

Experiment III
Counting Statistics
Neutron Activation

1. Purpose

We will study the statistics of counting experiments and test the applicability of the Poisson and Gaussian distributions.

We will study the effects of neutron activation and measure the half-life of aluminum.

We will refer to the book, *An Introduction to Error Analysis* by John R. Taylor, 2nd edition. You should purchase a copy and bring it to the lab.

2. COUNTING STATISTICS

2.1 Introduction

Measurements are inherently imperfect. Repeated measurements of the same quantity, therefore, give rise to variations in the values obtained. But if we attempt to measure something that is by nature random, a “perfect” measurement repeated many times would still lead to random results. Repeated counting of nuclear decays is a good example. In such cases, even though randomness is involved, some degree of order can be established by proper use of statistics. In particular, certain types of measurements give rise to specific statistical *distributions* of the data. In this section we will introduce three distributions: the Binomial distribution, the Poisson (pronounced *pwah-son*) distribution, and the Gaussian (or Normal) distribution, and see how they are related.

The experiments that follow will illustrate the applicability of the Poisson and Gaussian distributions.

3. Theory

3.1 The Binomial Distribution

Consider repeating an “experiment” (throwing one die, for example) n times. Let us define a successful outcome as getting a 1 showing on the die. It can be shown that the probability of getting v successes in n trials is given by the Binomial distribution (see Taylor, Chapter 10):

$$\text{Prob.}(v \text{ successes in } n \text{ trials}) \equiv B_{n,p}(v) = \frac{n!}{v!(n-v)!} (1-p)^{n-v} p^v \quad (1)$$

where p = the probability of a success in any one trial, and $1-p$ = the probability of a failure in any one trial. The factor $p^v(1-p)^{n-v}$ represents the probability of getting v successes in n trials in any one specific order. The other factor represents the number of possible orders to get v successes (see the example of dice in Taylor, page 228).

The binomial distribution becomes unwieldy for large values of n and v , and it is useful to examine some limiting cases.

3.2 The Poisson Distribution

Referring to eq.(1), in the special case of $n \gg v$ and $p \ll 1$, a useful simplification can be made.

For: $n \gg v$ (successes are rare),:

Approximation 1: $(1-p)^{n-v} \approx (1-p)^n$. (2)

Recall the relation for e:

$$e = \lim_{x \rightarrow 0} (1 + x)^{1/x} \quad (3)$$

Raising eq.(3) to the power \bar{v} (where $\bar{v} \equiv$ mean number of successes) gives:

$$e^{\bar{v}} = \lim_{x \rightarrow 0} (1 + x)^{\bar{v}/x} \quad (4)$$

Substituting $-p$ for x gives:

$$e^{\bar{v}} = \lim_{p \rightarrow 0} (1 - p)^{-\bar{v}/p} \quad (5)$$

Note also that:

$$p = \frac{\bar{v}}{n} = \frac{\text{mean number of successes}}{\text{number of trials}} \quad (6)$$

Putting eq.(6) into eq.(5) gives:

$$e^{\bar{v}} = \lim_{p \rightarrow 0} (1 - p)^{-n} \quad (7)$$

Since, in our case p is assumed small, we re-state eq.(7) as:

Approximation 2:
$$e^{\bar{v}} = (1 - p)^{-n} \quad \text{for small } p. \quad (8)$$

Combining eq.(2) and eq.(8) we get:

$$(1 - p)^{n-v} \approx e^{-\bar{v}} \quad \text{for } n \gg v \text{ and } p \ll 1 \quad (9)$$

Returning to eq.(1), the factor

$$\frac{n!}{(n - v)!} \quad (10)$$

may be simplified as follows:

$$\frac{n!}{(n - v)!} = [n(n - 1)(n - 2) \dots (n - (v - 1))]. \quad (11)$$

Convince yourself that eq.(11) is true by trying $n=10$ and $v=5$, for example. Note also:

$$n - \nu \approx n \quad \text{for } \nu \ll n$$

and therefore:

$$(n-1) \approx (n-2) \approx (n-3) \dots \approx n. \quad (12)$$

Note also that there are ν factors on the right side of eq.(11), and therefore:

