ADVANCED UNDERGRADUATE LABORATORY

GE
The Germanium Spectrometer

November 2011

Revisions:
  November 2011: David Bailey
  May 2011: David Bailey & Jason Harlow
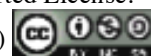 April 2011: converted to Word by B. Braverman
  January 2002: David Bailey

Outline

Germanium spectrometers are the highest resolution gamma-ray detectors in existence, and they are used extensively for both basic research and applied physics. The energy of gamma or beta rays can be measured with typical resolutions of 0.1%.

The goal of this experiment is to calibrate a germanium detector and to do one of several experiments. Possible measurements include (but are not limited to):

Basic Physics

Strong interactions

- Deuteron formation by neutron-proton strong interactions

- Nuclear interactions and excited nuclear states.

Electroweak interactions

- Beta decay spectra and searching for massive neutrinos.

- Energy loss of electrons in matter.

Applied Physics

Analyses of material composition and characteristics.

- Measurement of the thickness of thin films.

Measurements of environmental, geological, and industrial radioactivity

- Composition of uranium ore and the effect of refining.

- Radioactivity of dinner plates or air.

- Determination of the internal composition of a neutron source.

Detector Physics

- Physics of semiconductor radiation detectors.

- Positron annihilation

(These measurements are discussed in more detail starting on Page 10.)

Introduction

Germanium spectrometers are small, but very precise, electromagnetic calorimeters, i.e. they measure the energy of photons or electrons. Calorimeters and tracking detectors (e.g. drift chambers or bubble chambers) are the two major types of subatomic physics detectors. Germanium spectrometers are commonly used for a wide variety of low energy measurements, but they are too expensive (~$1k/cm^3) for high energy physics experiments that require very large calorimeters (~10^6 cm^3). Semiconductor tracking detectors are, however, very common in high energy physics detectors.

In intrinsic (ultra-pure) Germanium detectors, the kinetic energy of an electron is measured by collecting the electric charge produced by ionization along the path of the electron. The energy required to produce one electron-hole pair in germanium has an average value of about 3 eV. For example, a single 1 MeV electron track produces about 3×10^5 electron-hole pairs. It is possible to collect nearly all of these charges in a germanium detector if the impurities in the germanium have been essentially removed. The statistical variance in 3×10^5 pairs is so small that noise from random thermally excited electron-hole pairs is a major concern and is reduced by cooling the germanium crystal.

The energy of gamma rays can be measured in Germanium detectors because the energy of a photon can be transferred to electrons. Low energy gamma rays may be totally absorbed by the photoelectric effect producing a single electron with almost all the energy of the initial photon. The predominant interaction of gamma rays with germanium from about 100 keV to well above 1 MeV is through the Compton effect, so transfer of all the photon energy to electrons requires one or more Compton scatters followed by photoelectric absorption of the reduced energy scattered photon. Electron-positron pair production plays an important role at energies above $2m_ec^2$ (1.022 MeV). Cross sections for the basic quantum electrodynamic processes are discussed in Leo, the Review of Particle Physics, and Siegbahn.

Gamma ray spectra

When a nucleus undergoes beta or alpha decay, the final state nucleus may be in an excited state that then decays to the ground state by emission of one or more photons with specific energies. For example, when Cobalt-60 decays it turns into Nickel-60 in an excited state, which then decays to the ground state of ^{60}Ni by the consecutive emission of 1333 and 1273 KeV gamma rays. (See the Table of Isotopes for information on the decay of all known isotopes.)

Although the radioactive sources produce gamma rays of specific energies, the spectrum observed in a real detector is not simply a series of well-defined narrow lines. Figure 1 shows a typical spectrum for a single high-energy gamma ray. There are several processes that contribute to the observed spectrum.

