

Introduction to Nuclear Radiation

Introduction.

The nucleus of an atom is small (diameter: 10^{-4} the diameter of the atoms), massive (the mass of the atomic electrons is less than 10^{-3} of the nuclear mass), and, for most atoms existing in nature, stable. However, most natural nuclei with atomic number greater than 82 (Pb) are unstable, and change through radioactive disintegration (natural radioactivity), eventually becoming Pb. Also for all stable elements, nuclei that have different masses (more or fewer neutrons) than the naturally existing stable forms can be formed by nuclear bombardment. These nuclei decay by radioactive disintegration (artificial radioactivity) into stable nuclei by emitting various types of radiation. Finally, by nuclear bombardment we can create elements not existing naturally. Such atoms include elements 43, 61 and transuranic-elements (so far atomic numbers 93 through 106 have been made). All of these elements also undergo radioactive disintegration until a stable form is reached.

Half-life.

Each unstable nucleus has a well defined probability, λ , per unit time of decaying. If we have many atoms, N , the number per unit time disintegrating is clearly the number of atoms times the probability per unit time for one atom. So the change in N per unit time is:

$$dN/dt = -\lambda N \quad (1)$$

The number of nuclei remaining (not decayed) after time t is the integral of this equation:

$$N = N_0 \exp(-\lambda t) \quad (2)$$

where N_0 is the number of initial nuclei at time $t=0$. The time $T_{1/2}$ for half of the nuclei to decay is called the half life. It can easily be shown that:

$$T_{1/2} = (\ln 2) / \lambda = 0.694 / \lambda \quad (3)$$

Each unstable nucleus has its own characteristic mean life $\tau = 1/\lambda$ which is also defined as the lifetime of the nucleus.

Types of Radiation.

We know three kinds of radiation and they are called alpha (α), beta (β), and gamma (γ) rays. Alpha "rays" are helium nuclei with a net positive charge of 2 electron charges. When a nucleus emits an alpha particle its mass number (A) decreases by 4 units and its atomic number (Z) by 2 units so we have a different element remaining. Beta rays are electrons (negative charge) or positrons (positive charge). When a nucleus emits a beta particle its mass number remains the same but its atomic number increases (negative) or decreases (positive) by one. Gamma rays are photons of high energy, typically on the order of MeV^{1*} ($1 \text{ MeV} = 10^6 \text{ eV}$). When a nucleus emits a gamma ray, neither its mass number nor its atomic number changes. It typically goes from a higher level energy state to a lower level energy state. In every case the kinetic energy released (mostly to the α , β , or γ) is given by:

$$\text{KE} = M_i c^2 - M_f c^2 - M_p c^2 \quad (4)$$

where M_i and M_f are the initial and final nuclear masses respectively and M_p is the rest mass of the emitted particle (zero for gamma rays).

¹1 eV is the amount of kinetic energy gained or lost by a particle with one elementary electric charge e ($e = 1.6 \times 10^{-19}$ Coulombs) if accelerated through a 1 Volt potential difference. So $1 \text{ eV} = 1.6 \times 10^{-19}$ Joules.

Interactions with Matter.

All nuclear radiation interacts with and eventually is stopped by matter. How the three different kinds of radiation interact with matter will now be discussed in more detail.

Alpha Particles.

These particles, which are emitted with discrete energies of several MeV, interact mainly with the electrons of atoms in matter and only rarely strike a nucleus. Because their mass is large, they are not deflected much by the electrons and proceed more or less straight ahead until they stop at the end of a rather well defined distance or range. Because of their larger mass their velocity is much less than that of beta rays. The low velocity and double charge results in knocking many electrons off atoms (ionizing atoms and forming ions) and a very short range. A few centimeters of air or a piece of paper will stop alpha particles of several million volts of energy (MeV).

Beta Particles.

