Experiment no. 2	**Gamma-ray Spectroscopy using a Multi-Channel Analyser (MCA) & Half Life of a Short-lived Isotope**	

Radio-isotope handling note:	
Isotope:	^{137}Cs, ^{22}Na, ^{60}Co sealed calibration sources
Activity:	< 10 μCi (< 370 kBq)
Comments:	May be safely handled with fingers. Must be stored behind lead shield when not in use.

2.1. Spectrum Analysis of ^{137}Cs, ^{22}Na and ^{60}Co

A Multi-Channel Analyser will be used to acquire gamma ray spectra of some reference isotopes. Features appearing in these spectra in addition to the expected *photopeaks* will be explained, and the detector resolution as a function of energy will be determined.

2.1.1 Introduction

Gamma Interactions with Matter
When a gamma ray enters a detector, it must interact with the detector medium and produce a recoil electron by one of the following three processes before it is recorded as an event:
- the photoelectric effect,
- the Compton effect, or
- pair production.

The photon interactions occurring in the detector influence the shape of the resultant spectrum.
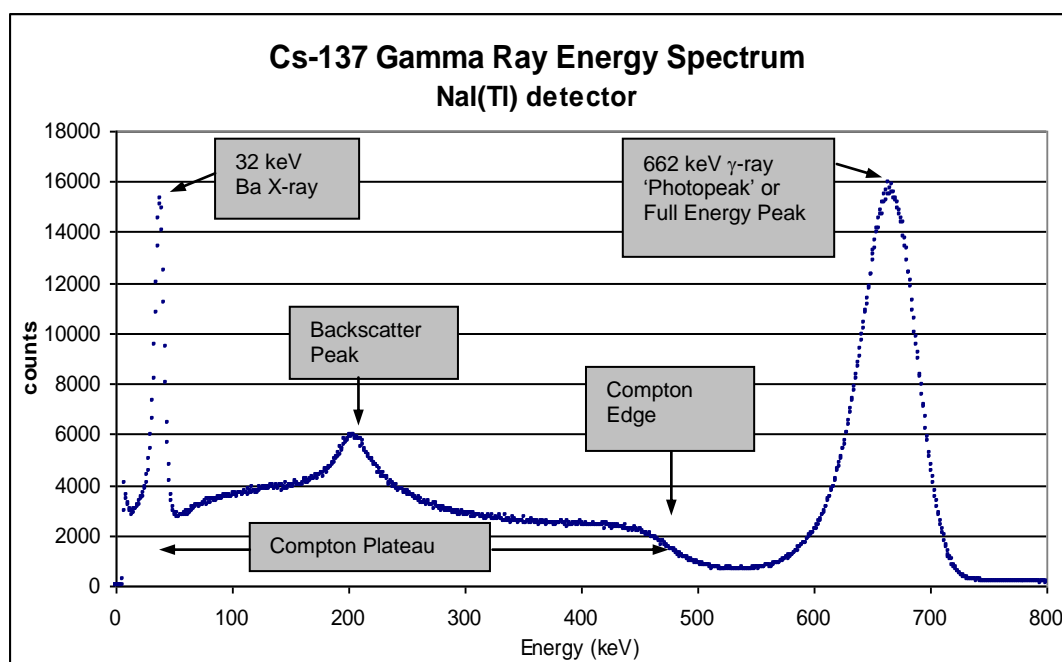**Figure 1** shows the ^{137}Cs spectrum, with the important features labelled.

Figure 1. ^{137}Cs γ-ray energy spectrum showing important features which result from the various gamma interactions in the detector crystal.

Photoelectric Effect

In the photoelectric process the gamma ray or X-ray gives all of its energy to the recoil electron. It is the recoil electron which produces the electron-hole pairs and the excitation/de-excitation in the detector that yield the output pulse. For the photoelectric process the output pulse from the detector is proportional to the energy of the gamma or X-ray that produced the interaction. In the spectrum these events will contribute to the full energy *photopeaks*.

Compton Effect

The Compton effect is where a photon loses energy via inelastic scattering with a charged particle. When an incident photon Compton scatters inside the detector, the recoil electron contributes to the energy recorded by the detector but the scattered photon may escape from the detector. There is a distribution of pulse amplitudes up to a maximum pulse height. This maximum pulse height produces the *Compton edge* and there is a statistical probability that each event can produce a pulse with any height up to this maximum with about an equal chance. Thus Compton events will provide a well distributed low energy area in the spectrum.

