GAMMA-RAY SPECTRA: Looking at Radioactivity in our Environment

Objectives

- to recognize that each kind of radioactive nucleus emits an unique set of energies of gamma rays
- to become familiar with the use of an high purity germanium detector and multichannel analyzer to detect and determine the energies of gamma rays
- to be aware of sources of radioactivity around us by measuring the gamma rays emitted
- to identify the isotopes in these sources from analysis of the gamma ray spectra

References (available at the Resource Centre, MP229)

W.R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, (Springer-Verlag 1987)

*Tables of Gamma-ray and X-ray energies*, (compiled booklet available at the wicket)


Introduction

In this experiment you will be investigating the gamma-ray spectra from radioactive sources around us. Everyone doing this experiment will start by looking at characteristics of the detector and will calibrate the spectrometer (parts 1 to 4). We then provide a number of things that you might look at. These include:

- The phenomenon of backscattering
- The "natural" background radiation in the room you are working in
- Radiation from "Fiesta" ceramic tableware; beautiful colourful dishes produced in the 1950s which used uranium to colour their glazes
- Depleted uranium (DU), the same stuff that was used in anti-tank shells during the Gulf War
- Antunite or Pitchblende rock samples
- Gamma-rays from fireplace ashes taken from burnt older trees
- Gamma-rays from anything else that you bring in that you might suspect as being radioactive and would like to check-out for gamma radiation
- Spectral phenomena due to sum peaks
- X-ray fluorescence from lead

This is a two-or-more-weight experiment. You must do all parts 1 to 4, and as many parts of 5 to 13 as interest you. Do not proceed in the order of numbering of 5 to 13, as that order is arbitrary. Rather, pick out, in advance, the order in which you would like to proceed. The number of weights assigned will equal the number of lab sessions of serious work on the experiment that you do.

The Germanium Detector

The solid state Germanium γ-ray detector is a device that gives an electrical pulse output whenever a γ-ray is absorbed by the detector. The size of each electrical pulse is proportional to the amount of energy from the γ-ray absorbed by the crystal. The process has two steps: first, the γ-ray gives its energy to a charged particle (electron or positron); second, the charged particle slows down in the crystal and in so doing, produces ionization in the crystal. The number of ion pairs produced is proportional to the energy imparted to the crystal by the electron. There is a high voltage applied to electrodes attached to the crystal, and so the charge from all the ion pairs is directly collected on these electrodes.

In order to form a spectrometer, the output of the detector is fed into an amplifier (to shape the pulse and
make it larger) and then into a multi-channel pulse height analyzer (MCPHA or MCA). The MCA analyzes each pulse that enters it and produces a histogram of numbers of pulses that have been received vs. pulse height voltage. The spectrum thus displayed is really an energy spectrum.

The shape of the gamma-ray spectrum
It would be most pleasant if all the energy of all γ-rays were always converted into electron energy which always produced ionization in the crystals. Unfortunately the mechanisms involved aren't quite so fair. There are 3 mechanisms by which photon (γ-ray) energies are converted to electron energies:

- **Photoelectric effect**: The photon is absorbed by a bound electron in an atom so that the electron leaves the atom with a kinetic energy equal to the photon energy less the electron's binding energy. This process is prevalent for photon energies less than ~150 keV.

- **Compton Effect**: The photon collides with an unbound electron (or an outer electron in an atom which has a binding energy much less than the photon energy). This resembles an elastic billiard-ball collision in which the photon leaves the collision with reduced energy and the rest of the original photon's energy becomes the kinetic energy of the electron. This process is prevalent for photon energies between ~150 keV and ~8 MeV.

- **Pair production**: The photon, in the vicinity of a nucleus, loses all its energy in the production of an electron - positron pair. The total kinetic energy of the electron plus positron is the photon's energy minus the rest-mass energy of the electron plus positron. \((2m_e c^2 = 2 \times 511 \text{ keV})\). This process is prevalent for photon energies greater than ~8 MeV.