Beta particles (electrons or positrons), in contrast to alpha particles, are emitted in a given decay with energies from zero up to a definite maximum (which is usually less than alpha particle energies). Except for very high energy beta rays (greater than several MeV) the main slowing-down interaction is with the electrons of the matter through which the radiation passes. Because of their much smaller mass, their velocity is much greater than alpha particles and since their charge is also less, they make far fewer collisions in a given distance and travel much farther in matter. Also because of their smaller mass they are deflected much more easily and do not travel in very straight lines. The continuous distribution of energies combined with the tortuous trajectory means that beta particles do not show a definite range but are absorbed approximately exponentially as a function of distance. The most energetic beta rays are stopped by a book of a few hundred pages rather than one page as with alpha particles.

Gamma Rays.

Since gamma rays (photons of energy $h\nu$) are uncharged, they pass through matter with very few interactions. However, with a well defined beam of gamma rays each interaction effectively removes the gamma ray from the beam either by scattering it out of the beam or by absorbing it so that it disappears. For very low energies (less than 0.2 MeV) and especially for high atomic number absorbers such as Pb, the main absorption mechanism is the transfer of all of the gamma ray energy to an inner electron which is ejected from the atom and absorbed in a short distance. This is the reason lead (Pb) is used to shield x-ray tubes. This phenomenon is called the Photo-electric effect.

For intermediate energies (0.1 to 2 MeV), collisions with outer electrons in which the gamma ray bounces off the electron in a new direction with reduced energy (the electron gets a good deal of energy and is absorbed in a fairly short thickness of material) are the most important. While this scattering effectively removes the gamma rays from a beam, they still continue to exist and experiments must be carefully designed to avoid confusion from scattered gamma rays. This effect is called the Compton Effect.

Starting at 1 MeV and becoming increasingly important at higher energy and for high atomic number materials, are interactions of gamma rays with atoms, in which the gamma ray is converted into a positron-electron pair (Pair Production) and the nucleus serves as a recoil to conserve energy and momentum. The produced electron and positron are absorbed in a manner described under beta particles.

The infrequency of collisions of gamma rays with matter and their removal from a beam in a single interaction results in absorption of an almost pure exponential character with distance for gamma rays of a single energy and also results in great penetration.

Typically it takes a shelf of books to reduce a gamma ray beam to a few percent of its initial intensity. Of course because of its greater density and higher atomic number, an inch or two of lead (Pb) will accomplish the same absorption.

Absorption of radiation. Because of the difference in density between materials, we usually measure the amount of material traversed in $[g\text{ cm}^{-2}]$ rather than the linear thickness traveled by the particle.

$$\rho x = \text{density } [g\text{ cm}^{-3}] \times \text{linear thickness } [cm] = \text{"thickness" in } [g\text{ cm}^{-2}]$$

$$\rho x = \text{mass of the absorber} / \text{area } [g\text{ cm}^{-2}]$$

When radiation is exponentially absorbed, the variation in counting rate with thickness is:

$$N(x) = N_0 e^{-(\mu/\rho)\rho x} \quad (5)$$

where N_0 is the counting rate at $x = 0$, $N(x)$ is the counting rate after the radiation traverses thickness x , μ is called the linear absorption coefficient (dimensions $[cm^{-1}]$ if x is in $[cm]$) and ρ is the density of the material in $[g\text{ cm}^{-3}]$. $\mu/\rho(E,Z)$ is a function of the energy (E) of the radiation and the atomic number (Z) of the absorber. It will, therefore, in general be different for different energies and absorbers. For gamma rays a simple exponential implies the presence of one and only one energy of gamma rays. If more than one energy is present, Eq. (5) would take the form:

$$N(x) = N_{01} e^{-(\mu_1/\rho)\rho x} + N_{02} e^{-(\mu_2/\rho)\rho x} + N_{03} e^{-(\mu_3/\rho)\rho x} \quad (6)$$

for three different energies and would not give a straight line on semilog paper.

