GAMMA RAY SPECTROMETER

In this experiment, the gamma ray spectra of various isotopes are studied using a gamma ray spectrometer consisting of a NaI(Tl) crystal (scintillator) optically coupled to a photomultiplier tube (scintillation detector), a tube voltage supply/signal amplifier, a pulse height analyzer, and a microcomputer. In a scintillation counter, the ionization and excitation produced by the passage of radiation is detected by the emission of weak flashes of light (scintillations) as the excited atoms of the crystal return to the ground state.

Theory:

Although the actual processes involved are rather complex, the following is a useful, simplified explanation of the detection of gamma rays by a scintillation counter.

Gamma rays (high-energy photons) interact with matter by three principal processes – photo-electric effect, Compton scattering, and pair production. It is the interaction of the gamma rays with the NaI(Tl) crystal (by one or more of these three processes) which allows their detection. The result of these interactions is that a gamma ray is converted (totally or partially) to kinetic energy of one or more electrons.

The sum of the kinetic energies of these electrons is equal to the energy deposited in the crystal by the incident gamma ray. These electrons lose energy by excitation and ionization of the atoms of the crystal. The de-excitation and de-ionization of these atoms result in the emission of fluorescent radiation (i.e. light, photons) of a frequency range characteristic of the crystal type. The intensity of the fluorescent radiation (the number of photons emitted) is proportional to the total kinetic energy of the electrons (which is equal to the deposited gamma ray energy) which caused the excitations. These fluorescent photons then travel through the crystal and strike the photocathode of the photomultiplier tube. The number of photoelectrons released at the photocathode by the fluorescent photons (photo-electric effect) is proportional to the number of incident fluorescent photons. The electrons produced at the photocathode are accelerated by a potential between the cathode and the first dynode. The oxide-coated surface of the first dynode, when struck by the photoelectrons, will emit 2 to 5 secondary electrons per incoming electron and these will be focused onto the second dynode. This multiplication on impact will continue until the electron cascade reaches the anode. The result is a voltage pulse across a load resistor connected to the anode. This voltage pulse can then be further amplified and analyzed.

It is important to note that the size of the voltage pulse at the anode of the photomultiplier tube is proportional to the amount of energy deposited in the crystal by the gamma ray, and that if the gamma ray is <u>stopped</u> in the crystal (i.e. all its energy is converted to electron kinetic energy), then the voltage pulse provides a measure of the incident gamma ray energy. Thus analysis of the phototube signals permits determination of the gamma ray energy spectrum.

Figure 1 shows the various stages involved in the conversion of the incident gamma ray to a voltage pulse at the phototube output.
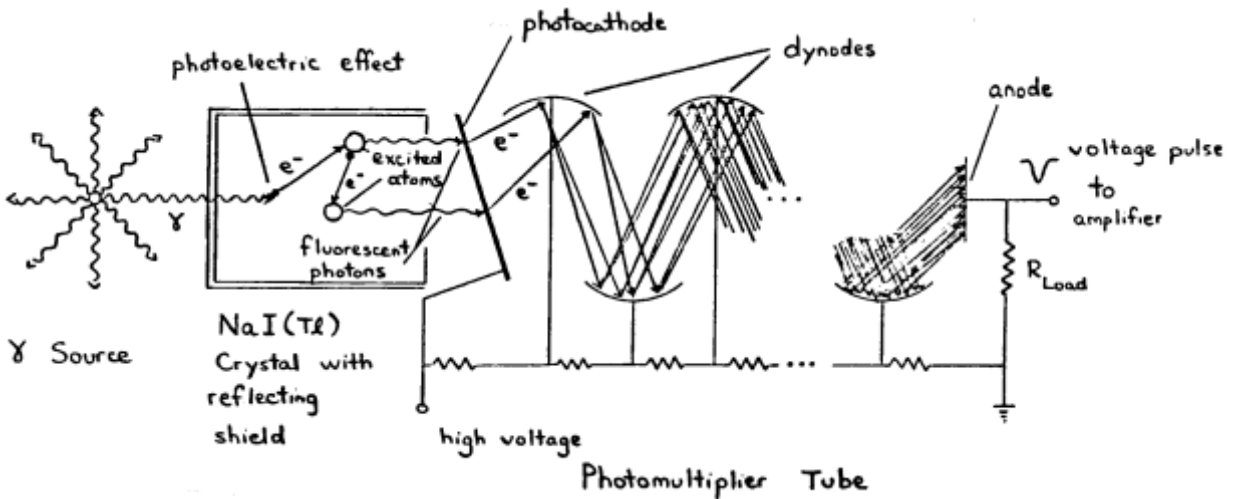
Figure 1

Shape of a typical Gamma Ray Spectrum

As mentioned previously, gamma rays interact with matter by the photo-electric effect, Compton scattering, and pair production.