The sharp full energy peak in the spectrum is due to gamma rays that have deposited all their energy in the germanium crystal. Low energy gamma rays are can easily transfer all their energy to an atomic electron in a single step by the photoelectric effect, but higher energy photons usually require several steps possibly involving Compton scattering, pair production, bremsstrahlung, positron annihilation, and the photoelectric effect.
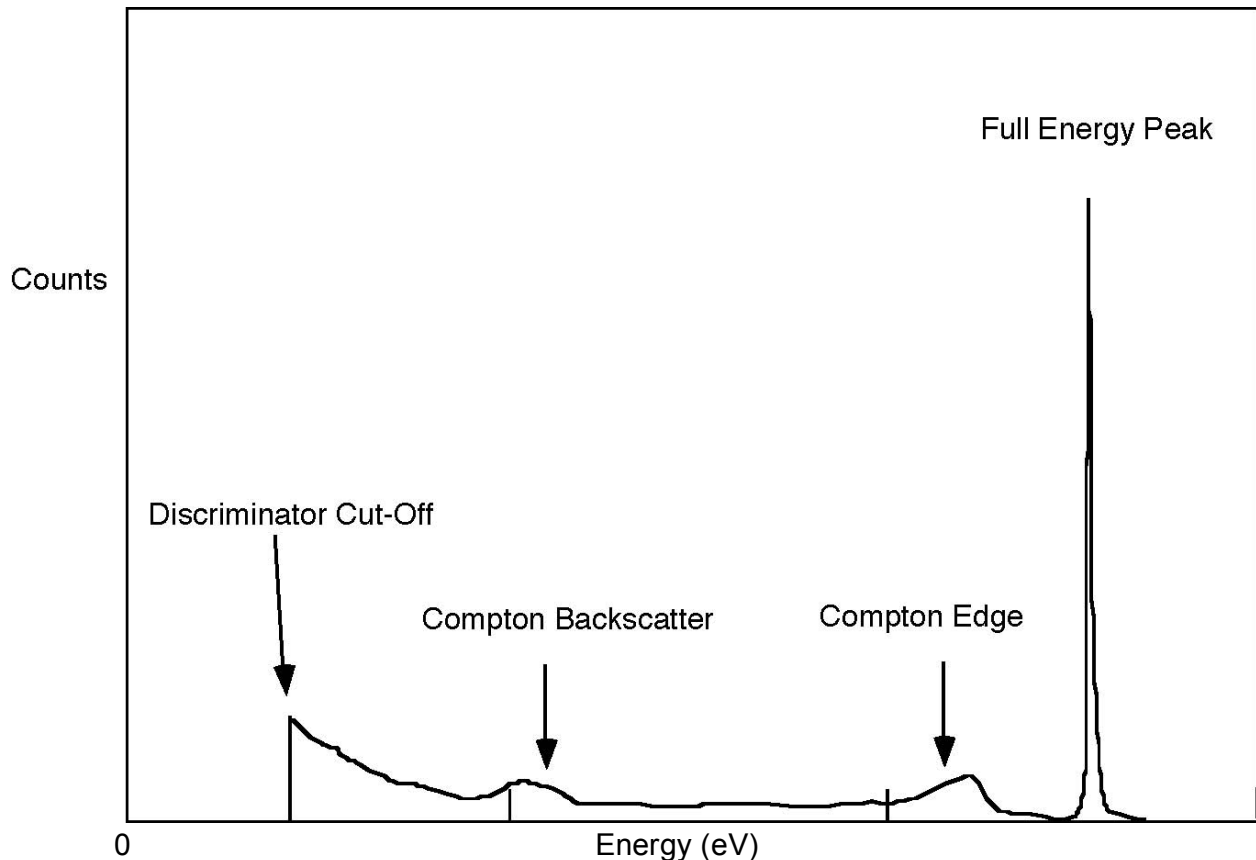
Figure 1: Sketch of a typical single gamma spectrum. A higher energy spectrum might include first and second escape peaks as well as a positron annihilation peak.

Compton scattering is the elastic scattering of a photon by a free electron. Atomic electrons can be considered as free electrons for gamma scattering if their binding energy is much less than the gamma energy. If a gamma photon Compton scatters inside the germanium and the scattered gamma is then absorbed by the photoelectric effect, then all the initial gamma ray energy is measured. If, however, the scattered gamma escapes the detector then only part of the gamma ray energy will be observed in the detector. The energy of the scattered photon can be anywhere between a maximum and minimum determined by relativistic kinematics and energy and momentum conservation. The differential Compton cross section has a strong peak at the maximum allowed energy transfer, so any gamma ray peak normally has an associated "Compton edge". A "Compton backscatter" peak is also sometimes seen from gamma rays Compton scattering from surrounding material into the detector.

For energies well above 1.022 MeV, the dominant photon scattering process in matter is pair production. Pair production only contributes to the full energy peak when both electron and positron stop in the sensitive volume of the Ge crystal and when the positron annihilation gamma rays are also totally absorbed. Since sometimes one or both of the (usual) two positron annihilation gamma rays escape the detector, high energy gamma rays typically have first and second "escape peaks" at 511 and 1022 kev lower than the main peak.

The rest of the spectrum is due to scattered and partially absorbed gammas as well as thermal noise and background radioactivity and cosmic rays.

General description of Germanium detectors

The set-up of a typical germanium detector is illustrated in Figure 2. The detector itself is sealed within a vacuum system and is attached to a *cold finger* that is in thermal contact with liquid nitrogen. Intrinsic Ge detectors are operated at liquid nitrogen temperatures for low noise performance, but they do not necessarily suffer if they are allowed to warm up slowly to room temperature. The detector is often shielded by lead to reduce the background from the natural radioactivity present in the air, walls, and floor.
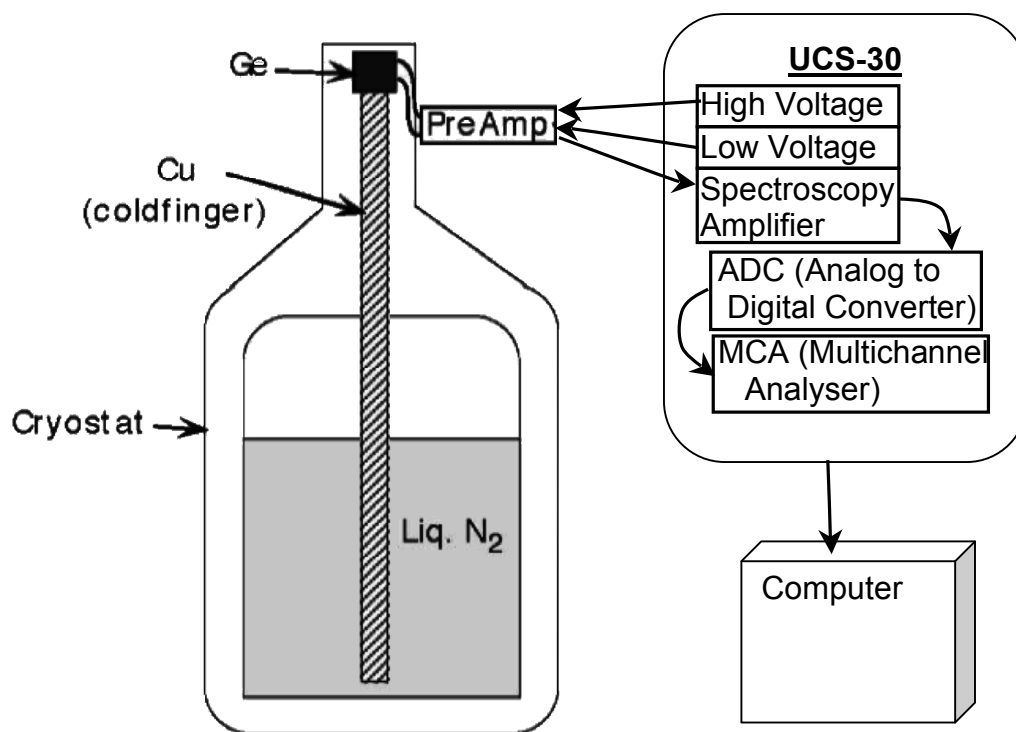