Radiation detectors

All radiation detectors make use of the interactions of matter with radiation described previously in which radiation separates electrons from their parent atoms (ionize them). The presence of the radiation is made evident by detecting the ionization. This is done in several ways:

1. The ions make a non-conducting substance conducting and the resultant current through the substance can be measured. This can either be a "steady" current from many particles or a pulse of current due to a single particle.
2. The detector can be so arranged that each ion pair generates many others in an avalanche so that a large pulse from the detector results.
3. As the radiation passes through material atoms are excited to higher energy levels and the light emitted as the electrons return to their normal positions can be picked up by a photomultiplier tube which gives an amplified pulse at its output.
4. The ionization leaves a trail of ions which can be made visible when a photographic plate is developed. (This is the way radioactivity was originally discovered and is still used for x-ray pictures today.)

Geiger Counter.

One of the detectors that we shall use is the Geiger Counter. It is a metallic cylinder with a small wire down the center and frequently has a thin "window" on one end to minimize absorption of the entering radiation. A schematic drawing of such a device is given below.

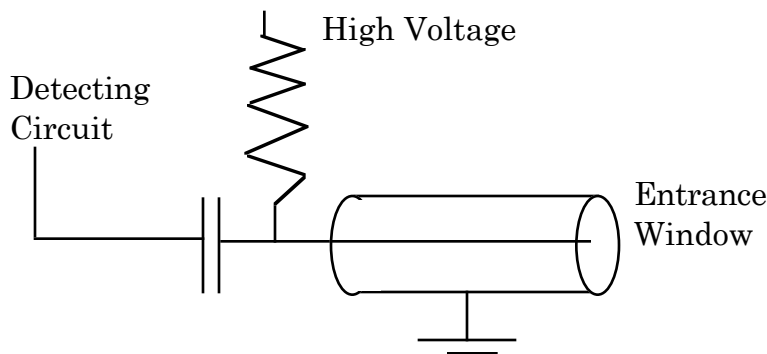


Fig. 1: Schematic of a Geiger-Mueller Tube.

The center wire (anode) is connected through a resistor to the positive side of a high voltage power supply. Each time an ion pair is formed in the counter volume, the electrons move toward the wire. Since, as you found in your electrostatic field experiment, the field near a small wire is very large, the electron gets sufficient speed to knock other electrons off atoms of the gas and these electrons knock still others off and an avalanche occurs. Light emitted from the avalanche knocks out electrons in other parts of the tube and the avalanche spreads the whole length of the wire. The potential of the wire is suddenly lowered by the arrival of the avalanche of electrons and this sudden drop in potential is passed through the capacitor (the capacitor keeps the high voltage away from the detecting circuits but lets the pulse through) to the detecting circuitry.

The counter is left filled with the heavier positive ions which drift slowly out to the outer cylinder which is the cathode. Until most of the tube is clear of positive ions, another avalanche cannot occur and the counter is not sensitive. This dead time is of the order of 10^{-4} seconds and can cause an appreciable loss of counts at high counting rates (more than 1000 counts/sec), and at too high counting rates can stop the counter altogether.

One of the most useful characteristics of the Geiger Counter is the fact that though it will not count at all for too low a voltage, above a certain critical voltage the number of pulses per second (counting rate) depends only on the number of particles entering and very little on the voltage for a range of 50 to several hundred volts. This "plateau" of counting rate means that the operating voltage is not very critical. Toward the high end of the plateau spontaneous counts begin to occur and at a little higher voltage the counter breaks into a continuous discharge which is harmful to it. An ideal response curve of a counter is shown in the figure below. For a real tube the plateau region does not extend so far in voltage. The operating voltage of your counter should be somewhere in the plateau