![Fig. 1 Idealized γ-ray spectrum showing only the full-energy peak](image)

Most radioactive sources emit highly mono-energetic γ-rays, *i.e.* the spectra consist of series of γ-rays with highly-defined energies. The "width" or variation in energy of γ-rays emitted is generally much less than an eV for photons with energies of the order of MeV. In the "most pleasant" scenario quoted above (all the energy of all γ-rays being always converted into electron energy which always produce ionization in the crystals) a \(^{137}\text{Cs}\) spectrum would appear as in Fig. 1. \(^{137}\text{Cs}\) emits only one energy of γ-ray, at 661.661 keV. Such a peak in the spectrum is called the *full energy peak* and can be the result of all the above three processes provided that eventually all the energy is absorbed in the crystal. *(e.g., If Compton scattering occurs, not only must the Compton scattered electron be stopped in the crystal so that ion pairs are produced, but also the outgoing photon must also undergo successive photoelectric effect or Compton scattering or pair production inside the crystal so that in the end, all the energy produces ionizations in the crystal.)*

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In reality, γ-ray spectra more resemble Fig. 2. The Compton plateau is the result of only part of the photon’s energy being absorbed in the crystal. In this case, the incoming γ-ray undergoes a Compton scattering, and the lower energy outgoing photon leaves the crystal, so that a lesser amount of energy is actually absorbed by the crystal. For one Compton scattering, simple kinematics (conservation of energy and momentum) forbids the electron from receiving more kinetic energy than

$$E_{\text{max}} = \frac{2E_\gamma^2}{m_\text{e}c^2 + 2E_\gamma}$$

$E_{\text{max}}$ is called the Compton edge, $E_\gamma$ is the energy of the γ-ray and $m_\text{e}c^2$ is the rest-mass energy of the electron. $E_{\text{max}}$, the maximum energy transfer corresponds to an angle of scattering of the photon through 180°. A 180° scatter transfers no energy. Compton scattering is a slowly varying function of angle and so there is a distribution of Compton events of energy less than the Compton edge.\(^1\)

A further departure from the "most pleasant" case produces a γ-ray spectrum in which each single peak is replaced by three peaks, one at full-energy, one at full-energy less $m_\text{e}c^2$ (= 511 keV), and one at full-energy less $2\times m_\text{e}c^2$ (= 1022 keV). This occurs when the photon entering the crystal produces an electron positron pair. When the electron and positron get stopped in the crystal, they lose all their kinetic energy to the crystal which is the γ-ray energy less ($2\times m_\text{e}c^2$). The positron then annihilates with an electron producing two photons, each of energy $m_\text{e}c^2 = 511$ keV. If these two photons leave the crystal, then the total energy absorbed in the crystal is $E_\gamma - 2\times m_\text{e}c^2$. If the energy of one of these photons is absorbed in the crystal, then the total energy absorbed in the crystal is $E_\gamma - m_\text{e}c^2$. And if both of these photons are stopped in the crystal, then the total energy absorbed in the crystal is $E_\gamma$. Clearly this process can only take place for $E_\gamma$ greater than $2\times m_\text{e}c^2$.

**Scattering outside the crystal**

Any photons scattered into the crystal by the shielding material, table tops, holders, source backing, etc., will have less than the full energy of the original γ-ray and this process will give rise to a general distribution of pulses across the Compton plateau. However, the kinematics of the problem together with the angular probability of scatter tends to produce a bump on the low energy part of the spectrum which is called the

\(^1\)You might try substituting some numbers into the equation for $E_{\text{max}}$ to find where you would expect the Compton edge for your sources. E.g. for the $^{137}\text{Cs}$ 662 keV gamma-ray, $E_\gamma = 1.3\ m_\text{e}c^2$, $E_{\text{max}} = 0.93\ m_\text{e}c^2 = 477$ keV, about 72% up the spectrum.
backscatter peak. Even if the holders of the source are removed and the detector is moved far from the table top, this peak, although smaller, still occurs from backscattering within the source itself and also from gamma rays that pass right through the crystal and are scattered back into the crystal from surrounding matter.