In the photo-electric effect, the gamma ray is absorbed by an atomic electron in the crystal. A portion of the gamma ray energy, equal to the electron binding energy, is used to free the electron from the atom, and the remainder of the gamma ray energy is converted into kinetic energy of the free electron. The x-rays resulting from re-arrangement of the ionized atom are also converted to electrons by the photo-electric effect. Thus the gamma ray energy is totally converted to electron kinetic energy which in turn is converted to fluorescent light energy from excited atoms in the crystal. Since the gamma ray stops in the crystal, the resulting pulse from the photomultiplier tube is proportional in size to the incident gamma ray energy.

In Compton scattering, the gamma ray transfers some of its energy to an electron in a collision, leaving the remainder as a scattered photon. This scattered photon may interact further with the crystal, either by the Compton process or the photo-electric effect, or it may leave the crystal. If the photon escapes from the crystal then the electron kinetic energy, and hence the amount of fluorescent radiation, due to the partially converted incident gamma ray is less than that which would have resulted if the gamma ray had been completely absorbed. Therefore, the voltage pulse from the phototube can be of any size, from just above 0 to just below that corresponding to total gamma absorption, depending on how much energy the scattered gamma ray deposits before leaving the crystal.

If the incident gamma ray has an energy greater than $2m_ec^2 = 1.02$ MeV, it can spontaneously disappear and create an electron and a positron. The remaining energy (incident gamma ray energy minus $2\,m_e$) appears as kinetic energy shared between the electron and positron. The electron and positron travel through the crystal, losing energy by excitation of crystal atoms. After the positron stops, it annihilates with a nearby electron, leaving two photons of 0.511 MeV energy. Either or both of these photons may be totally converted (absorbed), partially converted, or pass out of the crystal. Therefore, the output voltage pulse can have a number of sizes, ranging from that corresponding to the incident gamma ray energy to that corresponding to the incident gamma ray energy minus 1.02 MeV, depending on what happens to the 0.511 MeV annihilation photons. since the sources used in this experiment have a maximum gamma ray energy of 1.33 MeV, pair production does not play an important role in the gamma ray absorption.

Figure 2 shows a typical gamma ray spectrum, obtained by plotting number of pulses vs. pulse size (i.e. voltage), for a <u>monoenergetic</u> gamma source.
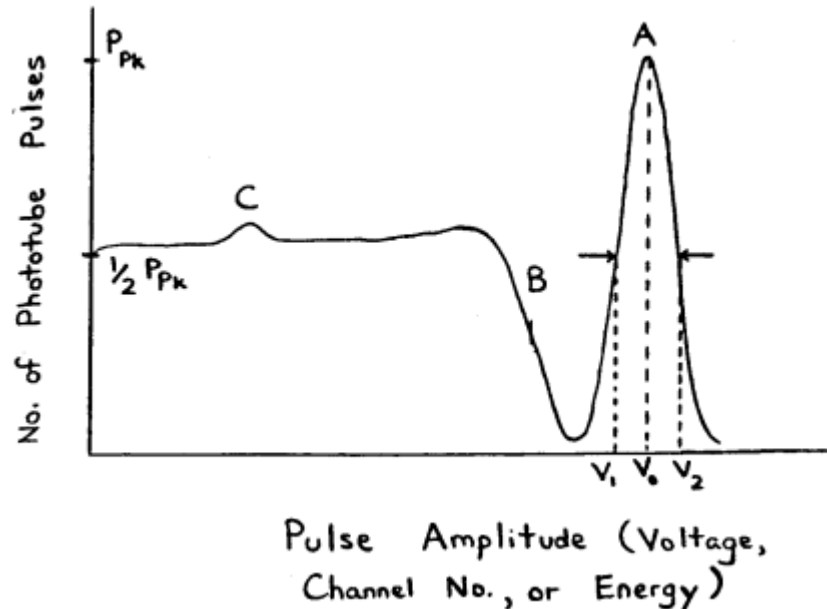

Figure 2

A number of features of this plot are worthy of mention. The peak at A results from complete gamma ray absorption whether by a single photo-electric event, or by Compton scattering followed by a photo-electric event. (Because the pulse amplitude per MeV is nearly independent of the kinetic energy imparted to the electrons for NaI(Tl), the response of the detector is linear. Thus the pulse amplitude is directly proportional to the amount of gamma ray energy deposited, no matter what the process.) Although the incident gamma ray is monoenergetic, the peak has a width due mainly to fluctuations in the number of electrons released at the photocathode per fluorescent photon.