Figure 2: Germanium spectrometer. The crystal sits on a "cold finger" with the other end in direct contact with liquid N_2.

To collect the charge liberated in a germanium detector a voltage must be applied. The detector is equivalent to a p-n junction having a thick layer of pure germanium at the position of the junction. For operation as a detector it is back-biased in the sense of an ordinary diode and is a good insulator at liquid N_2 temperatures. The charges released by the ionizing radiation drift rapidly to the electrodes, typically in times from 0.1–3 μs (mobility ~4-7 m^2/V•s @ 77 K). A low noise charge-sensitive preamplifier is connected to the detector output. The input stage of the preamplifier must generally be cooled to amplify such small pulses without introducing too much noise. (For a 1 MeV pulse and a total capacitance of 5×10^{-11} F, only 2μV noise would be greater than the rms intrinsic resolution of about 0.1%.)

The output of the preamplifier is then fed to the UCS-30 data acquisition box whose first stage is a high quality linear amplifier for pulse shaping and further amplification. The amplifier output is fed into an Analog-to-Digital Converter (ADC) which sends digitized pulse amplitudes to a multichannel analyzer (MCA) for sorting.

The preamplifier attached to the detector should not require any adjustment, but the high voltage, amplifier settings and multichannel analyzer system may all need setting. Each of our

germanium detectors is different, so you should match your detector to the physics you wish to investigate (see the experiments starting on Page 10).

Setting the high voltage

The sign of the applied high voltage for a detector depends on the way in which it is connected inside the vacuum system and must be known before any voltage is applied. If you apply the wrong sign voltage, you may fry the detector (which costs about $20k). The UCS-30 controls the high voltage. **If you think the high voltage has the wrong polarity, check with the supervising professor or the lab technician, DO NOT CHANGE IT YOURSELF!** The maximum allowed voltage (and polarity) are indicated on a label on the preamplifier. **DO NOT EXCEED THIS MAXIMUM VOLTAGE!** The detectors are not too sensitive to voltage, as long as most of the electron-hole pairs released by primary ionizing radiation can be collected. A voltage about 90% of the maximum is typically a good choice.

Germanium detectors have been found in practice to adjust slowly to applied voltages. Therefore it is wise to switch on the voltage well in advance of making measurements whenever precision is desired; an hour should be sufficient for stabilization. The full voltage should not be turned on or off all at once. Nevertheless, a few seconds after the operating voltage is switched on it should be possible to make preliminary measurements.

Adjusting the UCS-30

Look at the output pulses of the preamplifier. The amplifier converts these long-tailed (~0.1ms) pulses into a pulse of a few microseconds duration suitable for analysis in the multichannel analyzer. Make sure the UCS-30 is in Amp In mode, and that the sign of the Amp In polarity (in the High Voltage / Amp / ADC settings) matches the preamp pulses.

Explore the menus to learn the device's capabilities, referring to the UCS-30 Manual as necessary. The amplifier gain, discriminator threshold (minimum allowed pulse size), and conversion gain (i.e. number of MCA channels) can be adjusted. Try different values of the amplifier Peak Time to optimize the resolution.

The resolution and degree of symmetry in the measured peaks are likely be somewhat worse at very high counting rates. A useful rule-of-thumb is not to exceed 10% dead-time according to the UCS-30 program. (The "dead-time" is the fraction of time that the system is processing data and is not available to record new data.)

UCS-30 software

The UCS-30 system has software for data acquisition and several of analysis and display options. For example, energies and counts of gamma ray peaks should be measured using Regions-Of-Interest, not by reading the pointer on the screen. The bin spacing for the MCA should be such that any gamma ray peaks of interest are spread over at least 3 bins, and the full range covers the energy range of interest. You can save your data as a tab separated file for offline precision analysis.

Numerical analysis of the peaks

In exceptionally fine spectrometers the peaks are essentially Gaussian, though this depends on the settings of the amplifier and on the count rates. Obtaining really symmetric peaks is more difficult at high count rates.