Approximation 3:
$$\frac{n!}{(n-\nu)!} \approx n^\nu \quad \text{for } n \text{ large, } \nu \text{ small.} \quad (13)$$

Substituting the approximations given by eqs.(9) and (13) into eq.(1) gives:

$$B_{n,p}(\nu) \approx P_{\bar{\nu}}(\nu) = e^{-\bar{\nu}} \frac{\bar{\nu}^\nu}{\nu!} \quad (14)$$

for $n \gg \nu$, $p \ll 1$. Here $P_{\bar{\nu}}(\nu)$ is used to denote the **Poisson distribution** which may be interpreted as the probability of ν successes in n trials where the mean number of successes, $\bar{\nu}$ is small.

3.3 The Gaussian (or Normal) distribution

As $\bar{\nu}$ increases the Poisson distribution becomes difficult to use since both $\bar{\nu}^\nu$ and $\nu!$ become very large. In this case a further approximation is needed.

Consider the binomial distribution $B_{n,p}(\nu)$, given by eq.(1) for a fixed value of p (the probability of a success in one trial), when n (the number of trials) is large. But with the new assumption that ν (the number of successes in n trials) is no longer taken to be very small. In this case Stirling's approximation tells us that:

$$\nu! \approx \sqrt{2\pi\nu} \nu^\nu e^{-\nu} \quad (15)$$

for large ν . We will not derive this approximation, but numerical evaluation shown in Table I should indicate it is a good approximation as ν gets large.

Table 1

ν	$\nu!$	$\sqrt{2\pi\nu} \nu^\nu e^{-\nu}$	% error
1	1	0.92	8%
2	2	1.92	4%
3	6	5.84	2.7%
4	24	23.51	2%
10	3.6288×10^6	3.5986×10^6	1%

We can also approximate $\bar{\nu}^\nu$ as follows: First note the identity:

$$\ln \frac{\bar{\nu}}{\nu} \equiv \ln \left(1 + \frac{\bar{\nu} - \nu}{\nu} \right) . \quad (16)$$

The right side of eq.(16) may be expanded using the general form:

$$\ln x = (x-1) - \frac{1}{2}(x-1)^2 + \frac{1}{3}(x-1)^3 - \dots \quad \text{for } x < 2. \quad (17)$$

substituting $\left(1 + \frac{\bar{\nu} - \nu}{\nu} \right)$ for x , the expansion becomes:

$$\ln \frac{\bar{\nu}}{\nu} = \frac{\bar{\nu} - \nu}{\nu} - \frac{1}{2} \left(\frac{\bar{\nu} - \nu}{\nu} \right)^2 + \dots \quad \text{if } \bar{\nu} < 2\nu . \quad (18)$$

Since, in this approximation $\bar{\nu}$ is assumed not to be small, the higher terms become unimportant. Taking the antilog:

$$\frac{\bar{\nu}}{\nu} = e^{\frac{\bar{\nu} - \nu}{\nu}} e^{-\frac{1}{2} \left(\frac{\bar{\nu} - \nu}{\nu} \right)^2} \dots \quad \text{for } \nu \text{ not small} \quad (19)$$

Multiplying both sides of eq.(19) by ν and raising both sides to the ν^{th} power gives:

$$\bar{\nu}^\nu = \nu^\nu e^{\bar{\nu} - \nu} e^{-\frac{1}{2} \frac{(\bar{\nu} - \nu)^2}{\nu}} \dots \quad (20)$$

Substituting eqs.(15) and (20) into eq.(14) and canceling, we obtain:

$$G(v) = \frac{1}{\sqrt{2\pi\bar{v}}} e^{-\frac{(\bar{v}-v)^2}{2\bar{v}}}, \quad (21)$$

where $G(v)$ denotes the *Gaussian distribution* which is a good approximation when the number of trials n is large and the number of successes v in n trials is not small.

