Science of Nuclear Energy and Radiation

a Comprehensive Course for Science Teachers

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McMaster University

Notes to accompany Lab demonstrations

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The purpose of these lab demonstrations is to provide secondary school educators with some hands-on experience with radiation as a natural phenomenon and with some real-life radiation-related applications. We have tried to structure these demonstrations in a way that suggests the potential transfer of some of them to the secondary school setting. So, these demonstrations will range from the very basic to the relatively advanced.

Outline:

Day 1 (Monday, June 22) Radiation Detection

Lab #1 **Simple Methods of Radiation Detection**

Lab #2 **Radiation is Everywhere**

Lab #3 **Radiation Counting Statistics**

Lab #4 **The Inverse-square Law ($1/r^2$)**

Lab #5 **Radiation Shielding**

Day 2 (Tuesday, June 23)

Lab #6 **Gamma Ray Pulse Height Analysis**

Lab #7 **Neutron Activation Analysis**

General References

Day 1 (Monday, June 22) Radiation Detection

Lab #1 Simple Methods of Radiation Detection

Objective:

To "see" or detect normally invisible radiation. This experiment uses the Cloud Chamber and the Geiger-Mueller tube.

Theory:

What is called "ionizing" radiation is normally detected by means of the ionization caused by the charged particle or photon. If the detecting material is a gas, the ionization potential is in the range of 10 to 50 electron volts. For example, a charged particle moving through air loses 30 to 35 eV for each electron-ion pair formed. In a cloud chamber the ions formed become seeds for the condensation of droplets of a supersaturated vapour. The resulting vapour trail shows the path of the charged particle or photon.

By collecting the free charges created in a gas, we can obtain an electrical pulse signaling the passage of the charged particle or photon. The Geiger-Mueller tube is an example of a gas-filled detector. The G-M tube contains a gas and has a positively-charged wire running down its centre. A high voltage on the wire causes the charged particles to crash into atoms of the gas at high enough speeds to produce multiple ionizations from a single photon or charged particle. The wire attracts all the resultant electrons and the tube wall attracts all the ions. An electrical pulse results which can be processed to deflect the meter's needle and to produce an audible "click".

Equipment: cloud chamber, G-M survey meter, radiation sources

Experiment:

Use the cloud chamber to show the existence of various types of radiation from simple radiation sources. Compare this with the detection abilities of the Geiger-Mueller survey meter.

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Lab #2 Radiation is Everywhere

Objective:

Show the existence of background radiation all around us and attempt to "get a feel" for this as a quantity.

Theory of Scintillation detectors:

While gas-filled detectors, like the G-M tube, are excellent as a small, light-weight survey meter, they are poor for any application requiring accurate numbers of high energy photons. This is because of the low atomic number (Z) of the gases used and the low density of gases.

The most efficient method of gamma detection is the scintillator, of which Sodium Iodide (doped with Thallium) is a common example. The passage of a charged particle or a gamma ray
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produces a series of ionizations. This is followed by the emission of a large number of weak scintillations as excited molecules of NaI return to the ground state. The NaI crystal is well suited to X-ray and gamma ray detection due to the high Z of iodine and the consequent large number of electrons to interact with.