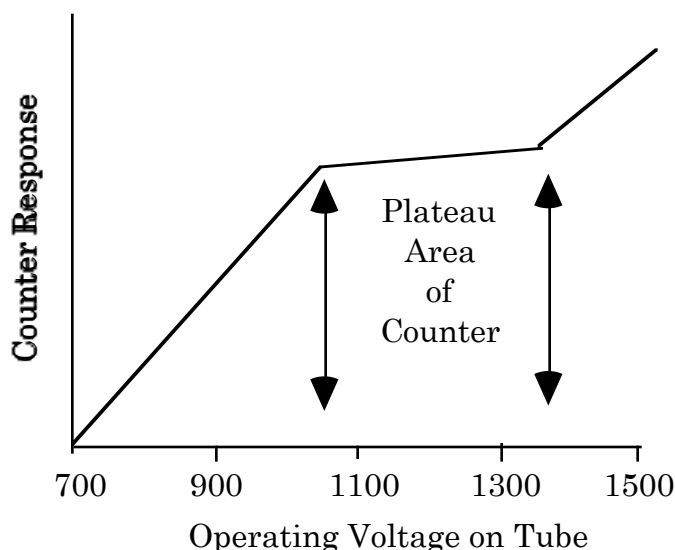


Fig. 2: Response of G-M tube as a function of applied voltage.

A Geiger Counter will count all charged particles which penetrate its window. However, alpha particles have such a short range that they have difficulty in penetrating even a thin window, especially if the source is a few cm away from the window. Gamma rays must strike an electron in the gas or very near the surface of the counter wall in order to produce a countable secondary electron. Because gamma rays travel large distances before making a collision, Geiger Counters have an efficiency of only a very few percent for detecting those which pass through the counter.

Efficiency of Geiger Counters

<u>Radiation</u>	<u>Efficiency</u>
α	Hard to get in counter - 100% if get in.
β	100%
γ	a few %

Scintillation Counters.

While the Geiger counter is useful in indicating the presence of ionizing radiation, it cannot give us any information about its energy, it has low efficiency for counting gamma rays and it has somewhat poor time response. A class of counters that overcome these difficulties are scintillation counters in which the incident radiation creates photons in proportion to the energy it loses and then these photons are amplified with a photomultiplier and converted into a voltage pulse whose amplitude is proportional to the energy deposited. One of the best of this kind of counters is an inorganic crystal of NaI doped with Tl. Some of its properties are summarized in the table below:

Sodium Iodide Scintillator

Density (g/cm^2)	3.67
Radiation length (cm)	2.59
Moliere Radius (cm)	4.5
dE/dx (MeV/cm) for MIP	4.8
Nucl. Int. Length (cm)	41.4
Decay time (ns)	250

Peak emission λ (nm)	410
Refractive Index	1.85
Light Output (photons/MeV)	40,000

Quantities of interest to us in the table include the Radiation length and Moliere Radius which are the length scales associated with electromagnetic radiation. For high energy electrons ($E \gg$ a few MeV), for example, the radiation length is the distance in which an electron loses all but $1/e$ of its energy and the Moliere radius indicates its transverse size. In this lab we shall be dealing with sources of a few MeV or less in which case the radiation length and Moliere radius are even shorter, assuring us that the particles (electrons or photons) deposit their full energy in our detector.

The decay time of a pulse is the time it takes to decay to $1/e$ of its original amplitude. Thus two pulses will not be confused if they come a few decay times (5 or 6) separated from one another.

The light created by energy deposition in the crystal is funneled by plastic light guides to the photocathode of a photomultiplier tube where it undergoes amplification on the way to being turned into a voltage pulse. Since the light collection process is not perfectly efficient (a typical number is 10%) and since a typical photocathode efficiency for converting photons into electrons is 25%, the 40,000 photons per MeV created in the crystal appear as about 1,000 electrons/MeV after the first stage of the photomultiplier tube. If the energy resolution of the detector were dominated by counting statistics only then we would expect a fractional resolution of $1/\sqrt{1000}$ or about 3% at 1 MeV. In practice, other effects tend to make this number somewhat larger.

The photomultiplier tube amplifies the initial signal by creating cascades of new electrons at several stages in proportion to the number of incident electrons. Typical gains in PM tubes can be 10^6 or more. The gain of the tube is proportional to the high voltage applied and thus we must take care that the tube voltage not change in the course of a measurement.

After amplification in the photomultiplier, the signal undergoes some shaping and then is fed to an analog-to-digital (ADC) converter residing in the PC. There it is turned into a number proportional to its amplitude suitable for display and manipulation by the PC.