For a gaussian peak superimposed upon a continuum b_i, the count in channel i will be

$$c_i = n_{\text{peak}} e^{\frac{-(x_i - \langle x \rangle)^2}{2\sigma^2}} + b_i \tag{1}$$

By simple counting statistics, the fractional uncertainty in the total number of counts (c_i) in a bin is simply $\sigma_{ci} = \dfrac{1}{\sqrt{c_i}}$. If the number of background counts (b_i) is known with relative accuracy σ_{bi}, then $n_i = c_i - b_i$, the net count in channel i, is known with fractional accuracy

$$\sigma_{ni} = \frac{\sqrt{c_i + (b_i \sigma_{bi})^2}}{c_i - b_i} \tag{2}$$

The best estimate of the mean energy, $\langle x \rangle$, of the peak is readily obtained from by weighting the bin contents by the reciprocals of their squared fractional error, i.e.

$$\langle x \rangle = \frac{\sum\limits_i \left(\dfrac{x_i}{\sigma_{ni}^2} \right)}{\sum\limits_i \left(\dfrac{1}{\sigma_{ni}^2} \right)} \tag{3}$$

It is sometimes difficult to estimate b_i under a peak, but luckily small errors of judgment in estimating σ_{bi} or b_i are often insignificant.

The best estimate of the Gaussian width, σ, is given by the root mean square of $x_i - \langle x \rangle$:

$$\sigma^2 = \frac{\sum\limits_i \left[\dfrac{(x_i - \langle x \rangle)^2}{\sigma_i^2} \right]}{\sum\limits_i \left(\dfrac{1}{\sigma_i^2} \right)} \tag{4}$$

The best estimate of the uncertainty in $\langle x \rangle$ is given by

$$\sigma_{\langle x \rangle} = \frac{\sigma}{\sqrt{\sum\limits_i \left(\dfrac{1}{\sigma_i^2} \right)}} \tag{5}$$

If the spectral peaks are not Gaussian, a careful centroid analysis (equation 4) is still called for, with weighting given by equation 3. The determination of widths must be based on scientific judgment as it will depend on the line shape.

Detector Calibration

The detector must be calibrated using known gamma ray sources, for example ^{137}Cs, ^{60}Co, ^{22}Na, etc. (Note: The student must not use any radioactive material without receiving instructions on their safe use from the supervising professor.) These sources produce gamma rays at well-known and precisely measured energies. It is important to use such sources to determine the energy scale for subsequent measurements. A number of gamma rays present in the ambient room radioactivity (e.g. from ^{208}Tl, ^{214}Pb, ^{214}Bi, etc) also provide convenient calibration points. A smoke detector containing ^{241}Am can be used for a low energy calibration point. Some calibration gamma ray energies are given in Table 1; the energies and intensities of other lines

can be found in the CRC Handbook of Chemistry and Physics or in the Table of Isotopes. The UCS-30 allows you to roughly calibrate the spectrometer using 2 or 3 known gamma rays.

Source	Energy (KeV)	Intensity (%)
^{22}Na	1274.53(2)	99.944(14)
^{40}K	1460.830(5)	10.66(13)
^{60}Co	1173.237(4)	99.90(2)
	1332.501(5)	99.9820(10)
^{133}Ba	302.853(1)	18.33(6)
	356.017(2)	62.05(19)
^{137}Cs	661.660(3)	85.1(2)
^{208}Tl	583.191(2)	85.2(7)
	860.564(5)	12.53(10)
	2614.533(13)	99.16
^{214}Pb	295.213(8)	18.5(3)
	351.921(8)	35.8(5)
^{214}Bi	609.312(7)	44.8(5)
	1120.287(10)	14.8(2)
	1238.110(12)	5.86(8)
	1764.494(14)	15.36(20)
	2204.21(4)	4.86(9)
^{241}Am	26.345(1)	2.4(1)
	59.537(1)	35.9(4)

Table 1: Energies of some calibration gamma rays from the Table of Isotopes. The number in brackets is the error on the last digit(s), e.g. 122.0614(4) = 122.0614±0.0004, or 2614.533(13) = 2614.533±0.013. Only a few gamma rays are listed here for each isotope; more may exist.

Linearity of the spectrometer

It is essential to measure the linearity of the spectrometer in order to know how much to trust the calibration. The "integral nonlinearity" of the spectrometer is the systematic deviation from the straight-line relationship

$$E = A_0 + A_1 x_\gamma \tag{6}$$

where E is the gamma energy and x_γ is the channel number in the spectrum corresponding to the gamma peak centroid (see Page 7). Note that x_γ is not generally an integer. The value of A_0 is usually non-zero because the analyzer has a zero offset – one of the adjustments of the analyzer.

A measurement of the integral nonlinearity can be made as follows. Three known gamma rays are chosen which are roughly equally spaced in energy. Preferably one chooses gammas that bracket the range of energies of relevance for your physics measurements, but this may not be possible. The spectrometer is calibrated using the high and low energy gamma rays of the three, and then the energy of the middle gamma is then measured. The integral nonlinearity is now defined as

$$\left| \frac{E_\gamma - E_2}{E_3 - E_1} \right| \tag{7}$$

Where E_1 & E_3 are the **known** energies of the low and high-energy calibration gamma rays, and E_γ is the measured energy of the middle gamma ray of known energy E_2. In a modern gamma spectrometer the integral nonlinearity should not be greater than 0.07%. **If your instrument is much worse than this, draw this to the attention of the professor in charge.**

Another way to measure the non-linearity is to calibrate your detector using a linear fit to the maximum number of gamma rays allowed by the program. The gamma rays should be well distributed over the maximum possible range of energies. The difference between the fit value and the input (true) value of every point should be less than about 0.1% of the highest energy calibration gamma. A long run on the natural room background is an easy way to get a wide range of calibration peaks, once you have identified the room background peaks.

