AH Physics Radioactivity Investigations

Note - some of these experiments and investigations have yet to be fully trialled by SSERC. Feel free to contact us before encouraging students to embark upon them.

Statistical significance of radioactive counting

No radioactivity investigation should be attempted without, to begin with, understanding basic concepts in measurement uncertainty. Assuming that the half-life of the radioactive source is very long compared with the duration of the experiment and that the mean count is greater than 10:

- Repeated measurements of count rate fall, approximately, into a normal (Gaussian) distribution.
- The standard deviation of the count N is its square root (= $\sqrt{N}$).
- About two thirds of readings lie within one standard deviation of the mean.
- About 95% of readings lie within two standard deviations of the mean.
- The standard deviation in the mean = $\sqrt{N_m} / n$ where N_m is the mean count and n is the number of measurements.
- The uncertainty in the mean, N_m, = $2\sqrt{N_m} / n$ to a confidence level of 95%.
- The condition for the difference between two counts N_1 and N_2 being statistically significant to a confidence limit of 95% is $N_2 - N_1 > 2\sqrt{(N_1 + N_2)}$.

A series of experiments introducing these concepts is given in the Appendix.

Investigations with sealed gamma sources (Cs^{137} or Co^{60})

Inverse square law: Although a standard Higher experiment, it is still worth carefully analysing the dependence of count rate with distance in an AH investigation. For one thing, it may be introduce the student in working with log-log plots. For another, the expected inverse-square outcome is not shown – or at least there are imperfections – and that begs the question as to why. One reason is that the Isotrak gamma source is recessed 7 mm. Another is scattering off nearby surfaces, including backscatter – the source and GM tube should be raised off the bench and kept out in the open lab well away from walls or apparatus. And another is the whereabouts of the point of detection, for, unlike alpha or beta radiation, which is detected at the window, gamma photons are detected anywhere within the tube's interior. All these factors have to be assessed, weighted and corrected for. Perhaps, thereafter, an inverse-square relationship will be seen to hold?

Half-value thickness of lead: Although another standard Higher experiment, this, too, bears further investigation. In the typical setup the GM tube points directly at the gamma source at a separation of about 6 cm and lead sheets are placed into the air gap, one by one. Surprisingly it does matter whether the absorber is placed next to the source. Radiation from a gamma source is isotropic, which is to say that it radiates in all directions in equal amounts of flux per unit solid angle. If the absorber is close up against the source, then a greater fraction of emissions will strike it than if it is further away. One of the physical processes that occurs when high-energy photons strike a material is Compton scattering. If the incident photon hits an electron, the electron is projected off in the forwards direction and a photon of

lower energy than the incident one is emitted, either forwards or backwards, such that momentum is conserved. The result is that the lead shield collects some of the photons emitted from the source and re-radiates radiation, some of which is detected by the GM tube. Thus the count rate is higher than you might expect.

Attenuation and atomic number: The attenuation of gamma radiation from Cs^{137} depends almost entirely on the photoelectric effect and Compton scattering. Photoelectric attenuation coefficients for elements are, very roughly, proportional to Z^4, where Z is the atomic number of the element in the absorber. There is a marked difference between how well different materials screen gamma radiation. It depends, as explained above, on the elemental composition.

Backscatter of gamma photons: Not an easy subject to investigate because of the difficulty in screening the GM tube from the source. Nevertheless it should be possible to show the dependence of back-scattering with the atomic numbers of back-scattering materials.

Investigations with sealed beta sources (Sr^{90})

Absorption of beta radiation: The absorption of beta radiation follows an approximately exponential law of the form:

$$N = N_0 e^{-\mu x}$$

where N is the count rate for absorber thickness x, N_0 is the count rate with no absorber, and μ is the coefficient of absorption. Here is an opportunity for plotting with a log-lin graph.

A complication is the radiation that results from the deceleration of charged particles in the Coulomb field of atoms. This is called 'bremsstrahlung'. Bremsstrahlung is dependent on the atomic number of the atoms, the greater the atomic number, the more you get. Thus, if you want to shield a beta source, you are better with Perspex than lead. It follows that if you want to show the exponential law of absorption, you are also better with Perspex. But no matter how thick the shield is, even with Perspex, there will always be some radiation. And that's the bremsstrahlung.

To screen the bremsstrahlung, you need to add some lead. A beta shield should have perspex first, lead second. Not the other way about. The difference is significant.