Background radiation

Will a counter in the presence of no specific source give zero counts? Not at all. Most nuclei of atomic number greater than 82 are naturally radioactive as are also a few lighter ones, such as Potassium 40. Also there are Cosmic Rays coming in from outside the atmosphere. Thus even with no source, a counter will count slowly. This count rate is called the counter background or background count. It can be reduced by various means, one of the most common of which is shielding. However for most of your experiments this background has to be determined and subtracted from your measurements to get the true counting rate.

Counting statistics

Read Chapter 11 of "An Introduction to Error Analysis" by John R. Taylor for additional information on counting statistics and the Poisson distribution. The normal or Gaussian distribution is discussed in chapter 5.

Since each nucleus emits its radiation independently, the radiation from N nuclei will be emitted randomly at an average rate $\sim N$. Thus in one second 20 nuclei may decay, in the next 24. Because each nucleus is independent the time of arrival of counts in a counter is also completely random.

Thus, if we take n readings (n very large) of the activity of a source, let the numbers be c_1, c_2, c_3 , etc. counts/min., the average count rate will be

$$\mu = (c_1 + c_2 + c_3 + \dots)/n = \sum c_i/n \quad (7) \text{ Not}$$

all of the c_i are the same. If they are large (≥ 10 , see page 210 of Taylor) and n is also large,

they will distribute themselves about μ roughly as shown in the figure. The figure illustrates two normal distributions each with the same average (μ) but with different sigmas or standard deviations (σ). What is shown here is the probability to measure a certain counting rate and obviously the most probable value to find is the average.

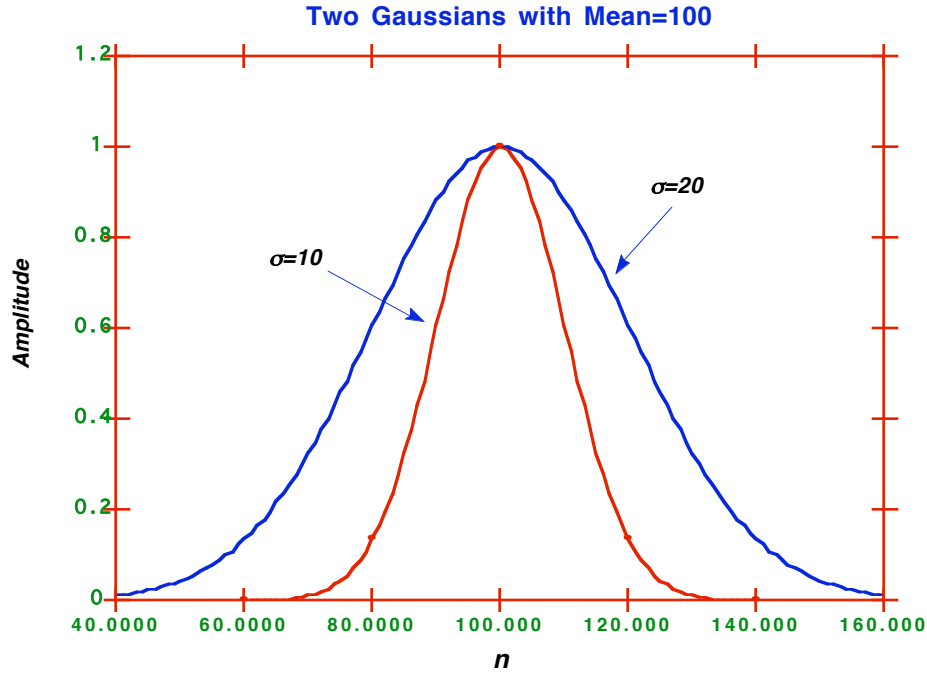


Fig. 3: Normal distributions with different standard deviations.