Some Compton events also contribute to the full energy peak when the scattered photons undergo one or more additional interactions if this results in complete absorption of the gamma-ray energy.

Pair Production

The pair production process may also contribute to the full energy peak if the energy of both the electron and positron are deposited in the detector. Partial energy deposition may occur if the positron annihilates within the detector and one or both of the annihilation quanta escape. In these cases, the event may contribute to a *single escape peak* or a *double escape peak*. The lecture notes contain a detailed description of the pair production process.

Peak to Compton Ratio

The *peak to Compton ratio* of a detector refers to the relative probability that a *detected* photon will be recorded in the full energy peak or the Compton region. This in turn depends upon the cross section for each reaction in the given detection medium. **Figure 2** shows graphs for the three important gamma interactions for both germanium and silicon.

Refer to Figure 2, specifically to the curves for the interactions in germanium. The absorption cross section, plotted in the y direction, is a measure of the relative probability that an interaction will take place in a germanium detector. These relative interaction probabilities, for the most part, determine the shape of the observed spectrum. For example, a photon with an energy of 100 keV has an absorption cross section of ~55 barns/atom for the photoelectric process. The corresponding Compton cross section is ~18 barns/atom. There is no pair production. This indicates that at 100 keV there are 3 times as many photo-electric interactions as Compton interactions, since this is the approximate ratio of the cross sections.
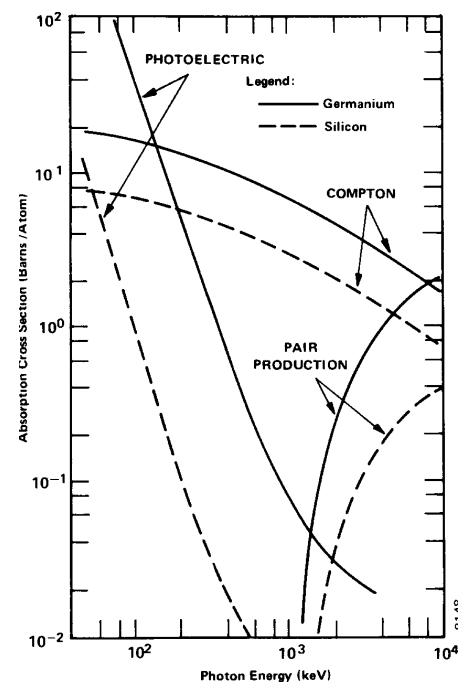

Figure 2. Gamma Interactions: Absorption Cross Sections

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The sum of counts under the photopeak (Σ_{pp}) would be at least 3 times the sum under the Compton distribution (Σ_c). For larger crystals Σ_{pp} would be even >3 times Σ_c because some of the scattered gammas from the Compton interactions would make photoelectric interactions before escaping from the crystal. For an infinitely large crystal there would be no Compton distribution since the crystal would then totally absorb all of the incident gammas.

Resolution

The *resolution* of a gamma-ray spectrometer is a measure of its ability to resolve two peaks that are fairly close together in energy (refer to **Figure 3**). The resolution of the photopeak is defined by the following equation:

$$R = \frac{\delta E}{E} \times 100 \tag{1}$$

where
> R = the resolution in percent,
> δE = the full width of the peak at half of the maximum count level (FWHM) and
> E = the energy at the centroid of the photo peak .

Sodium Iodide Resolution

Typical energy resolution that can be obtained with NaI(Tl) is ~7% for the 0.662 MeV ^{137}Cs gamma ray. For NaI(Tl) detectors the resolution is a strong function of energy. Variation of resolution results primarily from the statistical fluctuation of the number of photoelectrons which are produced at the photocathode surface in the photomultiplier tube.
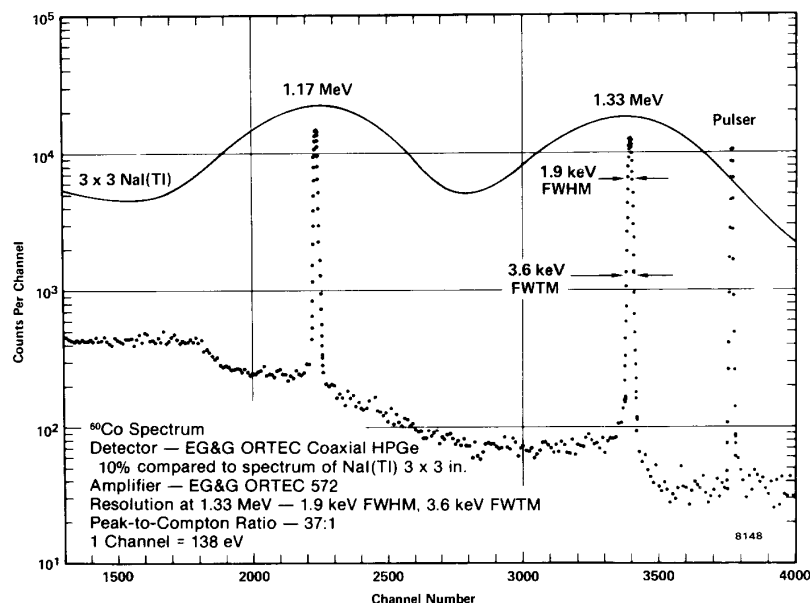