Statistical Variations in Pulse Height
The line (peak) shape and width (resolution) of the pulse height distribution are influenced by statistical fluctuations in the number of ion pairs produced in the germanium crystal. The idealized pulse height spectrum of Fig. 2 gets smeared out resulting in a spectrum similar to Fig. 3. The extent of smearing is represented by the resolution, the full width at half maximum, of the full-energy peak. Convention has it that what is called the resolution of a γ-ray detector is the full width at half maximum of the 1.333 MeV γ-ray from $^{60}$Co. Typical resolutions for the detectors used in this lab is about 2.5 keV.

![Fig. 3 A typical $^{137}$Cs γ-ray spectrum](image)

**What to do**
1. **Look at your apparatus** (see Figure 4 below)
Observe the Germanium detector. There is available (at the Resource Centre, Room 229) a cut-open damaged germanium crystal that you can look at. Also, notice the arrangement of the actual detector, with its liquid nitrogen refrigerant, and with its built-in preamplifier. Read the W.R. Leo reference to figure out how the detector works.

![Fig. 4 The experimental arrangement](image)
**Apparatus Notes**
The main components of the experimental system are:
- Metal enclosed Dewar containing liquid nitrogen;
- Lithium-doped germanium detector element in a thin walled aluminum cylinder, attached to top of Dewar.
- Adjustable, detachable sample holder mounted above the detector.
- Preamplifier module directly attached to detector module.
- Pulse amplifier, analyzer and high voltage power supply unit on bench and connected to preamplifier and computer (Spectech Universal Computer Spectrometer UCS-30)
- Oscilloscope to monitor gamma detection signals coming from preamplifier (Tektronix TDS 210).
- Software (UCS30 ) for controlling the gamma detector analyzer system and for recording and analyzing all experimental results
- Various known and unknown, low level emitters of gamma rays.

The apparatus is normally left fully connected on the laboratory bench, so do not rewire it without good reason.

**Startup and close down**
To turn the system ON, do the following (order is important):

2. Open the Spectech software (UCS 30) on the computer and find upper line of “menu” items and “tool bar” of control icons just beneath.
3. Open first the “Mode” menu and select the “PHA(Amp In)” option (using the Spectech as a pulse height analyzer with the unit’s pulse amplifier connected between the analyzer and the detector’s preamplifier). This tells the Spectrometer system the detector’s signal will enter via the unit’s “amplifier” BNC connector.
4. Click on the lightning flash icon (or select the “settings” menu and Amp/HV/ADC) to see the device settings menu. Here you set various analyzer device parameters. You may not need to change them during your set of experiment, except for the high voltage on-off.

Good starting settings for this apparatus are:
- High voltage: 1000V positive; ON (except when apparatus is not in service)
- Amplifier: Gain 2-4, Input polarity: negative, Fine gain 1 (as low as possible)
- Analyzer resolution: 1024 for quick tests (to 4096 for very precise spectroscopy)
- Discriminator limits: Lower (LLD), min (1.3); Upper (ULD), max (102.3)
- Peak time, 1 microsecond

Set up the oscilloscope. The following settings are usually good for a start:
- Vertical display Ch1 [DC coupling]: Sensitivity: 100mV/Div.
- Time base: set to about 10 ms/Div.
- Trigger mode: [Edge, Falling, Ch 1, Normal, DC]. Trigger level arrow on screen should be adjusted to just below zero, so repeated sweeps are seen.

When finished using the instrument:
- Make sure that data acquisition has been stopped.
- TURN OFF THE HIGH VOLTAGE; THEN CLOSE THE SOFTWARE.
- Turn off the Spectrometer and the Oscilloscope.
2. Observing pulses from the detector
When turning ON the spectrometer, notice that the High Voltage light is green – this indicates that the detector is ready but that no high voltage is being delivered yet. The Activity light should also be flashing. Now you can turn on the oscilloscope and look at some pulses. Without any radioactive sources, use a time scale of about 10 ms/cm, set the trigger level until you start to see occasional pulses. Each sharp negative step down corresponds to a gamma capture in the detector, with the height of the step indicating the captured energy. The Analyzer is continuously making digital measurements of amplitude at a fast rate, differencing the measurements over a 1 microsecond interval and recording any cases where the differences are between the LLD and ULD limits. (Limits are expressed as rough percent (1/102.4) of the analyzer’s full digital range.). The recorded events are displayed as histograms on the screen.