Normally, μ occurs more often than any other value but there is considerable spread. A normal distribution is completely defined by the average μ and the standard deviation or sigma (σ). If your counting rate follows a normal distribution (which it typically will do for rates >10) then one can say something about the probability of measuring a certain rate: 68% of all measurements will be between $\mu - \sigma$ and $\mu + \sigma$. This can be readily deduced by integrating the distribution between these values and normalizing it such that the total integral (from -8 to $+8$) is equal to 1. The curves shown in the above figure are not normalized that way. Sigma (σ) can be obtained from the measurements in the standard way:

$$\sigma = \left[\frac{\sum (c_i - \mu)^2}{n - 1} \right]^{1/2} \quad (8)$$

The statistical error for a given counting rate c_i is given in Taylor (p.211) by:

$$\sigma_i \approx (c_i)^{1/2} \quad (9)$$

Since, in the above distribution $c_1 \sim c_2 \sim c_i \sim \mu$, for any series of counts

$$\sigma \approx \sigma_i \approx (\mu)^{1/2} \quad (10)$$

The standard deviation of the mean, σ_m , which is derived from n readings is:

$$\sigma_m = \sigma \cdot n^{-1/2} = \left[\frac{\sum (c_i - \mu)^2}{n \cdot (n - 1)} \right]^{1/2} \quad (11)$$

But σ_m is also given by:

$$\sigma_m = \frac{(\mu)^{1/2}}{(n)^{1/2}} = \left(\frac{\mu}{n} \right)^{1/2} \quad (12)$$

The fractional standard deviation of the mean μ is:

$$\frac{\sigma_m}{\mu} = \left(\frac{\mu}{n} \right)^{1/2} \left(\frac{1}{\mu} \right) = \sqrt{\frac{1}{\mu \cdot n}} = \sqrt{\frac{1}{N_n}} \quad (13)$$

where N_n is the total number of counts in n measurements. We shall try to verify crudely the Gaussian distribution for our counts and we will always calculate the confidence interval in order to know whether one count rate is significantly different from another at a given level of confidence. This is done by measuring c_i and then calculating the probability for any other measurement by using the tables in Appendix A of Taylor.

Counting and Statistics Experiment

Counting and Statistics

Suggested Reading: Ch. 4, 5 and 11 in Taylor.

Experiment 7.1: Learning to Count

The principal device that you will use to measure radiation is the Geiger-Mueller tube, often just called a Geiger tube. Your experimental set-up consists of a Geiger tube with its High Voltage (HV) power supply, some signal conditioning electronics and a scaler with digital readout all shown in Figure 1. The scaler displays the number of counts (= #particles registered in the tube) in a given time interval. Record the serial numbers of these devices for future reference. Verify that the HV power supply is turned down to zero with its AC switch in the off position. The cables should be connected as indicated in Fig. 1. The principle of the Geiger tube operation is described in the "Introduction to Nuclear Radiation". Please read the relevant parts of that introduction before you start this experiment. There should be no HV on the Geiger tube yet at this point.

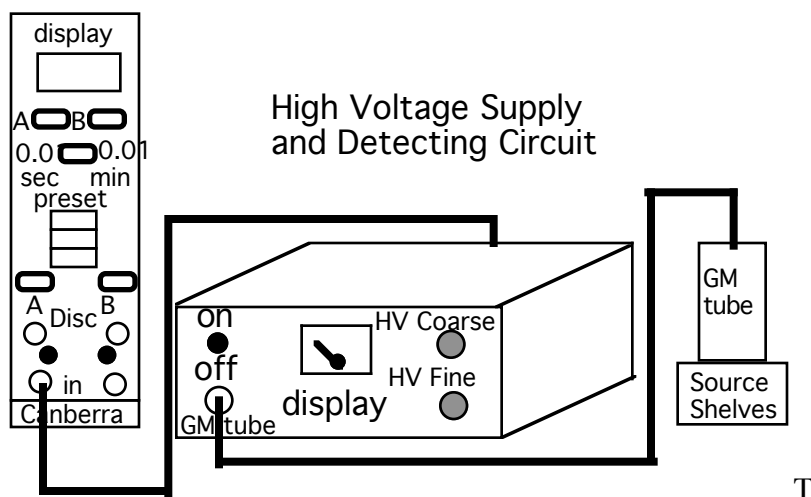


Fig. 1: Counter setup for radioactivity experiments

The scaler is located in a NIM bin, which supplies power to it. To switch the scaler on, switch on the power to the NIM bin. The scaler has two modes of operation: 1) it counts for a predetermined time interval or 2) it counts up to a given preset number of counts and displays the time it took. We will only use it in the first mode, where we count for a preset amount of time. The different switches should be in the following positions:

- Put the preset switch (above "PRESET") in the 0.01 sec position. Now the preset counting interval will be $0.01 * (N * 10 + M) * 10^P$ [sec], where you select N, M and P by dialing in the appropriate settings.
- The display either shows channel A or B, which is selected by the "DISPLAY SELECT" switch right below the display. Channel B will show the time and channel A will show the contents of the scaler. So if you switch to B and push "START" you will see time displayed. Make sure you understand this and try it out.
- The "SINGLE / RECYCLE" switch (left below preset time) allows you to either take one measurement ("SINGLE") or keep on repeating the measurements ("RECYCLE").

In the recycle mode the scaler will count for the preset time, stop for 10 seconds so you have time to record the result then reset the counter and start again. It will keep doing this until you stop it. If you want to control the time between measurements use the "START/STOP" switch, to start the scaler manually.

Now you should be familiar with the scaler. Select 30 seconds as your counting interval, switch the display back to channel A and put the scaler on SINGLE. To start the scaler counting you have to push "START".

Experiment 7.2: The Plateau

Always turn on the scaler before turning on or raising the HV on the Geiger tube.

Put your Cobalt (^{60}Co) source on the bottom "shelf" below the counter (as far away from the counter as possible). If you put it too close the count rate will be too high and you will not see the plateau. In general the highest counting rate should not exceed 1000 counts/second. Make sure the coarse high voltage adjustment for the Geiger tube is turned all the way down and switch on the AC power to the HV supply. Does the counter count? If so, record the count for 30 seconds. If not, turn the high voltage up in steps of 100V until the counter counts (be sure to restart the scaler) and take a 30 sec. reading. Once the tube starts registering particles you have reached a point on the response curve where it starts to be active.

WARNING: In case the tube starts discharging, which is indicated by an extremely rapid increase in the count rate or even audible sounds from the tube **decrease the voltage immediately** to a safe level.

Increase the voltage on the tube in steps of 50 Volts and at each voltage measure the count rate in your 30 seconds interval. In addition to recording your results, graph them concurrently, since the plateau is easier to find graphically. Very soon the difference in counting rate from one point to the next should become less than 5%. From this point continue raising the voltage in 50 Volt steps until the count rate has increased by another 25% or you have raised the HV another 200 volts. Repeat your measurements while decreasing the HV to check that they are reproducible. The high voltage supply limits you to about 1200V, which should be safe, but take care that the tube does not start discharging (see above).

Make a graph of count rate vs. Voltage and find the counter plateau, which is the region of the curve that is most nearly horizontal. Calculate the statistical uncertainty in the count rate and put the appropriate error bars on your graph. Pick a voltage near the low end of the plateau as your operating point. In principle you need to recheck this operating point each time the counter or scaler is turned on because changes can occur in both the counter characteristics the calibration of the high voltage meters. Most tubes have the value of their operating point indicated on them. Compare the value you find with the one given on the tube. Also record the width of your high voltage plateau in volts.

Experiment 7.3:

Set the Geiger tube at its operating point and take 25 readings of the counting rate for 30 sec. each. Calculate the standard deviation in the normal manner from the deviations from the mean and compare with the standard deviation calculated from the mean count. Make a histogram of your results (see pages 100-108 in Taylor). Does its shape agree with a normal distribution ?

Experiment 7.4:

Remove the source and repeat the process for the background radiation. Measure the background 10 times and calculate the average and the standard deviation of the average.

Assigned problems.

In your report on Experiment 7, include the solutions to problems 1 and 2. Show clearly your reasoning.

- P1.** Silver 110 (^{110}Ag) has a half-life of 2.4 min. How long will it take for a source of ^{110}Ag to decay to 1/8 of its original counting rate?
- P2.** If the source originally consisted of 2000 atoms, what would be the initial disintegration rate (dN/dt)?