3.4 Standard Deviation

Various formalisms are used to describe statistical fluctuations of experimental data. As we will show, the fluctuation most closely related to the Gaussian distribution is the *population standard deviation*. The standard deviation is defined by:

$$\sigma_n = \sqrt{\frac{\sum x_i^2}{n}} \quad (22)$$

where the x_i 's are the deviations of the individual values from the average:

$$x_i = \bar{v} - v_i \quad (23)$$

Careful evaluation shows that the best estimate of σ uses $n-1$ in the denominator. This form is referred to as the *sample standard deviation*:

$$\sigma_n = \sqrt{\frac{\sum x_i^2}{n-1}}. \quad (24)$$

However, in the Gaussian approximation n cannot be small, so there is little difference between eqs.(22) and (24). We will therefore use eq.(22).

In order to understand the significance of the standard deviation in the Gaussian distribution, let us make the following substitutions:

$$\text{Let } x = \bar{v} - v \text{ and let } h^2 = 1/2v$$

With these substitutions, the probability for a deviation x from the most probable value, eq.(21) becomes:

$$G(x)dx = \frac{h}{\sqrt{\pi}} e^{-h^2x^2} dx . \quad (25)$$

Putting this probability distribution into eq.(22) gives:

$$\sigma^2 = \frac{\sum_{i=1}^n x_i^2}{n} \quad (26)$$

$$\sigma^2 = \frac{1}{n} \int_{-\infty}^{\infty} nG(x)x^2 dx \quad (27)$$

$$\sigma^2 = \frac{h}{\sqrt{\pi}} \int_{-\infty}^{\infty} e^{-h^2x^2} x^2 dx . \quad (28)$$

The value of the integral is $\sqrt{\pi}/2h^3$. Putting this value into eq.(28) gives:

$$\sigma^2 = \frac{1}{2h^2} \quad (29)$$

Substituting this value for h into eq.(25) gives:

$$G(x)dx = \frac{1}{\sqrt{2\pi} \sigma} e^{-\frac{x^2}{2\sigma^2}} dx . \quad (30)$$

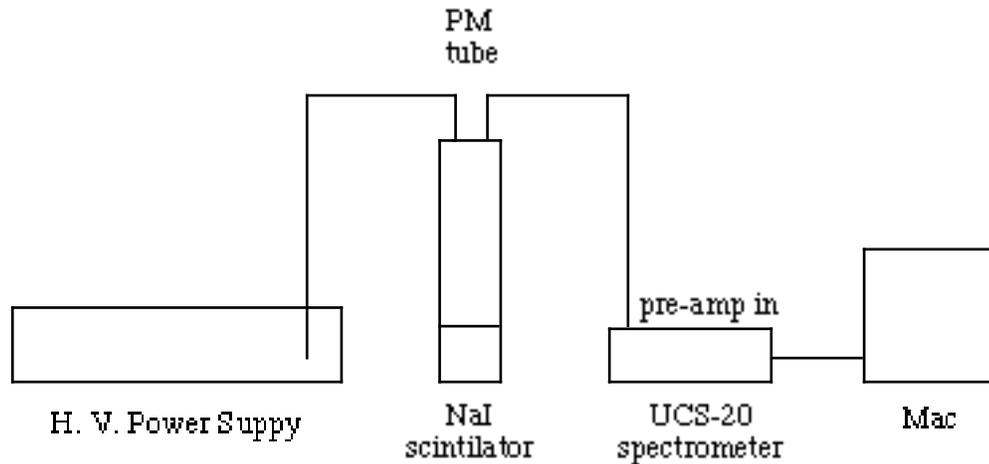
Eq.(30) leads us to the significance of the standard deviation in the Gaussian distribution:

$$\sigma = \sqrt{v} \quad (31)$$

whenever the Gaussian approximations hold.