Note: Observe what happens to the pulses when the high voltage has been turned on. Since there are no radioactive sources near the detector yet, where do you think these pulses are coming from? You can now use a radioactive source. Bring a $^{137}\text{Cs}$ source close to the detector. Start by holding the source at a distance of about 50 cm from the detector, and slowly bring it in closer. What happens to the pulses? You can control the distance between the source and the detector using the cylindrical holder. It is held in place by a white plastic screw, and can be slid up and down if the screw is loosened.

3. Observing a Cs137 spectrum
In order to start gathering data with the UCS30 Spectrum Analyzing software, it is important to understand how the software interacts with the output from the detector. The spectrometer is a device used for analyzing the distribution of the pulses generated by the detector. When the software is on Data Acquiring mode, each pulse seen by the Spectrometer is sorted into one of the 4096 channels displayed on screen based on the pulse height (Voltage Amplitude). Therefore, each channel corresponds to a different Voltage Amplitude. If you see an energy scale being displayed on the bottom instead of channel numbers, go into <Settings – Energy Calibrate – Uncalibrate>. Thus, after data is accumulated for some time, the number of counts in each channel represents the total number of pulses which had the corresponding amplitude observed during that time. Since the amplitude of each pulse is directly proportional to the energy of the gamma ray that generated the pulse, the software therefore displays (roughly) a spectrum of the energy of the photons coming into the detector, which represents the number of gamma rays vs. the gamma ray energy.

If you go into Settings – Amp/HV/ADC, you can change the amplification of the pulses performed by the Spectrometer. This amplification changes the amplitudes of the pulses by a factor of Coarse Gain x Fine Gain. What do you think the effect of changing the amplification has on the spectrum distribution? A good starting setting is Coarse 4 and Fine 1.5 (Total gain of 6).
You are now ready to start gathering data. Position the $^{137}\text{Cs}$ source on the holder, clear the current spectrum (if there is anything displayed on the screen) using the eraser icon on the toolbar, and click on the <Go> button. The spectrum you see should resemble Fig. 3. You might notice that the spectral curve has random fluctuations in it. This is the result of the randomness of the radioactive decay process. The expected fluctuation (uncertainty) in observing $n$ decays is the Poisson fluctuation, which corresponds to $\sqrt{n}$. Therefore, the relative (percentage) uncertainty on the number of counts goes as $\frac{\sqrt{n}}{n} = \frac{1}{\sqrt{n}}$. This relative uncertainty goes down as the number of counts goes up, therefore, you should expect the spectrum to look cleaner (have less fluctuations) the longer you collect data for. When you have acquired enough data, click on the <Stop> button to stop the data acquiring process. Note that you can change the x and y scales using the Y log button (which changes the y scale from linear to
logarithmic) and the two X buttons on the toolbar (which zoom in/out) around the point you click on.

4. Calibrating the Spectrometer

As you want to use the apparatus as a spectrometer which indicates counts as a function of energy, you need to provide an energy calibration (i.e. which channel corresponds to which energy). To perform the calibration, you will use different radioactive sources which emit gamma rays of energies shown in the following table.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life (years)</th>
<th>Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹³⁷Cs</td>
<td>30.17 y</td>
<td>661.661 keV</td>
</tr>
<tr>
<td>⁶⁰Co</td>
<td>5.271 y</td>
<td>1173.238 keV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1332.513 keV</td>
</tr>
<tr>
<td>¹³³Ba</td>
<td>10.7 y</td>
<td>80.999 keV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>356.014 keV</td>
</tr>
</tbody>
</table>

In order to calibrate the spectrometer, you need to identify which peak belongs to which gamma ray emitter. The calibration in the UCS30 software uses three points in the energy vs. channel space to relate the two quantities. The simplest calibration to perform is using both the ¹³⁷Cs source and the ⁶⁰Co source at the same time, as they provide 3 very distinct gamma ray energies (you might want to use a log scale as it makes the smaller peaks easier to see). Following the procedure highlighted in 3, gather data for the 2 sources until you can clearly see the three peaks.

