Health and Safety Instructions.

This experiment involves the use of radioactive sources and high voltages applied to the NaI scintillation detector.

The $\gamma$-ray spectrometer will be set up ready for use and the electrical connections should not be changed. In event of any difficulty, contact a Demonstrator or the Laboratory Technician.

The $\gamma$-ray sources are sealed sources for teaching laboratory use and are of low activity. Nevertheless they should be handled with great care using good laboratory practice.

The sources to be used (two rotating turrets of four sources each and the calibrated $^{137}$Cs source) will be in the central storage box at the start of each laboratory session.

- Transfer the sources to detector source box with the threaded rod provided,

- **Never touch the sources directly**

- Point the sources away from yourself during transfer.

If you are in any doubt about the correct procedure, contact a Demonstrator or the Laboratory Technician.
1. Aims

This experiment demonstrates the basic concepts of γ-ray spectroscopy. It uses a sodium iodide (NaI) scintillator detector interfaced to a multichannel analyser whose settings and data acquisition are controlled by a PC.

2. Apparatus

- Sodium iodide detector and photomultiplier tube with 1024 multichannel analyser.
- Data acquisition via interfaced PC.
- Lead-lined detector and source box.
- Storage box for radioactive sources and sealed isotope store.
- Sealed laboratory γ-ray sources (1” diameter) various nuclei in a rotating turret.

3. Background

(a) Scintillation spectroscopy and γ-ray interactions with matter.

There are three distinct mechanisms by which γ-rays interact with matter:

- The photoelectric effect,
- The Compton interaction,
- Pair production.

The photoelectric effect

In the photoelectric effect a γ-ray gives almost all of its energy to a bound electron on an atom in the target material to eject it from the atom with energy

\[ E_e = E_\gamma - B \]  \hspace{1cm} (1)

Here \( B \) is the binding energy of the electron, which is typically of the order of a few tens of keV. The photoelectric process is enhanced for absorber materials of high \( Z \) and the probability for photoelectric absorption scales according to \( Z/E_\gamma \).

The Compton effect

A.H. Compton observed that when a monoenergetic beam of γ-rays falls on a target, the scattered radiation consists of the primary beam and a modified beam, displaced to longer
wavelengths. He observed that the wavelength shift between the two beams depended directly on the angle of scatter.

The expression for the wavelength shift $\Delta \lambda$, is found in all the standard textbooks,

$$\Delta \lambda = \lambda' - \lambda = \frac{h}{m_0 c^2} \left(1 - \cos \theta \right). \quad (2)$$

Alternatively this result can be expressed in terms of the $\gamma$-ray energy,

$$h \nu' = \frac{h \nu}{1 + \left(1 - \cos \theta \right) \frac{h \nu}{m_0 c^2}} \quad (3)$$

Substituting $\theta = 180^\circ$ gives the greatest energy change corresponding to backscattering of the incident $\gamma$-ray photon. Energy conservation,

$$E_e = h \nu - h \nu'$$

shows this corresponds to the maximum energy of the scattered electron, this is the Compton edge.

---

**Figure 1:** interactions that occur when $\gamma$-rays from a radioactive source are being detected by a NaI scintillation detector.

### Pair Production

Pair production becomes important for higher $\gamma$-ray energies. In this process a $\gamma$-ray photon gives up all of its energy and forms an electron and positron pair. This must occur near the nucleus so that momentum can be conserved. The minimum energy needed for pair
production is $E_{\gamma}^{\text{Min}} = 2m_e c^2$ where $m_e$ is the rest mass of an electron or positron. $E_{\gamma}^{\text{Min}}$ is then equivalent to $2 \times 0.511 = 1.02$ MeV for pair production to occur.

There are additional interactions of $\gamma$’s with the surrounding material – backscattering and Pb X-rays. The various interactions are shown in Figure 1.

(b) $\gamma$-ray interactions in the sodium iodide (NaI) detector

The interactions with $\gamma$-rays and matter have been described in general terms in Section 3 above. A schematic view of these interactions is shown in Figure 1.

When $\gamma$-rays enter the NaI crystal, they interact primarily with the bound K or L electrons from the iodine atoms in the crystal. The binding energy of an electron in the iodine K shell is only $B = 33\text{keV}$ and so the recoiling electron takes most of the energy of the incident $\gamma$-ray. This recoil electron passes through the NaI crystal and loses energy by ionisation and electronic and thermal excitations. A fixed fraction of the electron energy will be converted to visible photons, which then impinge on the photocathode of the photomultiplier tube shown in Figure 1. These photons will produce photoelectrons from the photocathode surface of the photomultiplier which will be attracted to the first element of the dynode by a positive voltage. A cascade of electrons is produced down the elements of the dynode to give an electrical pulse at the anode which is proportional to the energy of the incident $\gamma$-ray. Pulses from the anode are fed through the preamplifier, amplifier and into the multichannel analyser for analysis. Figure 2 shows a block diagram of the electrical circuits that will be used for all parts of the experiment.