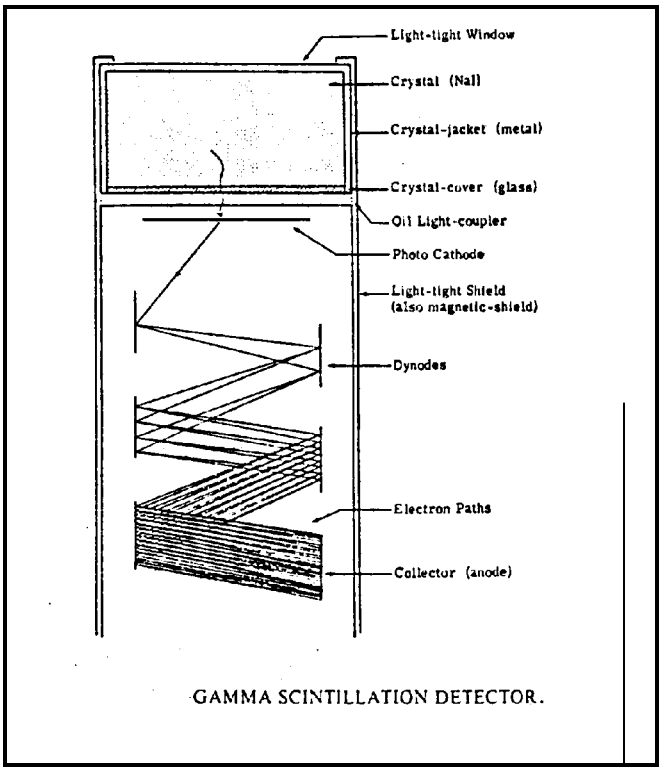

Fig. 1: Scintillation Detector

Figure 1 shows the basic Scintillator detector system. Since the quantity of light scintillations is linearly proportional to the energy lost by the particle or gamma photon that traverses the detector, the system can be used for pulse-height analysis of the electrical output of the photo multiplier tube, although we are not using it this way in this lab.

The *photocell* used to detect scintillations is extremely sensitive and is connected intimately with the crystal so the light is efficiently transmitted to the *photo-sensitive cathode.*

The photocell used is known as a *photo multiplier tube* (PMT), so-called because, for each electron dislodged from the cathode by a photon of light, nearly a million electrons reach the plate (anode) of the tube. This process of electron multiplication is made possible by a system of 10 or more electrodes, called *dynodes*, within the photo multiplier tube. Each dynode is biased at a higher voltage than the previous one for a total bias to the PMT of 800 to 1000 volts. The result is an enormous amplification within the tube itself. Further signal processing is carried out by other electronics, such as the Linear Amplifier, Discriminator, and Counter.

Equipment:
- G-M survey meter
- mineral rock from northern Ontario
- Sodium-Iodide scintillator plus associated electronics

Experiment:
1. Use the G-M survey meter to measure background radiation inside the building.
2. Take the survey meter outside and do some more measurements.
3. Return to the lab and measure the rock and compare this with natural background.
4. Measure background radiation within the building using the Sodium Iodide scintillator and compare these measurements to those of the G-M detector.

Analysis:

Use published tables for the efficiency of the Sodium-Iodide scintillator to estimate the number of gamma rays it can detect of different energies. Calculate the volume of the detector and compare this to the volume of the average human body. Estimate the number of gamma rays that pass through a human every second from natural radiation.

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Lab #3 Radiation Counting Statistics

Objective:

Get a feel for the statistics involved in radiation measurements.

Theory:

Radiation is a random phenomenon. While we can measure average rates of radiation intensity, radiative decay does not occur like clockwork. The accuracy of data depends on the size of the sample taken.

Typically, when doing an experiment, we measure the desired quantity a number of times and average the results to produce a mean value, $\bar{x}$. A more rigorous way of dealing with the data is to plot the distribution of the data in a frequency distribution, also sometimes called a histogram. The frequency distribution provides a visual representation of parameters such as standard deviation, σ, and "full width at half maximum" (FWHM), which help us to gauge the dependability of the calculated average. The data can usually be approximated by a Gaussian distribution (Bell curve) in which $\sigma = \sqrt{\bar{x}}$. By geometry, the full width at half maximum (FWHM) of a data set is 2.354 σ.

Equipment:

- Sodium-Iodide Scintillator, and associated electronics, including counter and timer.
- Cobalt-60 source

Experiment:

1. Measure the natural background radiation with the NaI for ten seconds. Write down the number. Proceed again about twenty times.
2. Measure the radiation from the Co-60 source for ten seconds. Record twenty measurements.

Analysis:

1. Do a histogram of both the natural background data and the Co-60 data.
2. Calculate σ for both data sets and compare the two.

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Lab #4 The Inverse-square Law ($1/r^2$)

Objective:

Demonstrate distance from a point source of radiation as an effective method of "shielding".

Theory:

Radiation from the Sun travels over such an enormous distance that we normally treat solar radiation as if it were in parallel beams. On the other hand, many terrestrial sources of radiation can be treated as if the radiation were coming from a single point. In this case, we can imagine a sphere with a radius of r around a source emitting N_o photons per second. The area of the sphere at the distance r is $4\pi r^2$ If $\Phi(r)$ is the flux of photons per unit area per second radiating out from the point source at a distance r, then:

$$N_o = \Phi(r)\, 4\pi r^2$$

Solving for $\Phi(r)$, we get:

$$\Phi(r) = \left(\frac{N_o}{4\pi} \right) \frac{1}{r^2}$$

Since $N_o/4\pi$ does not vary in this experiment, the flux should vary inversely with the square of the distance from the source.