4. Apparatus

We shall use some of the techniques of nuclear spectroscopy to generate large amounts of data from decays of unstable nuclei. We shall then attempt to fit the data to the distributions discussed above. The apparatus to be used is shown in the figure below.



Apparatus for counting nuclear decays

4.1 The detector

CAUTION: The crystal and PM tube are fragile! Please handle them with care.

To detect the gammas we shall use a sodium iodide crystal coupled to a photo-multiplier tube (PMT), powered by a high voltage supply. The gammas entering the detector produce electrical pulses which travel along the coaxial cable to be counted by the multi-channel scaler. This system offers a very convenient way to perform many repeated measurements of the decay rate (counts per second) of a radioactive source.

4.2 Multi-Channel Scaler (MCS)

The MCS provides 2048 *channels* or time slots. In this mode the MCS records the number of counts for a user-specified *dwelt time* in each channel and then moves on to the next channel to repeat the measurement.

Note that the MCS has another major function. It is often used to produce a histogram of pulse heights, and is thus also called a PHA (pulse height analyzer). We

will use the PHA function in this experiment only briefly, as preparation for the neutron activation part of the experiment.

4.3 Computer

A computer will be used for both the PHA/MCS functions and to run the analysis software (KaleidaGraphh). The analysis software will help normalize and make histograms of the data for precise comparisons with the Poisson and Gaussian distributions.

5. Experimental Procedure

These instructions will be most useful when read in the lab while viewing the apparatus.

Place a cobalt-60 radioactive source a few centimeters from the scintillator. Check that the PM tube is properly connected to the high voltage power supply and to the *preamp* input on the rear of the UCS-20 (Universal Computer Spectrometer).

5.1 High voltage power supply

Check that the power supply is set for negative voltage. Set the front panel switches to 1,000 volts. Turn on its power switch, wait (about 15 seconds) for the audible click and then turn on the high voltage switch. The power supply meter should deflect to the negative side.

5.2 MCS set-up

Plug the USB cable into the UCS-20 and into an unused USB port on the Mac.

Turn on the UCS-20. Double click on the UCS-20 icon to load its software.

Click *OK* on the copyright window. From the *Mode* menu, select *Multi-Channel Scaling*.

From the *Settings* menu, select *MCS dwell time, 10 msec* (milli-seconds). This setting dictates the duration of each counting “experiment.” From the *Settings* menu, select *conversion gain, 2048*. Drag the *lower level discriminator* (LLD) tab to about its 5% position. Drag the *upper level discriminator* (ULD) to its 100% position. This setting will serve to eliminate low level electronic noise.

5.3 Taking data

To begin acquiring data, click on the *Start* box. You should observe data being collected on the screen. The vertical axis indicates the number of counts in each 10 ms counting interval and the horizontal axis is the channel number (or “experiment number” in our case), multiplied by the dwell time (10 ms). You may wish to expand the vertical scale by clicking on the zoom in or zoom out buttons. The default vertical setting is the log scale with a maximum count = 16M.

Click and drag on the UCS window to move the cursor through the channels. The number of counts in each channel is displayed at the top of the window. Each channel represents one “experiment” which consists of counting nuclear decays for 10 ms in our case.

It is important to note that even though 2048 “identical” measurements have been made, the outcomes are not identical. Why?

5.4 Transferring data to KaleidaGraph

In the UCS-20 software: from the *Edit* menu, select *Copy Data Text Only*. In Kaleidagraph, under the *File* menu, select *New, Data Table*. Under *Edit*, select *Paste*. You should see two columns containing your data of channel number and counts. If unwanted columns appear, you may delete them by clicking on the title box at the head of the column (the entire column will be selected) and under *Data*, select *Delete Column*. Name the columns by double clicking on the top box of each column and typing the names, “Channel” and “Counts.” Since all values here are integers, you may want to suppress the trailing decimal and zeros. To do so, select both columns of data. Under the *Data* menu, select *Columns Format*. Under *Data Type*, select *Integer* and click *OK*.