Any significant electronic nonlinearities are most often found in the first 7% and the last 20% of the spectrum, so it is a good idea to avoid using the highest and lowest channels.

A nonlinearity of 0.07% can introduce systematic errors in your measurements exceeding ±1 KeV, compared to statistical uncertainties as small as ±10 eV, so using a linear calibration formula can lead to systematic errors of more than 100 standard errors (statistical)! For high precision energy measurements, one may have to use a non-linear fit, but one should then use the maximum number of calibration points possible, and the lowest order polynomial consistent with the calibration data. A non-linear calibration can improve accuracy, but can also lead to big extrapolation errors, so only use a non-linear fit if you have to.

The energy calibration may need to be redone, and the detector settings adjusted for optimal performance, once you start working on your specific experiment. For some experiments the calibration needs only to be good enough to identify peaks, for other experiments the accuracy of your final results depend directly on the quality of your calibration and the resolution of your detector. If you are interested in specific energies, you should use calibration points as close to those energies as possible.

Efficiency of the detector

For some experiments you may need the efficiency of the detector for specific gamma rays. This can be measured by using radioactive sources of known strength. The original activity and date of manufacture of such calibration sources are known, and the current activity can be calculated using the half-life. The efficiency depends on the gamma energy, the detector, and the geometry of the measurement. The efficiency for a specific energy gamma ray can be interpolated or extrapolated from the efficiencies for the calibration gamma rays. Note: By combining measurements of calibrated low energy sources with measurements of uncalibrated sources with both low and high energy gamma rays, it is sometimes possible to avoid risky extrapolations. See Leo for a further discussion and typical germanium detector efficiencies.

The efficiency for non-point geometries can be calculated using measurements of the point calibration sources in different positions simulating the geometry. If you cannot tell exactly where the radioactive material is located within the source holder, repeating the measurement after inverting the source allows an appropriate averaging to be made.

Some experiments using a germanium detector

You should do one of the following experiments or an equivalent experiment arranged with the supervising professor.

You should read the descriptions of all the experiments, since **useful information is spread among all the descriptions**.

Note: *You should not do any measurement you have done as part of a previous lab in a previous course. Check with the supervising professor if you are unsure.*

A. Observation of deuteron formation by neutron-proton strong interactions

This experiment studies the binding of neutrons to protons by the strong nuclear force to form deuterons. The deuteron weighs less than the sum of its proton-neutron constituents, and the energy is released on formation by a single gamma ray.

The initial hydrogen target should be paraffin wax, composed of carbon and hydrogen. A special intense radioactive source provides the neutrons (see Experiment B). The source, the target, and the detector should be arranged in an "L" shape and shielded such that the source does not directly irradiate the Ge detector or the student (i.e. you), but neutrons can reach the target and gamma rays from the target can reach the detector. (Note that gamma rays interacting in the lead shielding can produce lead X-rays which may be observed.) The number of gamma rays produced is not large, so to see the signal you need a lot of hydrogen and good shielding to reduce the very large gamma ray background produced by the neutron source. **The experiment must be done with the large horizontal axial Ge detector.**

The basic technique is to look for gamma rays that only appear when the target is present. Such gamma rays are most likely produced by neutron interactions in the target. Since the target is not pure hydrogen, it is necessary to also take data with a second target that contains hydrogen but not carbon, e.g. water. The gamma ray line that is observed with both targets but not without a target is presumably from deuteron formation. Measure the energy released in deuteron formation to the best accuracy possible. It is interesting to compare your deuteron yield to a previous Toronto measurement by Taylor, Neff, & King[‡].

A possible extension of this experiment is to look for gamma rays produced by neutron capture by other nuclei. (If you used paraffin and water, you already have data in which you can look for carbon and oxygen capture. If you want to irradiate uranium, look at Experiment G.2.) Gamma rays will be produced if the capture of the neutron leaves the final state nucleus in an excited state; the excited state then decays to the ground state by emitting gamma rays. Gamma rays may also be produced if the final state nucleus is unstable and decays by beta or alpha emission. Prompt neutron capture gamma rays have energies up to 10 MeV, e.g. 4.4, 4.7, 6.8, and 7.0 MeV for boron.[†] You can increase the number of thermal neutrons by surrounding the source and target with a moderator such as paraffin. Identify the nuclear transitions producing any gamma rays you observe. If you don't see anything, quote an upper limit on prompt gamma production per nucleus compared to the rate for deuteron formation gammas from water in the same geometry and gamma energy.

B. The neutron source: Interactions, Excitations, and Decays

The neutron source is a powdered mixture of a heavy alpha emitter (plutonium) and a light target element (Boron). This mixture is permanently sealed inside a brass canister to stop the alphas, betas, and many of the photons produced, but most neutrons are not stopped. It is thought to produce about 10^4 neutrons /s, but it is not calibrated. Even with the brass shielding, the source is still relatively intense, so make sure it is properly shielded with lead when using it or when it is temporarily on a desk in the lab. The brass canister is pretty solid, but **don't drop it or try to open it**.