Equipment:

- Sodium-Iodide Scintillator, and associated electronics, including counter and timer.
- Co-60 source
- measuring stick

Experiment:

1. Place the Co-60 source a fixed distance -- say 5 cm -- from the NaI detector and record a measurement for about 30 seconds.
2. Move the source to 10 cm and measure again for 30 seconds.
3. Move the source to 15, 20, 25 cm and repeat.

Analysis:

1. Construct a plot of the experimental data. Does this fit the form of the equation $N = N_o/r^2$ where "r" is the distance of the detector from the source?
2. Correct the data for background and an estimate for dead time in the scintillator and electronics.

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Lab #5 Radiation Shielding

Objective: To demonstrate material shielding of gamma radiation.

Theory:

Gamma radiation passing through matter is absorbed primarily by either the photoelectric effect, Compton scattering, or pair production. Gamma rays interact primarily with the electrons surrounding an atom, so the likelihood of absorption depends strongly on atomic number, also called *Z*. As the atomic number increases, so the shielding ability of a material increases.

The intensity of the gamma radiation which passes through a particular material is described by the formula: $I = I_o e^{-\mu x}$ where I_o is the original intensity of the beam, I is the intensity transmitted through a thickness, x, of an absorbing material, and μ is a "linear absorption coefficient" or "cross-section" for the material.
The "half-thickness" of a material, $x_{½}$, is related to μ by: $x_{½} = 0.693/\mu$.

By using a number of pieces of a material to shield gamma rays, we can roughly estimate its $x_{½}$. We can use this to calculation the absorption coefficient and use this to numerically compare the shielding properties of each material.

Equipment:
- Sodium-Iodide Scintillator, and associated electronics, including counter and timer.
- Co-60 source
- various shielding materials, e.g. Lead, Iron, Aluminum, Copper

Experiment:
3. Place the Co-60 source a fixed distance from the NaI detector large enough to permit placing of the shielding materials. Record the number of detected gammas in 30 seconds.
2. Place a single piece of Lead in the path of the radiation and count again. Add another piece of lead and count again. Continue with all pieces of lead.
3. Use the other materials in the same way.

Analysis:
1. Use the data to plot on graph paper radiation intensity as a function of material thickness.
2. Compare the result for the various materials.
3. Consider corrections in the data for background, equipment dead time, and lack of gamma beam collimation.

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Further experiment:

Another good experiment to perform at this point would be **Radiation Half-life**.

Objective:
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Demonstrate the phenomenon of radioactive decay and show how the rate of decay can be approximated using the concept of "half-life".

Theory:

Radioactive decay obeys an exponential relationship identical in form to that describing any population growth or decay, such as found with death rates for living creatures or growth of bacteria in a petri dish. The relationship is: $N(t) = e^{-\lambda t}$

The parameter, λ, is called the decay constant. Half-life, or $t_{½}$, is related to the decay constant by $t_{½} = 0.693/\lambda$.

Equipment:

- Sodium-Iodide Scintillator (or other radiation detector), and associated electronics, including counter and timer.
- A radiation source with a relatively short half-life

The second item can be manufactured at McMaster on site by neutron activation in the reactor core. Those who do not have a nuclear reactor in their back yard can do this trick by purchasing a small kit from Merlan Scientific which distributes in Canada for Pasco Scientific. The kit allows a small amount of the radioactive isotope Barium-137 to be extracted from Cesium-137. Cs-137 has a thirty year half-life, but decays to daughter product, Ba-137, which has a half-life of 2.55 minutes.

Experiment:

Once the Ba-137 is extracted, you quickly place it on the detector and start counting, say, for ten seconds. After twenty seconds, count again for ten seconds. Continue until there is no further discernible activity.

Analysis:

Plot the number of counts against time.

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Day 2 (Tuesday, June 23)

Lab #6 Gamma Ray Pulse Height Analysis

Objective:

To study the operation of gamma-ray detectors and the techniques of data analysis measures the energy of the gamma ray. This will include attempting to identify an unknown radioactive source.

Theory: [Full mastery of this section is not required to do the lab]

There are three principal ways in which gamma ray and X-ray photons interact with matter: (1) Photoelectric Effect, (2) Compton Scattering, and (3) Pair Production. The likelihood of each of these processes occurring is related to the energy of the photon.
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The Photoelectric Effect is a process by which a photon is completely absorbed by an atom which subsequently emits a photoelectron with an energy very close to the energy of the incident photon. The probability of this effect increases strongly with the Z (atomic number) of the material, depending on Z^4 to Z^5. The effect is much less likely to occur as the energy of the photon increases.