Figure 3. *Comparison of detector resolution*

To see the difference between detector resolutions, figure 3 shows a comparison of a standard NaI(Tl) detector compared to an ultra-high resolution liquid nitrogen cooled germanium detector.

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Spectrum Analysis of ^{60}Co, ^{22}Na and ^{137}Cs

The Compton interaction is a pure kinematic collision between a gamma photon and what might be termed a free electron in the NaI(TI) crystal (i.e electron binding energies are negligible). By this process the incident gamma gives up only part of its energy to the electron, depending on the scattering angle of the photon and electron. A "knock-on" collision scatters the electron forward, while back-scattering the photon, imparting the maximum energy transfer allowable in a Compton interaction. The energy of the scattered gamma can be determined by solving the energy and momentum equations for this "billiard ball" style collision. The solution for these equations in terms of the scattered gamma can be written as

$$E_{\gamma'} = \frac{E_\gamma}{1 + \left(\dfrac{E_\gamma}{m_e c^2} \right)(1 - \cos\theta)} \tag{2}$$

where E_γ and E_γ ' are the energies of the incident and scattered gamma,
θ is the scattering angle for γ', and $m_e c^2$ (= 511 keV) is the mass energy of an electron.

Gamma rays may scatter into the detector from materials around the apparatus, with less than their emission energies. Many of these events occur with a scattering angle of approximately 180° (why?) resulting in the prescence of a *backscatter peak* in the spectrum.

Hint: during an experiment, to quickly locate the backscatter peak in a spectrum, use the approximation $m_e c^2 \approx 0.5$ MeV, then Eq (1) reduces *approximately* to

$$E_{\gamma'} \cong \frac{E_\gamma}{1 + 4E_\gamma} \qquad \text{in units of MeV} \tag{3}$$

If the backscatter peak is not very pronounced in your spectrum, it can be increased by accumulating a spectrum with a sheet of lead absorber placed behind the source. This increases the number of 180° scattered photons reaching the detector.

The purpose of this experiment is to explain some of the features, other than the photopeaks, that are usually present in a pulse height spectrum. These are the *Compton Plateau*, *Compton edge* and the *Backscatter peak*.

2.1.2 Equipment required

- NIM Bin and Power Supply
- NaI(Tl) Crystal and Phototube Assembly
- High Voltage Power Supply
- Preamplifier
- Amplifier
- Oscilloscope
- Multi Channel Analyser: Ortec 928 Multi Channel Buffer, USB dual Port Memory cable, PC with Maestro32 spectrum software.
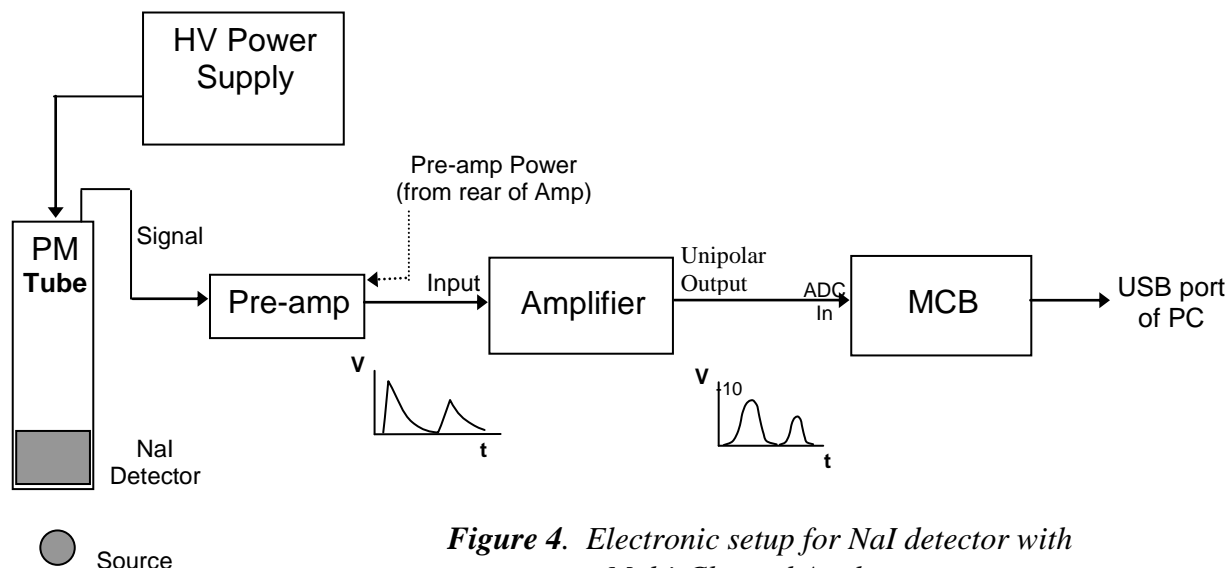- ^{137}Cs, ^{22}Na and ^{60}Co gamma sources

