A) RADIOACTIVE SOURCE AND SCINTILLATION DETECTORS

Radioactive nuclei decay by emitting beta or alpha particles. Often the decay is to an excited state of the daughter nucleus, which usually decays by emission of a gamma ray. The energy level sequence and therefore the gamma ray energy spectrum for every nucleus is unique and can be used to identify the nucleus. The energy levels and decay processes of $^{22}$Na, $^{60}$Co and $^{137}$Cs are given in Figure 1. The term beta decay means either $\beta^-$ (electron) emission, $\beta^+$ (Positron) emission, or electron capture by the nucleus.

The thallium-activated sodium iodide detector, or NaI(Tl) detector, responds to the gamma ray by producing a small flash of light, a scintillation. The scintillation occurs when electrons, and in some cases positrons, are given energy by the incident gamma ray and are stopped by the crystal. The crystal is mounted on a photomultiplier tube that converts the scintillation to an electrical pulse. The first pulse from the photocathode is very small and is amplified in 10 stages in a series of dynodes to get a large enough pulse. This is taken from the anode of the photomultiplier, and is a negative pulse.

The NaI crystal is protected from collecting moisture in the air by encasing it in aluminium, which also serves as a convenient mounting for the entire crystal photomultiplier unit.

There are three dominant gamma ray interactions with matter:
1) The photoelectric effect
2) The Compton effect
3) Pair production
Only the photoelectric effect produces an output pulse that is proportional to the gamma ray energy. In the photoelectric effect, all of the energy of the gamma ray is absorbed by an electron. In the Compton effect, the gamma ray scatters from an electron, giving the electron an amount of energy:

$$E_e = E - E'$$

where $E$ is the incident gamma ray energy, $E'$ is the scattered gamma ray energy which is a function of the angle of scatter (see Section D).

If the gamma ray escapes from the crystal, then the only energy deposited is the electron energy, and the output pulse is much less than that for the full energy. The spectrum is complicated by having many pulses not of the full gamma ray energy, as will be seen below.

If the gamma ray does not escape from the crystal, but either scatters again or gives up its remaining energy by the photoelectric process, then the full energy pulse is obtained. Since this is more likely in a larger crystal, the full energy efficiency increases by more than the increase in volume.

Pair production occurs when the gamma ray energy is greater than 1.022 MeV, but is not an important part of detection until energies of 2.5 MeV or higher. The positron and electron of the pair produced slow and scintillate, just as for Compton scattered electrons. When the positron comes to rest it annihilates with an electron, producing two 0.511 MeV gamma rays. Both of these must be absorbed to get the full energy peaks.
The maximum energy given to an electron in Compton scattering occurs for gamma scattering of $180^\circ$, and the energy distribution is continuous up to that point. This energy, known as the Compton edge, can be calculated from the incident gamma ray energy.

B) **GAMMA RAY SPECTRUM**

1) Connect the apparatus as in Figure 2. Place $^{137}$Cs source near the NaI detector, and set the HV supply at +1000 volts.

![Electronics setup](image)

**Figure 2  Electronics setup**

Set the amplifier gain and polarity so that the peak appears a little below the middle of the display. Collect the data long enough so that the spectrum appears to vary smoothly from one point to the next. It should appear as in Figure 3A. Identify the photopeak. The mass of data to the left of the photopeak is the Compton distribution, which has a maximum value at the Compton Edge. This is the response to a monomagnetic gamma ray of roughly medium energy. A very strong peak at low energy may be present if the discriminator is set low enough. This is the Ba x-ray at 37 keV, which follows internal conversion.

2) Read out the spectrum and make a graph of it.
3) Now place the $^{22}$Na source near the detector instead of the $^{137}$Cs source. Clear the memory and collect a spectrum. From the decay scheme (Figure 1) one could expect a similar spectrum to $^{137}$Cs, but there are now two peaks. The higher one at 1.27 MeV is the gamma ray expected, while the lower one is at 0.511 MeV and is the radiation from positron annihilation. This "511" radiation will always be present when positrons are emitted by nuclei. Read out the spectrum and plot a graph of it. It should appear as in Figure 3B.

4) Place a large piece of lead (such as a lead brick) next to the source and take a fresh spectrum. There will be additional counts in the Compton region of the spectrum due to scattering from the lead. Any material near the source will cause scattering of gamma rays, so this effect cannot be entirely eliminated.
C) ENERGY CALIBRATION AND RESOLUTION

1) From the graphs of the $^{137}$Cs and $^{22}$Na spectra determine the central channel of each photopeak and plot the gamma ray energy of the peak vs. the corresponding channel. (Alternatively, move the cursors to the peak channel and read the cursor channel from the display.) Estimate the position to the nearest channel, and estimate the uncertainty in determining the peak position. Plot the uncertainty in position as error flags, as in Figure 4.

![Figure 4 Energy calibration](image)

A straight line through the data gives the energy corresponding to each channel of the MCA. The line may not go exactly through zero. This is due to the NaI detector not being exactly linear at low energies, but can also be due to variations in the adjustment of the zero setting of the ADC. Non-linearity may also occur if the amplifier gain is high enough to bring pulses into saturation, but this can be checked with an oscilloscope at the amplifier output.

2) The calibration curve can now be used to determine the energies of a different gamma ray source. Collect a spectrum for $^{60}$Co and determine the energies of the two photopeaks that appear.