Apart from bremsstrahlung, how does the attenuation of beta radiation vary with the atomic number of the absorber? Not a lot. If the exponential law is rearranged to the form:

$$N = N_0 e^{-(\mu/\rho).b}$$

where ρ is the absorber density and b is the mass per unit area ($b = \rho.x$), the log-lin plot of ln(N) against b is about the same for all metials. The absorption of beta radiation is therefore almost independent of atomic number.

Scattering of beta radiation: To investigate the relationship between the rate of backscatter and the scattering material, point the beta source obliquely at the scattering material with an angle of incidence of 45° and point the GM tube obliquely at the radiation target. Shield the tube from the source, but not from the back-scattering target. The backscatter rate is approximately proportional to $\sqrt{Z}$, where Z is the atomic number of the scattering material.

Deflection of beta radiation in an electric field: Direct the beta radiation between the parallel plates of an air-cored capacitor at the GM tube with slotted diaphragm. Apply a high voltage to the capacitor (about 2,000 V per cm) until the count rate decreases. Move the diaphragm to the point where the beam intensity is a maximum. In order to see the effect, careful alignment is needed.

Deflection of beta radiation in a magnetic field: The GM tube is set up so that can be swivelled about while always pointing at the point where the beam crosses the magnetic field. First, with no magnetic field, rotate the detector through various angles to measure the variation in count rate with angle of rotation. Secondly, applying the magnetic field (neodymium magnets perhaps), re-determine the variation in count rate with angle.

Investigations with sealed alpha sources (Am^{241} or Pu^{239}):

Absorption experiments with a GM tube: The alpha source is Am^{241}. The energy spectrum of the alpha radiation is a line spectrum between 5.3 and 5.6 MeV. The confounder is the associated emission of gamma radiation whose line spectrum extends in energy to 0.125 MeV. To appreciate its significance set up the GM tube window 5 mm from the alpha source and, with counting periods of 10 s, compatre the count rates with no shield against shields comprising one, two and three sheets of paper, then 3 mm Perspex, and finally 3 mm aluminium. Understanding that all you are detecting are gamma photons except when the source is unshielded by anything but 5 mm air is crucial. You may then proceed to employ your Am^{241} source as a source of low-energy photons, comparing their effects with the medium-energy photons you get from Cs^{137}.

Absorption experiments with a spark counter or cloud chamber: Since neither detector detects the photons emitted from the alpha source, you are able to find the range in air of alpha radiation. This is not quite the whole range because the source is sealed by a precious metal foil 2 μm thick. After passing through the foil, the alpha particle energy has been reduced from about 5.5 MeV to perhaps about 3.5 MeV. You are therefore measuring the range in air of 3.5 MeV alpha radiation. The GM tube is really not much use at all in showing the range of alpha in air because the radiation needs quite a lot of energy to penetrate its mica window. Having done air, insert thin shields of metal or polyester film on the spark counter, if that is what you are using, or against the source if you are using a cloud chamber, and show that the range in air is reduced with the thickness of foil shields. Ideally the foil thickness should be about 5 μm. The density of polyester is about 1,000 times that of air. Roughly 1 μm of polyester is equivalent to 1 mm air in attenuating alpha radiation. If smoke is added to the air, is the radiation attenuated?

Efficiency of GMtube: This can be estimated for each type of radiation.

Investigations with natural radioactive sources (K^{40}, Th^{232}, or U^{238})

Obtain the specific activity of natural potassium.

Determine whether certain foodstuffs (LoSalt, brazil nuts) have detectable radioactivity.

Monitor the radioactive decay of decay-chain products collected from the electro-deposition of radon progeny on a charged rubber balloon or the filtration of dust from air (SSERC Bulletin 218).

Appendix:

Here are three introductory experiments with which to teach some basic concepts in measurement uncertainty. They should be given to anyone about to start an investigation on radioactivity.

Statistical analysis of radioactive emissions

To confirm, by observation, that

1. the standard deviation of the count is its square root;
2. about two thirds of readings lie within one standard deviation of the mean; and
3. about 95% of readings lie with two standard deviations of the mean.

Apparatus

Sr-90 sealed source, 74 kBq, AEA

Laptop with Data Studio

PASCO 500 Interface

GM tube, Alba or PASCO

DIY connector, DIL to jack plug (to fit an ALBA GM tube to a PASCO interface)

2 x clamp stands

Perspex shield

Substitute source and apparatus

If you do not have a sealed source of Sr-90, use any other sealed source, or 2 g of potassium chloride. With KCl the counting period should be increased to about one minute.

If you do not have Data Studio (PASCO), use another data-logging method, or, failing that, a scaler, and adapt the method.