To find the correct channel value corresponding to each peak, you need to define a Region of Interest (ROI). This is done by accessing the <Settings-ROI-Set ROI>. Click and drag the mouse cursor around the peak you are interested in (try to catch the entire peak and start and finish at symmetrical points around it as this will yield a better Centroid reading). Repeat the procedure for the other 2 peaks. Notice that you can select a particular ROI by clicking on it, and that the software displays some of the information about the shape of the peak on the bottom right: it’s Centroid and the Full Width at Half Maximum (FWHM).

You are now ready to calibrate. You can begin the calibration with <Settings – Energy Calibrate – 3 points>. It will ask what units you want to use, choose KeV (kilo electron volts). Then you will need to specify 3 channel numbers and the 3 corresponding energies. The best way to do this is to click on a ROI while you dialog window is up – this will automatically insert the Centroid of the chosen ROI as a calibration point. Enter the gamma ray energy that corresponds to the ROI you’ve chosen, and repeat for the 2 following points. As you can see, the bottom scale will now display correct energy readings.

Note that, as you probably won’t see any gamma rays with energy higher than 1500 KeV, that the higher half of your energy scale will not contain anything interesting. It is a good idea (but it is not required) to increase the amplification (gain) in the <Settings – Amp/HV/ADC> menu so as to re-scale your energy scale in order to “spread” your spectrum. This allows for better visibility of the important features of your spectrum. Note that you will need to re-calibrate your detector with a new data run if you choose to change the gain. In the end, record your preferred gain value so that you don’t have to go through the entire procedure the next time.
You can save your spectra to your Faraday account using <File – Save>, and choosing <My Network Places – Entire Network – Microsoft Windows Network – Pin – Upscale Samba Server (Faraday)>. You can also print whatever is on the screen using <File – Print…>.

Functions of the UCS30 Software
In the following experiments, you will be asked to study your spectra using a few different functions of the software. Here is an explanation of how to use some of these functions. Also, do not hesitate to explore the program, as it contains a few interesting features which will not be explained here.

Comparing Spectra
You can compare two different spectra on the same screen by saving both of them to a file. Open one of the files and choose <Strip Background – Load Background > and choose the other file. You can display either or both spectra on the same screen using the <Strip Background – Show Spectrum / Show Background / Overlay Spectrum and Background>.

Full Spectrum Background Subtraction
This function is used when you've saved both a “background” spectrum and a “signal” spectrum and you want to remove the background from the signal. This can be better explained by an example: if you saved a “background” spectrum using no radioactive sources and then added a $^{137}$Cs source to measure a “signal” spectrum, doing a background subtraction would remove everything but the contributions from $^{137}$Cs, and give you something like Fig. 3. This is done by opening your “signal” spectrum and then loading your “background” spectrum using <Strip Background – Load Background>. You can then perform your background subtraction by using <Strip Background – Strip Background from Spectrum >. This will perform a direct subtraction of the number of counts in each channel between the “signal” and “background”. Note that this means that you are expected to have run the “background” and “data” spectra collection for the exact same time period! You can do this using a preset, as explained below. Otherwise the subtraction will not make any sense (i.e.: the software does not perform any normalization!).

Changing the Discriminators
The spectrometer can only process a certain number of pulses over a given period of time. If it receives more than that amount, it will begin missing some pulses (this is called dead time: a percentage of the time when the spectrometer becomes unresponsive to input pulses). Since electrical noise generates a lot of counts in the low channel region (Do you have any idea why?), these counts will increase the dead time and impede the performance of the spectrometer. Therefore, the software uses a discriminator, a lower and upper limit to the channels over which it will not consider pulses. Therefore, no pulses in the channels under the lower level discriminator (LLD) and no pulses over the upper level discriminator (ULD) will be processed by the spectrometer. This is why you can see a small gap with no entries on the leftmost part of the spectrum. You can change these values by going into <Settings – Amp/HV/ADC>.