![Figure 2 - A block diagram of a typical system for $\gamma$-ray spectroscopy. The plotter and teletype are now replaced with a PC.](image)

Finally, we shall consider the data obtained from a $\gamma$-ray spectrometer used in conjunction with a multichannel analyser as described above. Figure 3 gives a schematic representation of the actual data, - in the form of a pulse height spectrum (this was actually obtained with a Nucleus Spectrum Type 88 MCA) when using a 137Cs $\gamma$-ray source. The $x$-axis (or abscissa) corresponds to the channel number, here 1 - 256, and the $y$-axis (or ordinate) to the counts per channel of the MCA. Naturally both of these axes must be normalised before quantitative
measurements of the $\gamma$-ray energies (x-axis) and of the activities of the sources (y-axis) can be made. This will be the object of the experiments discussed below.

(c) Pulse Height Spectrum from a $\gamma$-Source

Figure 3 - The pulse height spectrum for a $^{137}$Cs radioactive source obtained with a multi-channel analyser.

$\nu = 1022$kev $\nu = 622$kev $\nu = 323$kev

<table>
<thead>
<tr>
<th>$\Theta$</th>
<th>$\nu'$</th>
<th>$T_e$</th>
<th>$\nu'$</th>
<th>$T_e$</th>
<th>$\nu'$</th>
<th>$T_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1022</td>
<td>0</td>
<td>662</td>
<td>98</td>
<td>323</td>
<td>0</td>
</tr>
<tr>
<td>30</td>
<td>806</td>
<td>216</td>
<td>564</td>
<td>98</td>
<td>298</td>
<td>25</td>
</tr>
<tr>
<td>60</td>
<td>511</td>
<td>511</td>
<td>402</td>
<td>260</td>
<td>245</td>
<td>78</td>
</tr>
<tr>
<td>90</td>
<td>341</td>
<td>681</td>
<td>288</td>
<td>374</td>
<td>198</td>
<td>125</td>
</tr>
<tr>
<td>120</td>
<td>256</td>
<td>766</td>
<td>225</td>
<td>437</td>
<td>166</td>
<td>157</td>
</tr>
<tr>
<td>150</td>
<td>216</td>
<td>806</td>
<td>194</td>
<td>468</td>
<td>148</td>
<td>175</td>
</tr>
<tr>
<td>180</td>
<td>204</td>
<td>818</td>
<td>184</td>
<td>478</td>
<td>143</td>
<td>180</td>
</tr>
</tbody>
</table>

Table 1: Compton electron energies for given scattering angles.

The most significant feature of this spectrum is the strong photopeak at around channel number $\approx 100$. The nuclear energy level scheme for the radioactive decay of $^{137}$Cs to $^{137}$Ba is shown as an insert to Figure 3 and clearly this peak corresponds to the emission of the $\gamma$-ray with energy 0.662 MeV. Since the spectrum is linear, a $\gamma$-ray transition which had twice the energy (1.324 Mev) would obviously occur in channel 200 etc. There is also a small peak at channel number $\approx 31$. This ‘backscatter’ peak arises from events where a photon emitted from a $^{137}$Cs nucleus has been Compton scattered from surrounding material (lead shielding, lab bench etc.) into the detector and absorbed by the photoelectric process. Most of these photons scatter at approximately 180° hence the term ‘backscatter’. The Compton edge in this spectrum lies at channel number $\approx 70$. The region of the spectrum from the Compton edge down to the electronic cut-off corresponds to a distribution of pulses from the electrons produced by Compton interactions in the NaI crystal. An indication of the range of energies of $\nu'$ and $T_e$ involved, can be seen in Table 1.
4. Experiment

Experiment 1: Gamma Energy Calibration

In this section you will calibrate the PCA-P by using several known sources to determine the relationship between the channel number and the energy of the detected emission. This calibration will then be used in all of the following experiments. Instructions for working with the MCA software can be found in Appendix A.

1.1. Note down the values of all settings on the appropriate High Voltage supply in the electronics rack, and also on the amplifier situated next to the computer, and the MCA software (conversion gain and offset). These settings MUST be re-checked each day before you start work on the experiment. If any of these settings have changed please notify the lab-technician immediately.