Measure the gamma spectrum of the source, and identify the processes and excited states inside the source. The goal is to understand every peak in your spectrum. e.g. What are the isotopes? What decays and interactions are occurring? What excited states are involved? Draw any interaction and decay chains. You may see gammas produced by interactions in the brass or lead shielding.

C. Beta decay of ^{90}Sr and the mass of the neutrino

In nuclear beta decays, the weak interaction transforms either an up quark into a down quark with the emission of a positron and an electron anti-neutrino, or a down quark into an up quark with the emission of an electron and an electron neutrino. Since the quarks are inside nucleons, this either transforms a proton into a neutron or vice versa. In this experiment the goal

[‡] H.W. Taylor, N. Neff and J.D. King "A new determination of the deuteron binding energy", Physics Letters 24B (1967) 659;
http://resolver.scholarsportal.info.myaccess.library.utoronto.ca/resolve/03702693/v24i13-14/659_andotdbe.

[†] Prompt Gamma Neutron Activation Analysis data are available at http://www-nds.iaea.org/pgaa/pgaa7/, e.g. Boron-10 data is at http://www-nds.iaea.org/pgaa/pgaa7/isol/B-10.htm.

is to measure and understand the beta spectrum of Strontium-90, and to use this spectrum to set an upper limit on the mass of the electron neutrino. At least some neutrinos have non-zero mass, but we don't yet know which ones.[‡]

The energy spectrum should be measured for a thin walled Strontium-90 (^{90}Sr) source and a Kurie/Fermi plot made (see, for example, Perkins or Frauenfelder & Henley). Explain the shape of your spectrum. (Note: Any radioactive atom will keep on decaying until it reaches a stable isotope, so make sure you include all decays that occur.)

Set the best possible limit on the mass of the electron anti-neutrino by studying the beta spectrum near the endpoint.[†] In order to do this analysis, you may need to transfer your data to another computer and use a spreadsheet or other mathematical analysis program.) Since the betas must pass through both the source and detector containers, you may want to consider if the energy loss of electrons in matter may affect your conclusions (See Experiment D).

D. Energy loss of electrons in matter and thickness of thin films

Ionization energy loss is the primary mechanism underlying most particle physics detectors. (See, for example, our "High Energy Physics" experiment.)

The ionization energy loss of electrons can be measured by measuring the shift in the energy spectrum observed when thin sheets of material are placed between a ^{90}Sr source and your detector. Thin sheets of aluminum, lead, various plastics, and other materials may be used. You should investigate how the energy loss depends on the electron energy and the type of material. Energy losses should be given in the standard units of MeV/gm/cm^2. Are your results consistent with the Bethe-Bloch energy loss equation? (See Leo, Perkins, Frauenfelder & Henley, or the Review of Particle Properties, which also contains minimum ionizing energy loss values for many materials.) You may need to consider the effects of multiple scattering or bremsstrahlung.

Energy loss, absorption, or scattering of alpha, beta, or gamma radiation are the basis for a wide range of gauges ranging from \$10 home smoke detectors to $\$10^5$ industrial thickness gauges. Now that you understand energy loss in matter, can you us it to measure the thickness of a piece of paper? (Poor quality control can cost a paper company big bucks, so people have become rich devising ways to monitor the paper as it rolls out of a mill at ~200m/minute.) Devise and demonstrate a scheme to measure the thickness of a typical piece of paper or similar material, and report the accuracy of your method. Your method may not be very accurate or fast using our low intensity sources, but industrial thickness gauges use much more intense sources (e.g. 100 mCi) which improve any method and allow low rate techniques such as backscattering. A final production device using your scheme will be less expensive and more compact if it does not require high resolution or fancy analysis, e.g. a method that just depends on one or two count rates, with possible upper and lower energy thresholds. You can use a source (e.g. ^{22}Na) with a lower beta energy than ^{90}Sr, but ^{90}Sr has the advantage of having no gamma rays.

[‡] K. Nakamura and S.T. Petcov, "Neutrino Mass, Mixing, And Oscillations", Review of Particle Properties (2010); http://pdg.lbl.gov/2010/reviews/rpp2010-rev-neutrino-mixing.pdf.

[†] O. Kofoed-Hansen, "Maximum β Energies and the Mass of the Neutrino", Physical Review 71 (1947) 451-452; http://prola.aps.org.myaccess.library.utoronto.ca/abstract/PR/v71/i7/p451_1 .

R.G.H. Robertson and D.A. Knapp, "Direct Measurements of Neutrino Mass", Annual Review of Nuclear and Particle Science 38 (1988) 185-215; http://resolver.scholarsportal.info.myaccess.library.utoronto.ca/resolve/01638998/v38i0001/185_dmonm.

E. Radioactivity in the air.

Most atmospheric radioactivity is due to natural radon gas, but nuclear accidents anywhere in the world may also produce observable radiation[†]. The radon level at any location depends on the amount of naturally occurring uranium and thorium[‡] in the local rocks and soil (see http://www.umich.edu/~radinfo/introduction/natural.htm), and on the local ventilation. Radon levels in buildings (especially basements) vary by up to 5 orders of magnitude. The short-lived radon decay products are in secular equilibrium, i.e. it is being produced as fast as it is decaying (see Chapter 1 of Leo, or any book on radioactive dating).