Compton scattering involves a collision between a photon and an electron. The photon loses some of its energy to the electron and scatters off in a different direction as a lower energy photon. The amount of energy lost depends on the angle of the collision. If the unabsorbed portion of the original photon escapes from the detector, then all we detect is the Compton electron which tells us little about the original photon energy, since Compton scattering occurs across a broad range of energies. If, however, a detector is fairly large, the probability rises that the balance of the photon will be absorbed within the detector (by Compton or photoelectric effect), thereby capturing all the original photon energy and contributing to the "full energy peak". Compton is also dependent on Z but is less dependent on photon energy than the photoelectric effect.

Pair Production is the spontaneous creation of matter from energy. In close proximity to a nucleus an energetic gamma ray spawns a positron-electron pair. Each particle requires 511 keV for formation, putting a lower limit of 1.022 MeV on the incident photon. Any photon energy over 1.022 MeV goes into the kinetic energy of the pair. The probability of this effect occurring increases rapidly with higher photon energies. As both the positron and electrons lose their energy to the detector, this portion of the original photon is captured. Once the positron reaches a very low speed, it will annihilate with an electron, producing two 511 keV photons which fly apart in opposite directions. If both the 511 keV photons is captured in the detector, their energies will tally into the full energy peak. If, on the other hand, either or both of these 511 keV photons escapes from the detector, the result will tally into either a "single escape peak" or a "double escape peak".

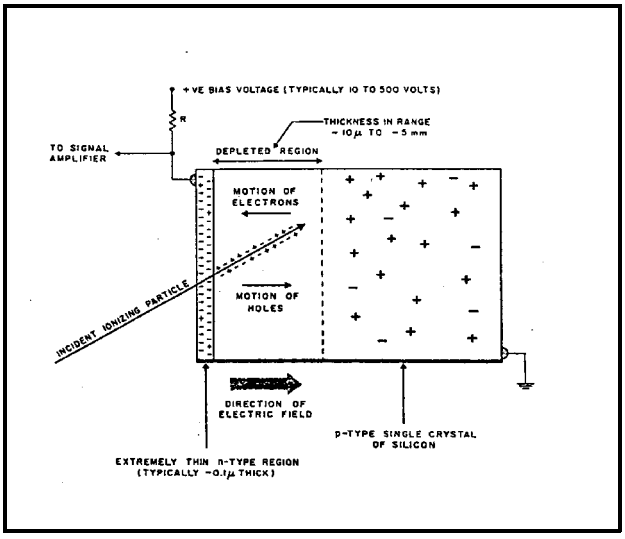

Fig. 2: Crystal ionization by passage of charged particles (or by passage of gammas creating charged particles).

Semiconductor-based Detectors

Of all methods of gamma detection, semiconductor-based detectors provide much superior energy resolution. Germanium detectors also require liquid nitrogen cooling, representing a large extra operating expense plus the weight and size burden of the liquid nitrogen Dewar. Germanium detectors also require a bias supply voltage of about 1000 volts.

Figure 2 shows the production in a semiconductor of electron-hole pairs via the incident particle or photon. This is somewhat analogous to the production of electron-ion pairs in a gas-filled detector.

Collection of the current of these

electron-hole pairs produces electrical pulses which are of lower initial current than those from a scintillator photo multiplier tube and so require somewhat more sophisticated electronic pulse processing systems.

The most important advantage of a semiconductor-based detector over scintillators and gaseous-based detectors is a large improvement in resolution. Resolution depends on a succession of factors. It turns out that more steps are involved in information processing in the case of scintillators. Every step is a source of error and the accumulation of these errors causes poorer scintillator resolution. Each source of error is a random effect, so, the statistical broadening of an energy peak can be approximated by Poisson or Gaussian statistics.

A multichannel analyzer (MCA) is an electronic instrument which measures the height of an electronic pulse corresponding to a radiation event. Since it takes a finite amount of time to measure a pulse, the MCA must close off its entrance to further pulses to prevent corruption of the measurement of the one it is working on. This processing period is called "dead time" and must be accounted for. Most MCAs show the percent of dead time while they are working.