The uncertainty in the peak position is related to the width of the peak. The full width of the peak at half of its maximum value (FWHM) is used to determine the resolution by:

$$\text{RESOLUTION} = \frac{\text{FWHM} \times 100\%}{\text{Peak Position}}$$
where the FWHM and peak positions are given in channels. The performance of a scintillation counter is usually specified in term of its resolution for the 0.662 MeV peak of $^{137}$Cs since the resolution depends upon gamma ray energy.

3) Calculate the resolution for each of the three photopeaks in $^{137}$Cs and $^{22}$Na. This will be about 8 to 9% for a crystal-phototube combination that is working properly. If it is higher, there may have been some damage to the unit, resulting in poor optical coupling, or the high voltage is too low (it should be about +1000 volts), or the counting rate is too high.

4) Calculate the energy of the Compton Edge for the 137Cs and 22Na gamma rays and compare to the value obtained from the spectrum.

D) COMPTON SCATTERING

The discovery by A.H. Compton that gamma rays act like particle was based upon interactions with electrons in a manner that can be explained by attributing definite momentum and energy to each gamma ray. In a collision of a gamma ray of energy $E$ with an electron, the gamma ray energy $E'$ after scattering through angle $\theta$ is given by:

$$E' = \frac{E}{1 + \frac{E}{mc^2}(1 - \cos \theta)}$$

where $mc^2$, the rest mass energy of the electron, is equal to 0.511 MeV.

For very small scattering angles the gamma ray energy is not changed very much since the factor $(1 - \cos \theta)$ is approximately zero and the denominator of the above equation is nearly unity. The largest energy loss of the gamma ray occurs at 180°, with the energy loss dependent upon the gamma ray energy. For low-energy gamma rays of the order of 50 keV, the energy loss is only a few keV, while at larger energies, of the order of 1 MeV or higher, most of the energy can be lost in scattering at large angles.
The cross section for scattering of gamma rays by electrons is also dependent upon the scattering angle and the gamma ray energy. It is calculated from the Klein-Nishina formulas:

\[
\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2} \left[ \frac{E'}{E} \right]^2 \left[ \frac{E'}{E} \frac{E'}{E} + \frac{E'}{E} \sin^2 \theta \right]
\]

where \( r_0 \) is the classical electron radius, equal to \( 2.82 \times 10^{-13} \) cm.

E) MEASUREMENT OF SCATTERED GAMMA RAY ENERGY

The \(^{137}\text{Cs} \) source should be enclosed in a lead container with a collimating slit so that the gamma rays are directed at only the scattering material. The NaI detector should also be shielded and collimated so that it directly views the scatterer, as in Figure 5. The scattering material should be an aluminium rod, about 2 to 3 cm in diameter. The detector should be moveable from angles of 15° to 150° from the incident gamma ray direction, at 20 cm from the scatterer.

![Figure 5 Mechanical Setup](image)

1) Determine the scattered gamma ray energies for \(^{137}\text{Cs} \) in 15° steps from 15° to the largest angle possible. Obtain a sufficient amount of data so that the channels near the peak in each case have at least 100 counts (10% statistical error).
2) Record the time (realtime) for each spectrum. To test the energy dependence most directly, the equation for energy vs. angle may be written as

\[ \frac{1}{E'} = \frac{1}{E} + \frac{1}{mc^2} (1 - \cos \theta) \]

3) Construct a graph of \(1/E'\) vs. \((1 - \cos \theta)\) as in Figure 6. Indicate with error flags both the estimated error in energy determination and the estimated error in \(\cos \theta\).

![Figure 6 Typical Data](image)

4) The graph of \(1/E'\) vs \((1 - \cos \theta)\) will show a straight line, in which the intercept on the vertical axis has a value of \(1/0.662\) MeV\(^{-1}\). The slope of the line is \(1/mc^2\). Determine the intercept and slope from your data and compare to the values expected.

F) MEASUREMENT OF THE COMPTON SCATTERING CROSS SECTION

From the scattered gamma ray energies \(^{137}\)Cs measured in Part E, calculate the experimental Compton scattering cross section values and normalize to the data at 15°. Plot the scattering cross section vs. angle, including estimated errors. Calculate the theoretical cross section values for all the scattering angles performed in the experiment and normalize to the data at 15°. Compare your experimental data for the scattering cross section with theory.
REFERENCES


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MCA-3 SOFTWARE GUIDE

I. DATA ACQUISITION
   a) Click “DATA OPERATIONS” icon
      i) Enter spectrum title as: 
         C:\MCA3\data\Spectrum Name
   b) Click “RANGE… PRESET” icon
      i) Set range to 256
      ii) Enable REALTIME PRESET checkbox
      iii) Enter the data acquisition preset time
   c) Click “DISPLAY OPTIONS” icon
      i) Select “SPLINE I” for type
   d) Start acquisition by clicking ‘start’ button
   e) Stop acquisition by clicking ‘stop’ button

II. REGION OF INTEREST (ROI)
   a) Press the right mouse button and drag it to define the region of interest
   b) Click “CREATE NEW ROI” icon to mark the defined ROI
   c) Goto “REGION” menu and select “FIT” to obtain ROI details.

III. PRINTING OF SPECTRUM
   a) Go to “FILE” menu and select “SETUP PRINTER”
      i) Change orientation to “Landscape”
   b) Next select “PRINT” from “FILE” menu
      i) Click “ADD” tab
      ii) Click “OK” to print.

IV. SAVING OF SPECTRUM
   a) Go to “FILE” menu and click “SAVE”