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Figure 4. *Electronic setup for NaI detector with Multi-Channel Analyser*

2.1.2 Procedure – Spectrum analysis of ^{137}Cs, [22]Na and [60]Co

1. As always, make sure you take detailed notes in your logbook throughout the entire class.

2. Recall the setup description from Experiment 1, section 1.1.5. Connect the electronics in the arrangement shown in fig 4. Remember to pay attention to cable types and **have the demonstrator check your circuit before applying power.**

3. Place the ^{137}Cs source 2-5 cm in front of the NaI(Tl) detector.

4. Adjust the amplifier gain so that the 662 keV gammas produce approximately a 4 V pulse as viewed on the oscilloscope.

5. The 662 keV photopeak for ^{137}Cs should appear at approximately channel 800 on the MCA. **See Appendix B for MCA Operation**. The channel number (marker) of the cursor location can be viewed in the bottom left corner. Lock and record the gain settings. **The gain should not be alterd again.**

6. Acquire a spectrum for sample, until the height of the photopeak is at least several thousand counts (or the peaks of interest are well formed).

7. Set a region of interest (ROI) around the photopeaks of interest, ensuring that it is wider than the shoulders of the peak where possible. See Appendix B.4

8. The calibration function is updated each time you add data and is not cleared when you clear a spectrum. The calibration function you should use in your data analysis is saved in the file of the last spectrum acquired as it has the most data points. Due to this, it is important that the calibration data is not cleared during calibration, only beforehand.

9. Enter the known energy of the photopeak in the calibration function of the software. See Appendix B.6.

10. Obtain a peak report. Record all the results, the FWHM will be needed to calculate the resolution. See Appendix B.5

11. Save the spectrum in both integer and ASCII formats. See Appendix B.7. Record filenames and locations in your journal.

12. Clear the spectrum, but **do not clear the calibration**.

13. Repeat steps 6 - 11 with [22]Na and ^{60}Co, be sure to use both known photopeaks for each of these isotopes; (ensure that the calibration is not cleared in between changing samples)

^{22}Na: 511 keV and 1274 keV ^{60}Co: 1173 keV and 1333 keV

14. Acquire a background spectrum and apply a background correction to all spectra acquired when completing your analysis. Pay attention to the acquisition time for each spectrum. *Why is this important for this step?*

2.1.3 Procedure – Spectroscopy and half-life measurement of an unknown sample

1. Ask your demonstrator for a mystery sample.
2. Acquire a 1 minute spectrum every 5 minutes (set a preset real time in Acquire > MCB Properties), for *at least* 20 minutes (30 minutes would be ideal).
3. Make sure you save and name the files sensibly. Record the file names and locations in your journal.
4. For each of these, record the total number of counts/minute in the entire spectrum from this source, using the Calculate > Sum function *when the cursor is NOT in a ROI*.
5. Determine the half-life of the unknown radionuclide, given the exponential nature of radioactive decay: $I = I_0 e^{-\lambda t}$ where *I* is the intensity (or count rate) at time *t* after an initial intensity, I_o. λ is the *decay constant* of the sample, with units of inverse time. *Hint:* You may find it useful to linearise this equation by taking the natural logarithm of each side.