5.5 Determining the mean value of counts

Determine the mean value of the outcomes of your 2048 “experiments.” The mean value may be expressed as follows:

$$\text{mean value} = \frac{\sum_{n=0}^{2047} E_n}{2048} \quad (32)$$

where E_n is the number of counts obtained in the n^{th} “experiment.” The sum in the numerator may be obtained using the software: Under the *Functions* menu, select *Statistics*. Find the sum in the *Counts* column and use eq.(32) to calculate the mean value of the counts of your set of experiments. Compare with the mean also given in the *Statistics* window.

5.6 Poisson data

Before we attempt to test the validity of the Poisson or Gaussian formalisms, we must gather data appropriate to each. The assumptions leading to the Poisson distribution imply that the mean value just calculated should be small (of order, unity). Review the derivations given above to understand this point!

Adjust the distance from the source to the detector so that the mean value of counts per interval is of order unity, then move the data to your KaleidaGraph.

6. Data analysis

We will use Kaleidagraph to create histograms and analyze your data from the MCS.

1. Use eq.(32) to calculate the mean value of counts obtained. Compare your calculated mean value with that shown in the *Statistics* window as in Part 5 above.

6.1 Creating a Histogram

- a. Select the *counts* column by clicking its title box.
- b. Pull down the *functions* menu and select *bin data...* Change the Min, Max, and # of bins as desired. For example, if the full range of data lies between zero and 10 counts/10 ms, choose min = 0 max =10 and #bins = 10. This choice will give integer values for the bin widths.
- c. Click on *recalculate, copy to clipboard*. Click *ok*.
- d. Pull down the *file* menu select *new*.

- e. Pull down the *edit* menu and *paste* the binned data into this new window.
You may wish to suppress the decimal and trailing zeros, as before.
- f. Pull down the *gallery* menu and select *linear, scatter* plot. Assign *histogram x* to the *x* axis, *counts* to the *y* axis, click *new plot*.

The histogram should be displayed. You may change the point markers by double clicking on the legend at the top of the plot.

6.2 Does the model fit the data?

Is the histogram consistent with the Poisson distribution? To answer this question you should compare the theoretical prediction of eq.(14) with your experimental results.

In particular, put the mean value you determined for your data into eq.(14) and calculate:

the probability for 0 counts in 2048, 10 ms runs,

the probability for 1 count in 2048, 10 ms runs,

the probability for 2 counts in ...

(also for 3, 4, 5, 6, 7 counts...)

the probability for 8 counts in 2048, 10 ms runs.

Re-scale (normalize) the histogram of your data to the peak value given by eq.(14) and compare it to the Poisson distribution. Is the histogram of your data well described by the Poisson distribution? When you are satisfied with your histogram, print it. On your printed plot mark the mean value you calculated at the beginning of Part E.

6.3 Gaussian data

Review the assumptions leading to the Gaussian formalism. Here we want a mean value of counts per interval to be about 20 or greater.

Move the Co-60 source closer to the detector and acquire data on the MCS again. Use the cursor to estimate the mean value of counts per 10 ms interval. Re-adjust the distance of the source or add another source as necessary to give a mean value sufficiently large (≥ 20). Once the count rates are high enough, be careful not to move the source or detector. For this part of the experiment it will be necessary to gather at least 6,000 runs (3 independent MCS sweeps). For each MCS sweep, transfer the data to the computer and erase the old data from the MCS. The three separate data files should be copied and pasted into one longer Kaleidagraph file. Use this longer data file to create a histogram in the same manner as done earlier.

7. Fitting a Curve to the Histogram in Kaleidagraph (Gaussian example)

- a. From your histogram, estimate the values of the constants a, b, c, d in the Gaussian form:

$$a + b \cdot \exp\left[-(x - c)^2 / d^2\right]$$

- b. Pull down the *curve fit* menu, select *general, fit 1*.
- c. Click the *counts* box.
- d. Click on the *define....* button. Type in *gaussfit(a,b,c,d)* using $a = 1$ and your estimated values of b, c, d. Click on OK.
- e. Click on OK in the *Curve Fit Selections* window, also.