Once the MCA has measured the pulse height, it finds the memory bin which most closely corresponds to this pulse height and adds one count to it. The more the number of memory bins (or channels), the greater the potential resolution of the instrument. MCAs do not come pre-calibrated so they can be optimized for a wide range of gamma ray energies. The energy to channel # calibration is performed in the field using sources of known gamma ray energies.

Equipment:
- Germanium detector and associated electronics: Hi-voltage power supply, pre-amplifier, linear amplifier, NIM-Bin
- Oscilloscope.
- Multi-Channel Analyzer
- Radioactive sources

Experiment:
1. Use the Germanium detector to detect background radiation. Display this on the oscilloscope as bipolar pulses and view a spectrum on the MCA. Note the background signal strength.

2. Acquire a spectrum of a Cobalt-60 source on the Multi-Channel Analyzer for 60 seconds. Integrate the count for all channels which are within the first peak. Print this and note:
    - the peak channel numbers for both peaks;
    - the integrated peak width;
    - the value of the gross integral

3. Lower the gain on the linear amplifier and acquire once again a spectrum from the Co-60 source. Integrate over the peak. Compare this with the result from step 2. Restore the gain.

4. Acquire a Cobalt-57 spectrum to calibrate the MCA for energy versus channel number.

5. Acquire a spectrum for an unknown radioactive source. Print the spectrum. Record all relevant channel numbers, as well as the integrals for any visible peaks.

Analysis:

1. Generate an Energy versus Channel # calibration curve for the MCA.

2. Use the above curve to determine the energy of the peaks for the unknown source. If there is more than one peak, the relative intensity of the peaks may be important in identifying the unknown. Use a standard table of gamma-ray energies for man-made isotopes to identify the unknown (e.g. C.E. Crouthamel, Applied Gamma-Ray Spectroscopy).

Discussion:

Figures 1, 2, and 3 below show the nuclear interaction processes for the extremes of small and large detectors as well as for an intermediate sized detector.