Using Presets
If you want to collect a set amount of data, you can use the presets available in the <Settings – Presets>. By choosing either Time or Integral Counts, you can force the software to stop collecting data after a set amount of time has elapsed, or until a set amount of counts have been recorded. Note that the Time menu offers two choices: Live Time and Real Time. Live Time corresponds to the amount of time when the spectrometer is recording data, i.e.: Real Time - Dead Time (dead time is explained in the section above). It is a better estimate of the amount of data collected than Real Time.
5. Backscattering of Gamma-rays
If you place the source about 10 cm away from the detector, and place a material of high atomic number, such as lead, at the back of the source (on the side away from the detector) you can observe gamma ray that came off the back of the source now being scattered back into the detector by the lead, having lost energy on being scattered. You may observe these backscattered gamma rays using the $^{137}$Cs source of section 3 and taking and saving two spectra, one without the lead scatter and one with it in place. You only need to count about 5 or 10 minutes to acquire sufficient statistics to see backscatter. Compare the two spectra using the method highlighted in the Interlude.
For $^{137}$Cs on lead, you should see backscattering spread around 150 keV to 300 keV. If you do see additional sharp peaks below 90 keV, it is probably from x-ray fluorescence in the lead. See part 13 below for details.

6. Observation of background Gamma-rays in the room
You are now ready to use the spectrometer to identify some unknown radiations. One interesting measurement is that of the room background. As the background levels are low, you will have to count overnight in order to obtain a spectrum that is statistically precise. Because of the large number of lab sessions that may use the apparatus, we have provided a booking list at your apparatus. Find what time slot is available, and start your data collection at the beginning of that time. See Appendix 1 for the procedure for automatic save collect and save. Please book the apparatus for overnight use on the sign-up sheet at the apparatus and put a "do not touch" sign on the apparatus. You will be able to come back any time after the save time to transfer your data into your own file area. Make sure that there are no other radioactive sources in the room during collection as they may show up in your spectra.
Your data analysis involves looking at the spectrum and identifying each peak by forming a ROI for each one. You can check which peak corresponds to which gamma ray by looking on the isotope identification using the "Tables of Gamma-ray and X-ray energies" reference. Whether what you see makes sense can be judged by considering the following section.

Understanding what you find in the radioactive background
There are various radioactive isotopes in our environment. Some are manufactured, using nuclear reactions as found in nuclear power reactors or nuclear weapons explosions, or by bombarding nuclei using particles from an accelerator. Intentionally produced isotopes are found in the radioactive sources you will be using to calibrate your spectrometer. Unintentionally produced isotopes were found in quite measurable levels following the large scale nuclear bomb testing that fortunately ended in 1963. The nuclear reactor accident at Chernobyl in Ukraine widely spread radioactive particles. (In this lab we sampled air following that accident in May 1986 and measured gamma rays from dust on filter paper from $^{131}$I (8 day half-life), $^{134}$Cs (2.1 year half-life), $^{137}$Cs (30 year half-life). Air samples taken this current year show none of these.
Other radioactive isotopes occur naturally. Some are currently present because they were formed by the stellar nuclear reactions from which the materials of our planet originate and have half-lives comparable to the age of the solar system. Examples of these are $^{40}$K (1.3×10$^9$ year half-life), $^{232}$Th (1.4×10$^{10}$ year half-life), $^{235}$U (7.0×10$^8$ year half-life) and $^{238}$U (4.5×10$^9$ year half-life).
The three long-lived parent isotopes $^{232}$Th, $^{238}$U, $^{238}$U are already mentioned above. Their sequences of daughter products are indicated in the footnote.²