1.2. Position the $^{137}$Cs source in the four-source turret, at a distance of around 3 cm. To ensure that this is a suitable distance from the photomultiplier, the dead-time (shown on the bottom right-hand corner of the screen) on the detector should be zero (or close) when you are taking measurements. If the dead-time is too high then it means that the rate of emission is too high for the PCA-P to collect all of the signal. At the same time, you should make sure that you collect enough of a signal to give a good spectrum.

1.3. If you are working with the N1a apparatus, you must turn on the High Voltage using the software. Use the “MCA” pull-down menu, select “adjust”, select “HVPS” and turn on the HV. The voltage should be at 935 Volts. For the N1a apparatus the HV is housed on the photomultiplier and is controlled from the PC via a serial connection.

1.4. Acquire a spectrum until you observe a well defined peak. This should be similar to that seen in figure 3.

1.5. Save the spectrum to a file, save work as toolkit file (*.TKA)

   - Name your file
   - Save in the desk top folder ‘Spectra’

1.6. Determine the channel number of the photopeak position (including and error estimate). This can be done ‘by eye’ or using the peak analysis facilities offered by the software.

1.7. The known energy of the $^{137}$Cs is listed in Table 2. Record the channel number of the photopeak position.

1.8. Using the same settings, collect spectra for the $^{22}$Na and $^{60}$Co sources in the four-source turret. Measure the channel numbers of the centroids of the photopeaks and tabulate against the known photopeak energies for each source.
1.9. From the data you have collected, make a linear plot of the energy of the photopeak versus the channel number of the centroid of the photopeak. Fit a straight line to determine the relationship between energy and channel.

Experiment 2: Identification of unknown sources

2.1. Collect spectra from the unknown sources labelled with a single

- yellow dot,
- blue dot,
- green dot.

Use your calibration graph and Table 2 to identify the three unknown sources.

<table>
<thead>
<tr>
<th>ISOTOPE</th>
<th>HALF LIFE</th>
<th>(f_{g}) (fraction of (\gamma)'s per decay)</th>
<th>GAMMA PEAKS OF INTEREST (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{60})Co</td>
<td>5.62 years</td>
<td>0.99</td>
<td>1.173, 1.332</td>
</tr>
<tr>
<td>(^{22})Na</td>
<td>2.62 years</td>
<td>0.999</td>
<td>0.511, 1.275</td>
</tr>
<tr>
<td>(^{54})Mn</td>
<td>303 days</td>
<td>1.00</td>
<td>0.835</td>
</tr>
<tr>
<td>(^{137})Cs</td>
<td>30 years</td>
<td>0.92</td>
<td>0.662</td>
</tr>
<tr>
<td>(^{133})Ba</td>
<td>7.2 years</td>
<td>-</td>
<td>0.080, 0.276, 0.302, 0.356, 0.382</td>
</tr>
<tr>
<td>(^{109})Cd</td>
<td>453 days</td>
<td>-</td>
<td>0.088</td>
</tr>
<tr>
<td>(^{57})Co</td>
<td>270 days</td>
<td>-</td>
<td>0.014, 0.122, 0.136</td>
</tr>
</tbody>
</table>

*Table 2: Properties of various gamma ray sources.*

Experiment 3: Gamma Spectrum Analysis

This part of the experiment will familiarise you with the types of interactions that occur with a gamma emitter and the resulting spectra. You should become familiar with the basic science associated with gamma decay, and with gamma ray spectroscopy using a NaI scintillation detector and multi-channel analyser.

3.1. Using the same electronics and energy calibration as for the experiments above, collect a spectrum of a \(^{137}\)Cs source for a time period long enough to acquire a good spectrum. From the spectrum, identify the following features:
3.2. Determine the energy at which the features observed in (3.1) occur, and compare to the theoretical values. The theoretical value for the position of the Compton edge can be found using equations (3) and (4). The backscatter energy, $h\nu$, can be found by solving equation (3) for $h\nu = 0.662$ MeV and $\theta = 180^\circ$. Derive the correct value for the Compton edge, and compare this with what you have obtained from the spectrum.

A lead x-ray peak can be produced by photons which strike the lead shield, and produce a fluorescent 74.96 keV x-ray. Some of these x-rays will interact with the NaI detector and produce a 74.96 keV x-ray peak in the spectrum. The lead x-ray is produced by the initial photon from the source interacting with the lead by the photoelectric process. Recall that in the photoelectric process the gamma gives all of its energy to a bound K or L shell electron, thus knocking it out of its orbit.

