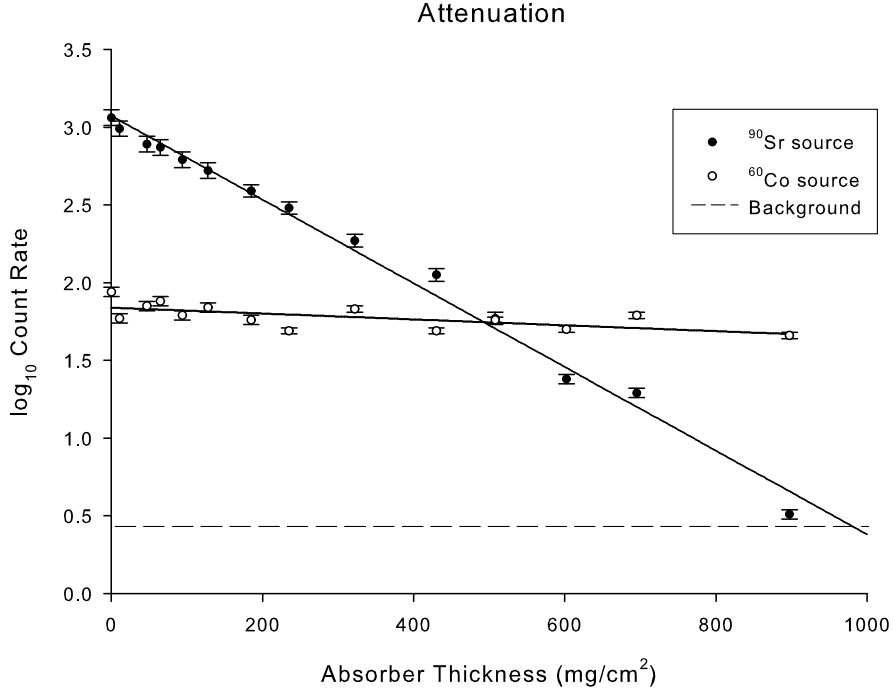


Figure 5: Attenuation of β -particles and γ -rays

5 Conclusion

During this experiment some of the performance characteristics of the GM detector were found, including its starting potential at 365V, plateau length of 100V and optimum operating voltage, 520V. These measured values agree with the published values for this particular GM tube (MX168), with a maximum threshold voltage of 370V and minimum plateau length of 100V [3]. The shape of the GM characteristic curve (figure 1) shows that at low tube potentials the multiplication of gas ions is small, so all the output pulses fall below the threshold value and do not register a count. As the voltage is raised the tube gain increases until some of the output pulses exceed the threshold value. When almost all the output pulses are large enough to be counted, the count rate is roughly constant through the plateau region. The slight slope is due to a residual increase in counting efficiency. As the potential is increased further, a steeper rise in count rate is observed, where the GM tube starts to break down. This can be damaging to the detector if operated in this region for a long time. The gradient of the plateau region was $0.07 \pm 0.03\%$ per volt. This gradient tells us about how fluctuations in voltage within this region affect the count rate. Such a small percentage change suggests that a variation in

the HV will not affect the number of pulses counted, so a stable voltage supply is not required for the detector to be effective.

The integral and differential bias curves provide information about the pulse height fluctuations of the GM tube. In integral mode the single channel analyser counts all the pulses that are above the threshold voltage value, so the integral bias curve suggests that almost all the pulses are above the threshold value until a voltage of $\sim 0.55\text{V}$ is reached. At this point the number of counts falls suddenly to zero. In differential mode the analyser will only count the pulses that are greater than the threshold voltage, but smaller than the threshold plus window value. The differential bias curve shows virtually no counts at low threshold values, but increases sharply at $\sim 0.5\text{V}$. This suggests that almost all pulses from the analyser fall within a small range of threshold values and are therefore of a roughly constant height. This is a characteristic of the GM tube. An ionisation event will produce an avalanche of electron-ion pairs and an increased electric field, however the process is self-limited, so the pulse amplitude of the GM tube is independent of the type or energy of the original radiation event.

The dead-time of the detector was then calculated and found to be $42 \pm 2\mu\text{s}$. This value is of the right order of magnitude, since the published value is quoted as $100\mu\text{s}$ [3]. This dead-time arises due to the fact that any detector is insensitive for a short time following each output pulse in order to redistribute the ions produced by an event into a normal electric field.

The random nature of radioactivity was demonstrated by taking 50 consecutive readings from ^{90}Sr source. The histogram in figure 3 shows a good agreement with the Gaussian distribution, which was fitted using information about the frequency of counts in an interval range and the general Gaussian form (equation 2). The FWHM was found to be 97.6, giving a standard deviation, $\sigma=41.4$ counts and the centroid, or mean was 1013.2 counts. The mean and standard deviation from the raw data were found to be $\bar{x}=1019.6$ counts and $\sigma=31.9$ counts respectively. Although the mean from the Gaussian distribution is lower than that of the measured data, the standard deviation is larger, so it falls within the range from the original readings.

Figure 4 agrees with the inverse square law (equation 4) by showing a linear relationship between $1/C^{1/2}$ and source to detector distance, x . This means that by doubling the distance from the source, the dose of radiation received will decrease by a factor of 4. For this experiment the gradient of the line is related to the constant $k^{1/2}$, which was found to be $400 \pm 16 \text{cms}^{-1/2}$ and the y-intercept, is related to the correction factor for distance and was calculated as, $d = 1.96 \pm 0.24 \text{cm}$.

Finally, the attenuation of β -particles and γ -rays was demonstrated using the ^{90}Sr and ^{60}Co sources (figure 5). The β -particles from the ^{90}Sr source decreased almost linearly as a function of aluminium absorber thickness, until eventually the count rate dropped to the background level. The maximum range of the particles could therefore be extrapolated and an end point energy found for β -particles in aluminium of $E_{\beta}^{max} = 1.86 \pm 0.2 \text{MeV}$. The published values of E_{β}^{max} for β 's from ^{90}Sr and the daughter ^{90}Y are 0.55MeV and 2.27MeV respectively [2]. The measured energy compares well to the quoted value for ^{90}Y , but since the end point energy for ^{90}Sr is much lower, all the β -particles from this isotope would be stopped by an absorber thickness of 180mgcm^{-2} . The count rate from the ^{60}Co source showed no attenuation as the absorber thickness increased. Although both β -particles and γ -rays are produced as the source decays, the quoted end point energy for the β -particles is 0.32MeV . Using equation 5, a maximum range of 40.8mgcm^{-2} is produced, suggesting that all the particles are attenuated very quickly in the aluminium, leaving just the counts from the γ -rays. This graph therefore demonstrates that γ -rays have a much longer range than β -particles and it takes several centimetres of a more dense material (such as lead) to attenuate them.

This set of experiments has demonstrated some of the fundamental principles of ionising radiation and its detection. The performance characteristics of the GM tube that were found compared well to the published values for the specific detector, the random nature of radioactive decay was represented well by a Gaussian distribution and the inverse square law illustrated the linear relationship between measurements of count rate over different distances.

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