²Products of $^{232}$Th decay are $^{228}$Ra, $^{228}$Ac, $^{228}$Th, $^{224}$Fr, $^{224}$Ra, $^{220}$Rn (an inert gas), $^{216}$Po, $^{212}$Pb, $^{212}$Bi, $^{212}$Po, $^{208}$Tl, $^{208}$Pb.
Products of $^{235}$U decay are $^{231}$Th, $^{231}$Pa, $^{227}$Ac, $^{227}$Th, $^{223}$Fr, $^{223}$Ra, $^{216}$Po, $^{212}$Bi, $^{212}$Po, $^{208}$Pb, $^{207}$Tl, $^{207}$Pb.
Products of $^{238}$U decay are $^{234}$Th, $^{234}$Pa, $^{234}$U, $^{230}$Po, $^{226}$Tl, $^{226}$Pb, $^{222}$Rn (an inert gas), $^{218}$Po, $^{214}$At, $^{214}$Rn (an inert gas), $^{210}$Pb, $^{210}$Bi, $^{210}$Po, $^{206}$Hg, $^{206}$Tl, $^{206}$Pb.
The footnote, with its listing of 45 products of the decay chains, is provided here to help you see the reason for finding gamma rays from various isotopes when counting the radioactive background in the room. Note that the presence, in all three chains, of the inert gas, radon (\(^{222}\text{Rn}\)), is the reason that several of these products appear in the air around us. The radon provides a way that products after radon appear in the air around us, as radon can diffuse through the earth into the air without being caught to form a chemical compound, and then it can decay.

7, 8, 9, 10 & 11: Other Gamma-ray emitters
To do any of the following, you will use the approach outline before (Observation of Background). As indicated in the Introduction, there are other items that emit gamma rays that you might want to count. If they are weak emitters, you will probably put them as close to the detector as possible. However, if the "dead time" is greater than 5\%, you should move the sample further away from the detector\(^3\). In weaker samples, a number of peaks you measure will probably come from the background. This is particularly important for the fireplace ashes (part 10) and for the "anything else" (part 11) which are very weak sources. If you have already made background measurements, and provided that you have kept the amplifier and high voltage settings the same and are using the same detector, you can use your background spectrum for subtracting the background radiations. If you haven't already measured the background, you will have to count the background for at least as long as you count the particular sample. There are two approaches to background subtraction.

a) - Background subtraction by using ROI counts
In this approach you count the new spectrum, create ROIs for all the peaks, identify those peaks, and find the net counts in each peak. Then you use the net counts in each ROI of background peaks that you identified in part 6, and normalizing these net counts to the live times\(^4\), you can subtract off the background.

b) - Background subtraction by subtracting full spectra
To perform this, follow the instructions given in "Functions of the UCS30 software".

7. The "Fiesta" Tableware and its Gamma Rays
In the 1960s, a line of dishes under the name "Fiesta" appeared in the US. They were very attractive and had brilliantly coloured glazes. It turned out that nobody did a health check on them; the glazes contained uranium and thorium (probably no more harmful than eating off glazes containing lead). We have managed to get some of those dishes. Identify what radioactive isotopes are in the plates.

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\(^3\)If you don't understand "dead time", look at the W.R. Leo reference or ask your demonstrator.

\(^4\)To normalize the background peaks, multiply their net counts by the ratio of the live time of the new spectrum to the live time of the background spectrum.
The expanded form of footnote²
8. Gamma Rays from Depleted Uranium
Depleted uranium, which gained fame in the Gulf War, is mostly $^{238}$U left over when most of the fissionable $^{235}$U, which is naturally found in the uranium ore, is removed to be used in reactors or bombs. $^{238}$U emits mainly alpha particles (against which we have shielded in the casing of the sample). However there are gamma rays emitted by the daughter products in the decay. Identify which daughter isotopes produce those gamma rays.

9. Radioactive ore - antunite and pitchblende rocks
Pitchblende and antunite are naturally found ores. Pitchblende was the ore Marie Curie refined when she first identified radium. Identify the gamma rays from one or both rocks and indicate what isotopes they come from.

10. Wood fire ashes
The ashes in the jar are taken from a woodstove that burned 50-year-old elm. What activities do you find and why do you think they are there? You may have to count the ashes overnight, do background subtraction and pay attention to having no other sources in the room.