This experiment involves filtering atmospheric air using an air blower. A bit of thought about alpha or beta decays should convince you that radioactive decays will usually result in a charged ion, not a neutral atom. Such ions in the air will typically attach themselves to a dust particle, so by filtering the dust out of the air, a measure of the radioactivity can be made. (See, for example, Whyte and Taylor.[††])

Barring nuclear accidents, the observed radioactivity on the filter paper will be very similar to the natural room background radioactivity, so careful background shielding and monitoring is necessary. A background spectrum of at least 24 hours duration should be taken and all peaks in it should be understood.

The blower is usually hung outside from a window in the first year lab. The results for both amount and type of radioactivity generally depend on the length of time for filtration, and on the weather. As a comparison, also run the blower in a basement lab (consult the supervising professor for a good spot) or other interesting location. Do the radon levels differ? Are the different isotopes in the same ratios?

You should run the blower about an hour, but the optimum time depends on the lifetimes of the radioactive isotopes observed. To see the short lived isotopes, your counting equipment should be ready to receive the sample when you turn off the sampler, to minimize the time taken from when air sampling stops to when counting begins. All time intervals must be measured and your final results corrected for the finite lifetime of the observed isotopes. You should report the activity (Bq/m^3) of the air for any isotopes observed.

Inflated balloons[§], after charging by rubbing against (clean) hair, can also be used to collect radioactive ions from the air. You can try this method to crudely measure relative radon concentration in different locations.

F. Uranium

A plastic presentation case with Ontario uranium ore and uranium oxide powder is available. (Use only this sealed source; radioactive powder is very dangerous if breathed in.)

[†] Following the Chernobyl accident on 26 April 1986, air samples taken here in the Physics Department were found to contain ^{137}Cs, ^{134}Cs and ^{131}I. These products arrived quite suddenly on 11 May 1986.

[‡] See thorium and uranium decay chains at http://hepwww.rl.ac.uk/ukdmc/Radioactivity/UTh_chains.html.

[††] G. N. Whyte and H.W. Taylor, "A Radioactivity Experiment Using Activities Filtered from the Air", Am. J. Phys. 30 (1962) 120-124; http://dx.doi.org.myaccess.library.utoronto.ca/10.1119/1.1941929

[§] D. Austen and W. Brouwer, "Radioactive balloons: experiments on radon concentration in schools or homes", Phys Ed. 31 (1997) 97-100; http://iopscience.iop.org.myaccess.library.utoronto.ca/0031-9120/32/2/016.

Measure and explain the gamma spectra of the uranium ore and the uranium oxide. Can you estimate the percentage of uranium in the piece of ore? Can you measure both ^{235}U and ^{238}U?

Try at least one of the following:

(1) Pitchblende

Compare the Ontario ore with the piece of Bohemian pitchblende. (This piece is fairly radioactive; leave it in the taped up glass fronted box and take care not to drop it.)

(2) MicroCandu?

Nuclear reactors work because neutrons can induce fission of uranium, so it may be interesting to measure the gamma spectrum of the uranium oxide when it is being irradiated by our portable neutron source. (See Experiment A for an explanation of how to arrange the source, target, and detector.) Use paraffin as a moderator. Do the neutrons have any observable effect, or do we have too little uranium and too few neutrons?

(3) Radioactive Dinner

Currently the most common radioactive consumer products are smoke detectors, but in the past, uranium was commonly used to make bright orange glazes for ceramics. We have several plates purchased before such glazes were banned. Measure the radioactivity of a plate and calculate the amount of uranium in the plate. (Please do not drop the plates.)

Estimate the annual gamma dose received from the plate by someone who used the plate every day. The dose from gamma rays can be estimated from the formula:

$$D = \frac{2AE}{r^2} \tag{8}$$

where

D = Dose Rate (in μSv/hr)
A = the activity of the source (in MBq)
E = the total gamma energy emitted per disintegration (in MeV)
r = the distance from the source in metres

Note: To convert to traditional units (rem, Ci) to SI radiation units(Sv, Bq), use 1 Sievert (Sv)= 100 rem and 3.7×10^{10} Bequerels (Bq) = 1 Curie (Ci). Typical doses from natural radiation are a 1 or 2 mSv/year, but a few places have a natural background over 10 mSv/year.

The alpha and beta radiation from the plates is probably more dangerous than the gamma radiation, since this radiation is mostly deposited internally from uranium leached out of the glaze by acidic foods and then eaten. The alpha and beta dose depends on the unknown leaching rate and is hard to calculate. It is not safe to try to measure the leaching rate.

G. Semiconductor detector physics

Semiconductor detectors are important for measuring both the energy and the positions of subatomic particles. Germanium and silicon detectors are the highest resolution calorimeters used in nuclear physics, and almost all high energy physics collider experiments have silicon

vertex detectors. Current important areas of research on semiconductor radiation detectors include room temperature operation and radiation hardness.[†]

The observed width of a gamma ray peak comes from three sources:

(1) The natural line width, $\Gamma_{nat} = \hbar/\tau$ where τ is the mean life of the state from which the radiation is emitted. For a mean life of 10^{-17} s, $\Gamma_{nat} \approx 120$ eV FWHM (Full Width at Half Maximum). (For a Gaussian distribution, $\Gamma_{FWHM} = 2.35\,\sigma$, where σ is the standard deviation.)

(2) Noise in the preamplifier and other electronics contributes a constant line broadening Γ_{noise} which should be independent of energy.