Report 2: Spectrum Analysis of ^{137}Cs, ^{22}Na and ^{60}Co

At least the following should be included in the <u>results</u> section of your report:

- Supply computer generated plots of the spectra for the ^{137}Cs, ^{22}Na and ^{60}Co γ-sources.
  <u>*Label all relevant features on your graphs with name and energy.*</u>

- <u>Calculate</u> the location (i.e. energy) of Compton Edge and Backscatter Peaks for all photons.
  <u>*Present your results in a table.*</u>

- For the NaI detector you used, calculate the peak resolution for each of the five photon energies.
  <u>*Present your results in a table.*</u>

- Present the spectrum of your 'unknown' isotope, complete with labelled photopeak energies. Use the calculated Compton Edge and Backscatter Peak energies to exclude any peaks which are not *photopeaks*.

- Present a plot of your half-life decay data. Determine the half-life of the radionuclide, including the uncertainty in your answer.

- Include the raw data used for the half-life calculation in the appendix.

At least the following points should be <u>discussed</u> in your report:

- Comment on the relationship between detector resolution and gamma ray energy for the NaI detector. Give reasons for this relationship.

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- Identify the isotope, and explain your supporting evidence. If the isotope cannot be identified, show isotopes that have some supporting evidence, and state why they are not valid. Cite any references used.

Appendix B: MCA Operation

The Multi Channel Analyser (MCA) consists of the following components:
- Ortec 926 Multi Channel Buffer
- USB Dual Port Memory cable
- PC with Maestro32 spectrum software

B.1 Initialisation

1. Turn on PC and log on with your standard RMIT login
2. Run *MCB Configuration* from the desktop, or search for it
3. Wait for instruments to be found
4. Click *Renumber All*
5. Click *Ok*
6. Run *Maestro32* from the desktop

B.2 Settings

Acquire > MCB Properties > ADC > Conversion Gain = 2048, Gate = Off

> Presets > Real Time = Live Time = *blank* (for unlimited counting)

You can enter a particular real or live time and the spectrum will acquire for that amount of time and then stop automatically.

Calculate > Settings > x = 2 (for FW1/xM => FWHM)

B.3 Basic Operation

Acquire > Start/Stop/Clear
OR
Rick click > Start/Stop/Clear

B.4 Defining a Region of Interest (ROI)

1. Use arrow keys to position cursor at LHS of peak
2. ROI > Mark (or Alt-m)
3. Use arrow keys to move cursor to RHS of peak
4. ROI > Off (or Alt-o)

OR
1. Use the mouse to drag a box spanning the required channels
2. Use Mark/Unmark to add or remove channels to this ROI

B.5 Analysis

Calculate > Peak Info
OR
Place the curser in the ROI and right click > Peak Info

B.6 Calibration

1. Before taking any measurements, clear any existing calibration, Calculate > Calibration > Destroy Calibration. Ensure this is done before the FIRST calibration point only.

2. Set ROIs around all known photopeaks (note x-ray peaks)

3. Place curser in ROI

4. Calculate > Calibrate > And enter corresponding peak energy

5. Repeat for each photopeak

6. Note that the calibration function does not erase when a spectrum is cleared

7. Repeat for different isotopes

8. When you save a spectrum, the calibration function is saved in the file footer information
   For example:

   ```
   $MCA_CAL:
   3
   -7.056123E+000  1.021778E+000  0.000000E+000  keV
   ```
        a   b   c

   These three numbers are the coefficients of the quadratic calibration function, such that the energy, E, of a particular channel number, Ch#, is given by:

   $E = a + [b \times (Ch\#)] + [c \times (Ch\#)^2]$
   $E = -7.056123E+000 + 1.021778E+000 \times (Ch\#) + 0.000000E+000 \times (Ch\#)^2$

B.7 Saving spectrum files

The MCA has two file formats :

- binary: **'Integer .CHN'** and
- ASCII: '**ASCII .SPE**'

The binary file format is readable by the MCA (but generally not by other software). Files which you may want to re-load into the MCA should be saved in binary format.

ASCII files can be opened using other software (word processors, spreadsheets, etc.) but do not contain all the info required by the MCA, and cannot be re-loaded.

It is usual practice to save most spectra twice – once in each format – just in case

ASCII files can be opened in Microsoft Excel. Open as "Delimited" > "Space delimited" to get one data entry per cell.

B.8 Suggested Excel functions

LINEST: Fits a function and generates statistics of a linear data set using a least squares approach.

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