3.3. Collect a spectrum with a $^{22}$Na source, again using the same electronics and energy calibration. This time place approximately 2 cm of lead absorber behind the source. This will enhance backscattering, and the production of lead x-rays, which are discussed below. Detect the following features:

- The photopeak
- The Compton edge
- The backscatter peak
- The lead x-ray peak

3.4. Determine the energy at which these peaks occur, and compare to the expected values.

Experiment 4: Energy Resolution of $^{137}$Cs

The ability of a detector to resolve two gamma ray peaks that are close together in energy is measured by a quantity called the resolution of the detector. For a NaI detector the resolution $R$ can be obtained from the pulse height spectrum by solving the following equation:

$$ R = \frac{\text{PeakWidth}}{E_0} \times 100\% $$

Where $R$ is the resolution in percent, $\Delta E$ is the measured width (in energy) of the photopeak at one half the maximum peak height (Full-Width Half Maximum - FWHM), and $E_0$ is the energy number of the centroid of the photopeak.
4.1. Place the $^{137}$Cs source in position and accumulate a spectrum for a time period long enough to obtain about 5000 counts in the maximum photopeak channel.

4.2. Using the MCA Data Acquisition Software obtain $E_0$ and $\Delta E$ (see appendix).

4.3. Using the equation above calculate the resolution for the detector.

**Appendix A: Using the MCA Data Acquisition software**

Figure 2 shows the electronics arrangement that will be used for all parts of this experiment. Make sure that all the power is off before setting up and making any connections.

The photomultiplier tube is connected to a high-voltage source and its output is connected to a pre-amp. The output of this pre-amp is then connected to the negative input of the linear amplifier. The bipolar output of the amplifier is connected to the PCA-P multichannel analyser card in the computer.

The PCA-P is a multichannel analyser which has 1024 channels where each channel corresponds to a particular energy of the spectrum. Data acquisition and analysis can be performed using the PCA-P program.

**To get started:**

The program should already be started. The multichannel analyser works using a menu based system. The menus can be accessed by pressing the first letter of the appropriate menu. You can leave a menu at any stage by pressing the mouse button.

**To acquire data:**

- The screen can be cleared at any time (except when you are acquiring data) by pressing the ‘CLEAR’ button
- To start collecting data, press F4.
- To stop collecting data, press F4.

When you begin acquiring data, there are 2 times that appear at the bottom of the screen – REAL and LIVE. Live time is the important time for stopping data collection.

**Saving the data:**

To save the data on to the PC,

Save your work as Toolkit File(*.TKA)

Name your file and save in the desktop folder ‘Spectra’

**To Open in Excel**

- Open Excel
• Click open
• ‘Files of Type’ click ‘All Files
• Click Spectra and open
• Click on named file and open
• Text import wizard appears
• Check Delimited and Finish
• Row No’s = channel No’s

Analysing the data:

Once a spectrum has been acquired, it is possible to see how many counts are in a certain channel, and to analyse the peaks. You can move up and down the spectrum using the mouse. Alternatively, you can use the cursors. To analyse the peaks and obtain the FWHM and peak centroid you can use the REGION OF INTEREST facility.

Appendix

Method for obtaining FWHM and peak centroids.

Step 1-Mark the region of interest (ROI)

• Click the centre of the peak that you wish to analyse
• Press [Ctrl] + [Ins] to bring up the ROI markers
• Drag the markers around the peak
• Press [Ins] to add the ROI

Step 2—Locate the peak centroid

• On the menue bar navigate to: Analyze>Peak Locate>User Specified
• If you only require the peak centroid, check the “Generate Report” Checkbox. Otherwise this can be omitted
• Click [Execute]

Step 3 – Analyse peak area

• On the menue bar navigate to: Analyze>Peak Area>Sum/Non Linear LSQ fit
• Check the “Generate Report” checkbox

• Click [Execute]

The results will now be displayed in the report window.

Ctrl insert for markers

Move markers around by dragging with mouse

Press insert to mark Region of Interest

This will colour the region of interest red, and will give you such information as the centroid (centre peak), and the full width half maximum (FWHM), by using a Gaussian fitting program. This information will be used in the experiments.

• Analyze

• Peak Locate

• User Specified

• Execute

Then:

• Analyze

• Peak Area

• 1 sum Generate report

• Execute

Gain controls:

The spectra are scaled properly by using the course and fine gain. A very energetic source will need a different energy per channel than a feeble one. To change these

• go into the set-up menu (press S)

• adjust conversion gain and/or conversion offset.

The system must be calibrated for these settings of gain, and must be re-calibrated every time you make a change. The settings can be checked on the left hand side of the screen. It should say GAIN and OFFSET. Unless you have problems seeing a given spectrum these settings should not be changed from those you find at the beginning of the experiment. Speak to a demonstrator before you do so.
To exit from the system:

Press ALT Q