Theory

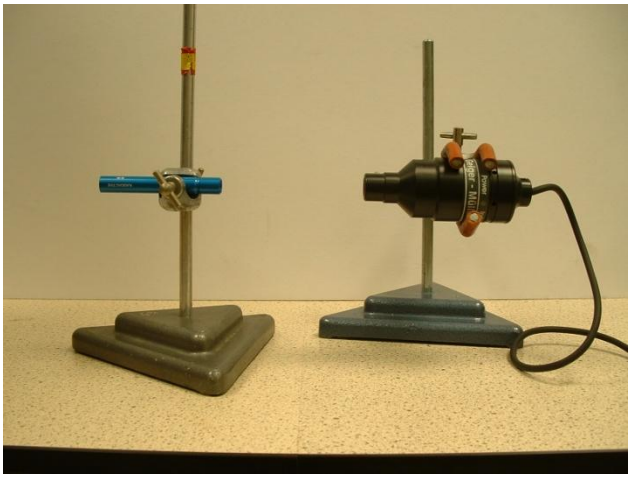
Suppose the count from a radioactive sample whose half-life is very long is taken many times and analysed statistically, a frequency distribution of the results can be shown to follow a Poisson type of distribution.

If the count, N, is greater than about 10, the Poisson frequency distribution of counts is approximately a normal (Gaussian) distribution. If N_m is the mean value of the counts, then $\sqrt{N_m}$ is approximately equivalent to the value of the standard deviation (σ) of the counts. The significance is that roughly 2/3 of the counts are within one standard deviation of the mean value, that is within the range [$N_m - \sigma$; $N_m + \sigma$], where $\sigma = \sqrt{N_m}$. Conversely, under the same conditions, after a single measurement, N, the unknown best value, N_m, has a 68% probability of lying within the range [$N - \sigma$; $N + \sigma$], or a 95% probability of lying within the range [$N - 2\sigma$; $N + 2\sigma$].

The standard deviation of a mean value derived from n individual values of count is given by $\sigma/\sqrt{n}$ or, in this case, $\sqrt{N_m}/\sqrt{n}$.

What to do

1. Start up Data Studio on the laptop (data analysis software from PASCO). Connect a GM tube to the PASCO Interface and programme the computer to take readings of count at 1 a second.
2. Set up the ^{90}Sr source about 10 cm from the GM tube window and monitor the count rate. Adjust the separation until the count rate is about 60 $(1\ s)^{-1}$.
3. Shield yourself with the Perspex screen.
4. Using a histogram display, take one hundred readings of the count. The histogram should have a bell-like shape typical of the normal distribution where there is a random uncertainty.
5. Then copy the readings onto a graphical display (y-axis is count rate; x-axis is time).
6. Use the statistical function to calculation the mean value N_m.
7. Calculate the standard deviation in the count using $\sqrt{N_m}$.
8. Activate the *Smart Tool* to use as a marker.
9. Count the measurements lying outside the range $N_m \pm \sqrt{N_m}$. They should be around 33.
10. Count the measurements lying outside the range $N_m \pm 2\sqrt{N_m}$. They should be around 4 or 5.



Natural potassium – an example of a low-activity source

Purpose
To find out to a known confidence limit whether a substance is radioactive.

Apparatus and materials
Potassium chloride
Spatula
Electronic balance, 100 g capacity
GM tube
Scaler counter
Watch glass
Clamp stand

Discussion
K-40 is a naturally occurring radionuclide with a natural abundance of 0.01%. It is a beta/gamma emitter. We can regard potassium salts as being weakly radioactive. But how do we tell that a weakly radioactive substance is actually radioactive? That is the purpose of this demonstration.

You will measure the count from a fraction of a gramme of potassium chloride (KCl) and compare with the background count. Is the count from the KCl source distinguishable from background? To say with reasonable confidence that KCl is radioactive, you have to show that the normal distributions from the 2 counts don't overlap significantly. This is why the statistical analysis experiment with *Data Studio* is so useful, because it gives you a simple mathematical tool for easily working with standard deviations.

Let N_1 = Background count

Let N_2 = Uncorrected count from KCl

Then $N_2 - N_1$ = Corrected count from KCl

Standard deviation in $N_1 = \sigma_1 = \sqrt{N_1}$

Standard deviation in $N_2 = \sigma_2 = \sqrt{N_2}$

Standard deviation in difference $= \sqrt{(\sigma_1^2 + \sigma_2^2)}$

$= \sqrt{(N_1 + N_2)}$

Condition for the difference being statistically significant to a confidence limit of 95%:

$$N_2 - N_1 > 2\sqrt{(N_1 + N_2)}$$

(If the difference is at least twice the standard deviation in the difference then it is significantly different to a confidence limit of 95%.)