11. What else?
Do you have any objects that you would like to check to see if they emit gamma rays? Bring them in and count them.

12. Sum Peaks
If two $\gamma$-rays enter the detector within a time interval short compared with the amplifier pulse output length, then the pulses pile-up on top of each other and a sum peak appears as if at an energy equal to the sum of the two individual $\gamma$-ray energies. Sum peaks are usually very weak, broad and skewed. Using $^{137}$Cs, see what peaks you can find other than the 662 keV $\gamma$-ray. Can you explain the shape of that spectral peak? Observe the pulses on the CRO that produce these peaks. Note that the higher the counting rate, the more pile-up you will observe. (You probably will want to put the source directly against the detector.) Note what happens if you increase the source-detector distance. Also $^{133}$Ba is another handy isotope for observing sum peaks. At high counting rates, the complex abundance of seven $\gamma$-ray lines plus an x-ray line gives rise to various other pile-up peaks. You might also look for sum peaks in $^{60}$Co.$^5$

13. X-ray Fluorescence
X-ray fluorescence occurs when high energy photons are made incident on a target material and these cause K-shell electrons to be ejected from the target. Electrons cascade down to fill this inner shell hole and the target emits its characteristic x-rays. Start by raising the gain of the amplifier so that channel 4000 corresponds to about 400 keV. You may also have to change the lower level discriminator (LLD) setting, as described in the Interlude (You will then have to recalibrate.) Can you now see the characteristic X-ray from the daughter product $^{56}$Ba resulting from the decay of the $^{137}$Cs? If you can't, it may be that the geometry of the particular germanium detector you are using makes it insensitive to photons of that low energy which are easily absorbed. (You will find that only some of our detectors can see the low energy photons.)

$^5$Note that the sum peak that you see with $^{137}$Cs has a different shape than that with $^{60}$Co. In the $^{137}$Cs case, the pile-up is from two uncorrelated (in time) gamma rays that have come from two different nuclei in the source. In the $^{60}$Co case, the nuclear transition that produces the 1.173MeV gamma ray is then followed (in the same nucleus) by another transition that produces the 1.333MeV gamma ray. Thus, the emission of these two gamma rays is correlated in time.
Using the $^{137}$Cs source, place a 1/8 inch lead plate between the source and the detector. You should see a new x-ray peak, characteristic of the lead. To check what is causing the new peak, repeat your observation without the $^{137}$Cs and then without the lead. Note that characteristic X-ray energies depend only on $Z$, not on $A$. You can find tables of X-ray energies in the *Tables of Gamma-ray and X-ray energies* reference.

If you are unclear about the distinction between $\gamma$-rays and X-rays, please see the W.R. Leo reference, or consult your demonstrator. Be clear that the main distinction is not one of energy (both are photons of various energies) but rather one of origin.

**Appendix: "The Common Sense"

**Safety Note**

See the section from [www.physics.utoronto.ca/services/health_and_safety](http://www.physics.utoronto.ca/services/health_and_safety) with regard to handling radioactive materials and lead. In particular, note the following cautions on radiation: the sources we use in the lab are weak, so that when properly used, they subject the user to a small fraction of the radiation one receives in every-day life. However, as with any toxic material, it is important that you minimize the exposure you receive as any exposure does damage (be it small) to your body. Thus, place the sources you are using in a location away from yourself and other persons. Total radiation exposure is proportional to the source strength, the time you are exposed and a distance factor which for gamma rays drops off as the inverse square of the distance, and for alphas and betas, even faster. In other words, don't put the sources in your pocket, or even immediately in front of you on the bench.

**Background Precautions**

Radioactive sources placed near your experimental apparatus often affect the data being taken more than being a health problem. In all experiments there are background counts which appear due to radioactivity in the building walls, in the ground, and in other sources in the room, as well as from cosmic radiation. The background from sources in the room can be reduced by keeping your own and your neighbours' unwanted sources far from your counter, and also by shielding your counter.

*Updated by Gordon West and Pier-Olivier DeViveiros in 2007. Previous versions: jbv – 2001*