KaleidaGraph will iterate using your values of a, b, c, d as starting approximations. Note that the fitting routine depends on the starting estimates you have given it. If the fit does not appear to be close to your histogram, re-examine the values of a, b, c and d and modify them as needed.

After fitting is completed, pull down the *plot* menu, and click on *display equation*.

The best fit values of a, b, c, d and their errors are shown.

Print your histogram with the Gaussian fit. Mark the mean value and the values of one standard deviation on both sides of the mean on your plot. Is the relation between the mean and standard deviation as predicted in eq.(31)? Is the Gaussian formalism an adequate representation of your data? Note that both distributions become better models for the data as the number of “experiments” becomes larger.

8. NEUTRON ACTIVATION OF ALUMINUM

8.1 Theory

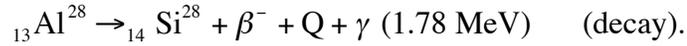
8.1.1 Activation

Matter can be made radioactive if it is irradiated with neutrons. This process is very important in chemical analyses of trace elements, since very small quantities can be identified through their radioactive decay products.

Al-27 is the only stable isotope of aluminum. When we irradiate Al-27 with neutrons Al-28 is formed:



The Al-28 is an unstable isotope and undergoes beta decay to an excited state of Si-28. This excited state of silicon-28 has a very short lifetime (0.5 ps) and quickly decays to its ground state by the emission of a gamma of energy 1.78 MeV:



Here Q represents the kinetic energy of the betas. The maximum energy of the betas leaving the source is 2.8 MeV, although some energy is lost as the betas leave the source.

We will count both the betas and gammas in order to measure the lifetime of the Al-28.

8.1.2 Exponential decay

The half-life of a radioactive isotope is defined as the time required for the number of nuclei of that isotope, present in a sample, to be reduced by one-half through radioactive decay. Before describing this procedure in detail, we examine the origin of the exponential relationship for nuclear decay and show that the half-life of an isotope is related to the probability of decay of an individual nucleus.

The decay rate of a sample of N unstable nuclei is given by

$$\frac{dN(t)}{dt} = -N\lambda \quad (32)$$

where $N(t)$ is the number of unstable nuclei present at any time t , and λ is the probability per unit time for a single nucleus to decay. Thus the total number of decays per unit time is proportional to the number of nuclei present. The solution to eq.(32) is

$$N(t) = N_0 e^{-\lambda t} \quad (33)$$

where N_0 is the number of nuclei present at time $t = 0$. That eq.(33) is a solution to eq.(32) may be verified by substituting eq.(33) into eq.(32). It can be shown that the *mean life-time* of the

particle is $1/\lambda$, which is the time required for the number of unstable nuclei to drop to N_0/e .

The rate of nuclear transitions, however, is most commonly expressed in terms of the half-life $t_{1/2}$ of the isotope -- that is the time it takes half of the nuclei in a sample to decay. For $t = t_{1/2}$,

eq.(33) gives

$$\frac{N(t_{1/2})}{N_0} = \frac{1}{2} = e^{-\lambda t_{1/2}}$$

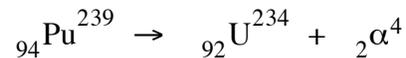
so that

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

Thus, we see that the decay probability, λ , is inversely proportional to the half-life.

8.1.3 The Neutron howitzer

The neutron howitzer provides a large flux of neutrons. The source of neutrons in the device is a multi-step process. The long-lived radioactive isotope Pu-239 (half-life 24,000 years) decays as follows:



The energy of the alpha-particle is 5.1 MeV. The plutonium is mixed with beryllium inside the howitzer. Beryllium absorbs the high energy alpha particles from the plutonium decay and emits neutrons:



The neutrons leave the beryllium with an energy of several MeV. In the howitzer the plutonium-beryllium neutron source is surrounded by paraffin shielding. Neutrons are slowed down and eventually stopped by collisions with protons (hydrogen nuclei) in the paraffin. When

irradiating the samples, it is desirable to have a quantity of protons (paraffin or plastic) between the neutron source and the samples. Slow moving neutrons are more likely to be captured by nuclei than the very fast moving neutrons emitted in the plutonium-beryllium reactions.