(3) Counting statistics of electron-hole production in the semiconductor. It takes an average energy of $\varepsilon \approx 2.96$ eV to produce an electron-hole pair in a germanium crystal. The number of electron-hole pairs produced when a gamma ray is absorbed is

$$n = E_\gamma / \varepsilon \tag{9}$$

and the standard deviation is

$$\sigma_{stat} = F\left(\frac{\sigma_n}{n}\right) E_\gamma = \frac{F E_\gamma}{\sqrt{n}} = F\sqrt{E_\gamma \varepsilon} \tag{10}$$

Where the "Fano factor" F is a constant which corrects for the fact than ε is only an average energy which does not include the constraining effect of energy conservation on the fluctuations; the correct quantum statistics are too subtle to be easily calculated and so F must be measured. The Ge crystal typically contributes a full width at half maximum of very roughly

$$\Gamma_{Ge} = 1.3\sqrt{E_\gamma} \text{ keV} \qquad (\text{ for } E_\gamma \text{ in MeV}) \tag{11}$$

The total width is the quadratic sum of these contributions :

$$\Gamma^2 = \Gamma_{Ge}^2 + \Gamma_{noise}^2 + \Gamma_{nat}^2 \tag{12}$$

Γ_{nat} is usually small and can be neglected, so a plot of Γ^2 against E should give $F\sqrt{\varepsilon}$ and Γ_{noise}.

Measure the gamma peak energy resolution as function of energy for your detector. What are $F\sqrt{\varepsilon}$ and Γ_{noise} for your detector?

Measure the central value and width for several gamma rates at high and low rates. Are the central values or widths affected by the rate?

Measure the resolution, the calibration factor in channels/eV, and the efficiency for different voltages from almost zero up to the maximum allowed. What is the optimum voltage?

Measure the efficiency for your detector as a function of energy when the source is flush with the centre of the front face of the detector. (This maximizes the geometrical acceptance of the detector.) If the count rate is too high for some of your calibration sources, move the source back and use a weaker source to measure the geometrical scaling factor.

[†] See P. Luke and M. Amman, "Room-Temperature Replacement for Ge Detectors—Are We There Yet?", IEEE Trans. Nucl. Sci. 54 (2007) 834-842; http://www.nuc.berkeley.edu/courses/NE204/Papers/Luke_RoomTemperature_IEEE_2007.pdf.
  J.J. Velthuis et al., "Radiation hard diamond detectors", Nuclear Inst. and Meth. A 591 (2008) 221-223; http://resolver.scholarsportal.info.myaccess.library.utoronto.ca/resolve/01689002/v591i0001/221_rhdpd

H. Positron Annihilation

When a positron annihilates with an electron, two gammas are usually produced. This process is the strongest γ-ray line of astrophysical origin.

If an unbound electron and positron annihilated at rest into two gammas, the energy of each gamma would simply be half the mass of the electron-positron system, *i.e.* equal to the mass of the electron (or positron). In matter, positrons usually annihilate with an atomic electron so the annihilation is not likely to occur at rest. The resulting gamma rays will be Doppler shifted by a factor $(1 \pm v/c)$ which will broaden the line, and the line might also be shifted and broadened by the effect of the effects of the binding energy of the electron. (See, for example, the extensive measurements of Iwata, Greaves, and Surko[†].) The range of positrons from the most common β^+ source, Na-22, is small so they will usually annihilate in the plastic source disk, but you can try putting various materials (e.g. Lead) on top of the source to see if you can study annihilations in other materials. Measure the annihilation line with enough accuracy to estimate the speed and kinetic energy of the electron/positron system. Compare this energy to what you might expect for atomic electrons. Can you tell if the positrons are more likely to annihilate on inner or outer electrons? Is the central value of the line in agreement with the known value of the electron mass?

References

CRC Handbook of Chemistry and Physics, CRC Press. The 68th edition was used for this write-up. The newest electronic version is at http://www.hbcpnetbase.com/

H. **Fauenfelder** and Ernest M. **Henley**, "Subatomic Physics", 2nd ed., Prentice Hall (1991). [QC776.F723]

W.R. **Leo**, "Techniques for Nuclear and Particle Physics Experiments", Springer-Verlag (1994). [QC 793 .46 L46]

D.H. **Perkins**, "Introduction to High Energy Physics", Addison-Wesley (1987). QC 793.2 P47

"**Review of Particle Physics**", K. Nakamura *et al*. (Particle Data Group), J. Phys. G 37 (2010) 075021; http://pdg.lbl.gov.

K. **Siegbahn**, (editor), "Alpha, Beta- and Gamma-Spectroscopy", vol. 1 N-Holland (1965) pp 42-51,54, 62-9. [QC771 .S5]

"**Table of Isotopes**", 8th ed., J. Wiley (1996), editors: R. Firestone and V. Shirley, QD 601.2 F57 1996. This information is searchable online at http://www.nndc.bnl.gov/nudat2/.

UCS-30 Manual, Spectrum Techniques, http://www.spectrumtechniques.com/manuals/UCS30_Manual.pdf.

[†] K. Iwata, R.G. Greaves, and C. M. Surko, "γ-ray spectra from positron annihilation on atoms and molecules", Phys. Rev. A 55 (1997) 3586-3604; http://pra.aps.org.myaccess.library.utoronto.ca/abstract/PRA/v55/i5/p3586_1.