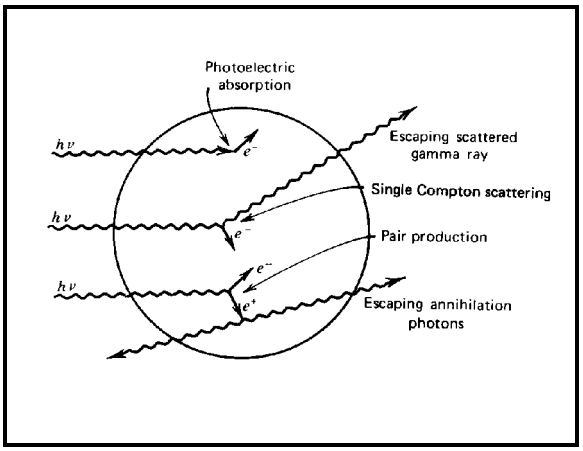

Fig. 1: "Small" detector

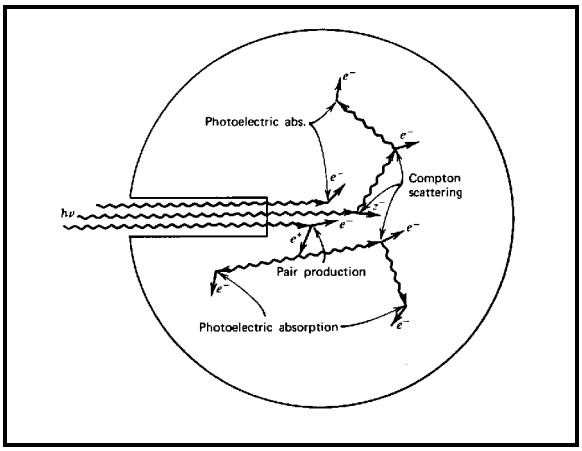

Fig. 2: "Large" detector

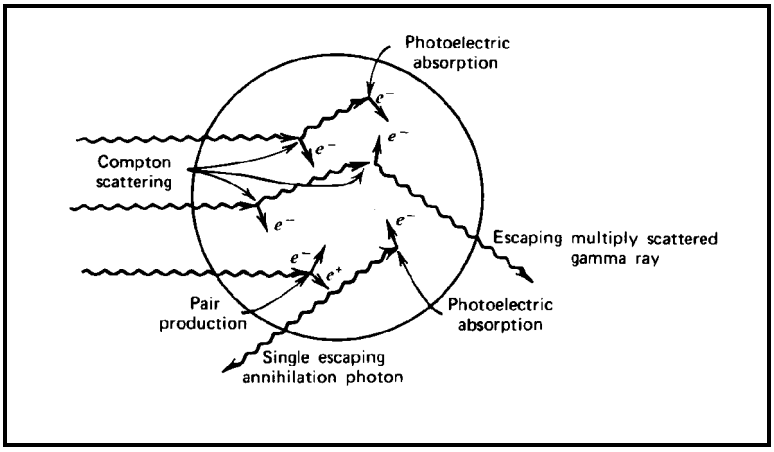

Fig. 3: Intermediately sized detector

1. What spectrum would you expect to result from a 2 MeV gamma-ray entering a small Ge detector? This would be best shown with a drawing. Repeat for a medium size and for an infinite size Ge detector.

2. What do the terms "live time" and "dead time" mean and how do they differ from "real time"? Why is it important to measure in units of live time?

3. What are the possible sources of error in using the Ge detector to identify unknowns?

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Lab #7 Neutron Activation Analysis

Objective:

To study the technique of isotope analysis by which a sample is subjected to neutron bombardment and the resultant radioactive nuclides are identified.

Theory:

An isotope of atomic mass A and atomic number Z when placed in a neutron flux will, in general, absorb a neutron to become the isotope (A+1, Z). Some resulting isotopes, being unstable, will decay, emitting one or more gamma rays with energies characteristic of the particular unstable isotope. The "activation" of the isotope is given by the expression:

$$N_{(A+1)} = \frac{\Phi \sigma_{aA} N_{oA}}{\lambda_{(A+1)}} \left[1 - e^{-\lambda_{(A+1)} t_R}\right] e^{-\lambda_{(A+1)} t}$$

and the activity is $dN_{(A+1)}/dt$, where Φ is the reactor neutron flux, σ_{aA} the cross section for neutron absorption, N_{oA} the atomic density of the isotope A, t_R is the irradiation time, t is the time after irradiation, and $\lambda_{(A+1)}$ is the decay constant of the active isotope.

A radioactive nuclide may be identified, therefore, by two separate types of information:

(i) the energies of the gamma full energy peaks produced by activation;
(ii) the half-life of each full energy peak produced by activation.

The figure for Φ at the position where the irradiation will be performed is $(5 \pm 1) \times 10^{12} n/cm^2/s$.

Experiment:

1. Set up the Multi-Channel Analyzer and the Ge detector. Before performing the activation, acquire a spectrum of the test sample to determine its original state of activity.

2. Irradiate the test sample in the reactor core for a fixed time period. Observing safety precautions, return with the sample to the measurement equipment.
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3. Acquire a test spectrum of the irradiated sample. You may need to attenuate the flux of β particles to avoid saturating the detector. Adjust the gain of the linear amplifier for optimum representation of the spectrum. (At some point, use two standard sources to calibrate the MCA for energy versus channel number.)

4. Fix the sample in relation to the detector.

5. Acquire a spectrum. Record:
   i) the time at which acquisition commences;
   ii) the channel number of all full energy peaks and other significant features (i.e., single escape peaks, Compton edges, etc.);
   iii) the integral for each full energy peak;
   iv) the channel number for the lower and upper edges of the "window" for each peak and the number of counts in each of these channels.

6. Repeat the above at regular intervals until the activity is significantly diminished.

Analysis:

1. Generate an Energy versus Channel # calibration curve for this set of data.

2. Use the energy peak information and the half-life information to attempt to identify the radioactive isotope(s) in the irradiated test sample. Correct for background. Use tables of natural isotopic abundance and activation cross sections to attempt to identify the original isotope(s) before activation.

Discussion:

1. By what steps would one determine not only the presence of various elements in an original unirradiated test sample, but each element's concentration.

2. The neutron flux of a nuclear reactor is inherently unstable as a function of time. While one experiment proceeds, other users' activities can change the flux shape or density. How might these variables be eliminated?

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General References

1. Knoll, Glen F., Radiation Detection and Measurement, 2nd Ed., John Wiley & Sons, Canada Ltd., 1989.

2. Crouthamel, C.E., Applied Gamma-Ray Spectroscopy, 2nd Ed., Pergamon Press, 1970.

3. Experiments in Nuclear Science, AN34 Laboratory Manual, 3rd Ed. revised, ORTEC, Oak Ridge, Tennessee, 1984.
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