Materials used to slow the neutrons in this manner are referred to as *moderators*. The thick layer of paraffin between the neutron source and the outer walls of the howitzer is necessary to reduce the flux of neutrons emitted into the room.

9. Experimental Procedure

Note:

The neutron howitzer is kept in the basement, well away from your lab, in order to reduce background counting rates.

9.1 Pulse height adjustment

Select *PHA mode*, start collecting data and adjust the high voltage and PHA gain so that the Co-60 peaks appear about 2/3 of full scale on the horizontal (pulse height) axis. Adjusted this way, the PHA will be sensitive to the 1.78 MeV gamma of the activated Al, as well as most of the betas.

9.2 MCS set-up

Reset the dwell time to 8 seconds. Keep the lower-level discriminator tab near the low end of the horizontal axis. Drag the upper level discriminator tab to the maximum channel number. This setting allows the MCS to accept the full range of energies of betas and gammas entering the scintillator.

9.3 Background radiation

With no radioactive source near the detector, acquire data for 2 or 3 minutes.

From the counts registered deduce the *background* count rate. These background counts are caused by cosmic rays and trace radioactive materials present in the building materials.

Your tutor will give you four squares of aluminum to irradiate. Before exposing the Al to neutrons, test it for radioactivity with your detector. Do you observe counts greater than background?

9.4 Irradiate your aluminum with neutrons

DO NOT WALK OR STAND IN FRONT OF AN OPEN HOWITZER PORT!

**When the Lucite plug is removed,
the howitzer emits an intense flux
of neutrons through the open port.**

Your tutor will help you expose your aluminum samples to the neutrons for about **5 minutes**.

9.5 Taking data

Be prepared to return quickly to the lab and start your measurements as soon as possible. Spread the aluminum disks around the scintillator in a single layer. Stacking them will cut down on the rate of betas reaching the detector.

Collect data for about 15 minutes, i.e., until the count rate drops to background levels.

9.6 Data analysis

After collecting the data, transfer it to KaleidaGraph as before. It is desirable to create some new columns. First let us create a column which converts all the channel numbers to times. To do so, double click on the title box of the third column. Re-name this column *time*. Click on the *channel* column title box. Note that the columns are re-numbered 0, 1, 2. Since each MCS channel represents 8 seconds, we should multiply each channel number by 8 to create a column of times (in seconds). Under the *windows* menu select *formula entry*. Type in the equation: $c2 = c0 * 8$. Click *run*. Check that the *time* column is filled in with values you expect.

Plot the data by pulling down the *gallery* menu and selecting *linear* and *scatter* plot. Assign the columns to the *x* and *y* axes and click on *new plot*.

Use KaleidaGraph to fit your data to an exponential decay plus a constant (background) of the form:

$$y = a + be^{-t/c}$$

To do so pull down the *curve fit* menu and select *general, fit 1*. Click on *define* and enter the following formula:

$$m1 + m2 * \exp(-M0/m3); m1 = \text{estimate}; m2 = \text{estimate}; m3 = \text{estimate}$$

where you must enter estimates for the constants m_1 , m_2 and m_3 derived by looking at your plot. Click *OK*. In the *curve fit selections* window check the box to select the column to be fit. Click *OK*. Pull down the *plot* menu and select *display equation*. This window shows values for the constants which give the best fit of the data to the functional form you provided.

What is its *mean* life (time to drop to $1/e$ of its initial activity)? What is the half-life of Al-28? What is the dominant source of uncertainty in your measurement? Estimate that uncertainty.