One point of this demonstration is that, whatever we may wish, it shows that we cannot avoid taking radioactive substances into our bodies. Potassium is ubiquitous and lots of foodstuffs have it.

What to do
(During this experiment, analyse while you count.)

1. Measure out 0.5 g KCl on a watch glass.
2. Record the count from background for 1 min.
3. Record the count from the sample for 1 min.
4. Analyse the results. Is the sample radioactive to a confidence limit of 95%?
5. Again record the count from background for 1 min.

6. Again record the count from the sample for 1 min.
7. Sum the two pairs of counts and re-analyse. Is the sample now radioactive?
8. Again record the count from background for 1 min. Repeat for another 1 min.
9. Again record the count from the sample for 1 min. Repeat for another 1 min.
10. Sum the counts for 4 minutes and re-analyse. Is the sample now radioactive?

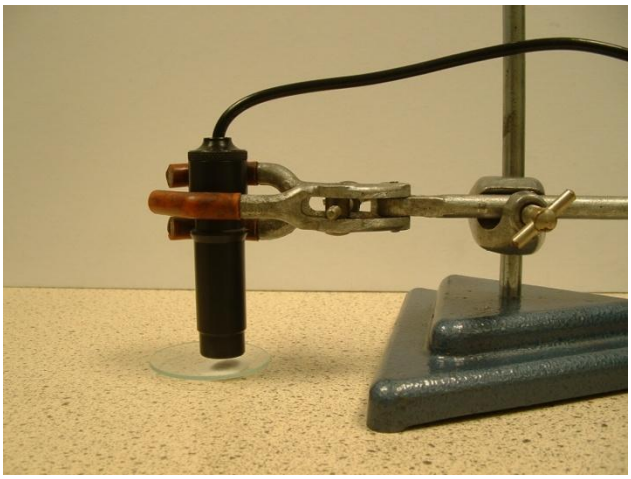
Further comment

Here is a powerful way of finding out whether two results agree or not:

Agreement: $N_2 - N_1 < 2\sqrt{(\sigma_1^2 + \sigma_2^2)}$

Differ: $N_2 - N_1 > 2\sqrt{(\sigma_1^2 + \sigma_2^2)}$

You can use this rule in many applications in AH Physics.



Searching for a radioactive tracer

Purpose
To search for a radioactive tracer concealed in a sealed tube.

Apparatus and materials

Potassium chloride
Sodium chloride
Filter funnel, small
Drinking straw
BluTac
GM tube
Scaler counter
Clamp stand

Discussion

This is a simulation of releasing a radioactive tracer into the environment, or, in a medical application, injecting it into one part of the body, and looking to see where it goes. Because the only unsealed radioactive substance that can be used in a school is potassium or one of its compounds, the substance we make use of is potassium chloride.

Potassium is naturally radioactive. Along with uranium and thorium, the naturally-occurring isotope, K-40, is one of the three common primordial radionuclides found on our planet. The natural abundance of K-40 in potassium is 0.0118%. 89% of the emissions are beta, whose energy spectrum goes up to 1.32 MeV. The other 11% of emissions are gamma at 1.46 MeV. Both types of emissions are highly energetic and thus easily detected with school equipment.

Now down to the details. To be practicable, the simulation has to be done with potassium chloride in its solid form. This, the pretend tracer, should be inserted to part-fill a tube, the remainder of which is topped out with sodium chloride, a non-radioactive material. Both are white, fine-grained substances that look the same and pour easily.

The tube wall should be thin so as not to absorb much of the beta radiation. A drinking straw would be suitable. If the counting period is limited to 100 s then the amount of KCl needed is roughly 1.2 g to tell it from background with a ZP1481 tube. This about quarter fills a 5 mm dia. drinking straw.

What to do

1. Prepare your tube by plugging one end of a drinking straw with Blutac and gently pouring in potassium chloride to the one-third mark with the help of a small filter funnel. Top up with sodium chloride and plug the tube with more Blutac.
2. Set up the GM tube with its window centred on the first third section of the straw. Count for 100 s.
3. Shift the GM tube to the second and third sections of the straw and recount.
4. Has the radioactive part been found?

Analysis

Condition for the difference being statistically significant to a confidence limit of 95%:

$$N_2 - N_1 > 2\sqrt{(N_1 + N_2)}$$

(If the difference is at least twice the standard deviation in the difference then it is significantly different to a confidence limit of 95%.)

(See the previous experiment for the theory.)