Since the release of electrons at the cathode can be approximated by a Poisson distribution, the standard deviation, δN, of the actual number of electrons released, N, from the average, $\overline{N}$, is $\sqrt{\overline{N}}$. Now $\overline{N}$ is proportional to the energy deposited in the crystal, so the percentage fluctuation, $(\delta N/\overline{N}) \times 100\%$ (which equals $(1/\sqrt{\overline{N}}) \times 100\%$) is proportional to $1/\sqrt{E}$. Therefore the resolution of the spectrometer, expressed as a percentage (full width of peak at half maximum (FWHM) divided by value at peak) is roughly proportional to the inverse square root of the gamma ray energy. In Fig. 2, the measured resolution would be $[(V_2 - V_1)/V_0] \times 100\%$, where V_2, V_1, and V_0 are pulse amplitudes expressed as voltage, channel number, or energy.

The continuum for pulse amplitudes from 0 to B is due to the various amounts of gamma ray energy absorbed by the crystal for Compton scattering. Point B, the Compton edge, represents the maximum energy imparted to the crystal by the Compton process. The deposited gamma energy corresponding to point B can be found from the Compton scattering equation, knowing the incident gamma ray energy:

$$E_B = E_\gamma - \frac{E_\gamma}{1 + \frac{E_\gamma}{mc^2}(1 - \cos 180°)}$$

where E_γ = incident gamma ray energy
                         m = electron mass

If only one interaction were possible between the incident gamma ray and the crystal, the spectrum would drop sharply to 0 at B, then rise again at A, because there would be no possible interaction yielding pulse amplitudes (gamma energy losses) between B and A. The occurrence of multiple interactions between the gamma ray and the crystal results in a moderation of the slope of the Compton edge and a continuous distribution of pulse amplitudes.

The small peak at C is due to gamma rays that are backscattered from the source shielding or the photomultiplier window into the crystal, where they are converted. Gamma rays that backscatter at 180° are most likely to enter the crystal and be detected, so the energy corresponding to C is:

$$E_C = E_\gamma' = \frac{E_\gamma}{1 + \frac{E_\gamma}{mc^2}(1 - \cos 180°)}$$

The ratio of the number of gamma rays completely absorbed in the crystal to the number which are only partially converted and escape (size of peak relative to size of continuum) depends on a number of factors. Low gamma source energies and large crystals favour complete absorption. The photo-electric effect increases with respect to the Compton process with increasing atomic number of the crystal atoms, so crystals made from high Z materials will also favour complete absorption. Also, the slope of the Compton edge becomes more moderate as the crystal size is increased due to the higher probability of multiple interactions.

Apparatus:

The output pulses from the photomultiplier tube are amplified and then sent to the pulse height analyzer. The pulse height analyzer, an EG&G Ortec card in the microcomputer, digitizes the input pulses and displays a spectrum of number of pulses versus channel number. The channel number is proportional to the pulse amplitude and hence also to the deposited gamma ray energy.

The tube voltage supply/pulse amplifier (Model 2010 Nuclear Amplifier Analyzer) control settings have been properly adjusted, and should not be changed.

The following instructions apply to the operation of the PC-based pulse height analyzer.

1. Turn on the scintillation amplifier/high voltage power supply. Check that the settings are:

    COARSE GAIN: 20
    FINE GAIN: 2.6
    Analyzer switch: INTEGRAL

If any of these settings are different, consult your lab instructor.

2. Log on to the Arts and Science Computer Labs network.

3. In the 'MAESTRO 32' Program Group, click on the 'MAESTRO for Windows' icon to load the software used by the multi-channel analyser card.

4. Maximize the Maestro window. Click on the 'Zoom Out' button, 🔍, until the full range of channels is displayed in the main window (the 'Horizontal Full Scale' box should read 2048). Deselect 'Log' and select 'Vertical Auto Scale' by clicking in the appropriate boxes (Log A).

5. From the **Display** menu, select **Preferences ▷ Fill All**.

Data acquisition is controlled from the **Acquire** menu:

> **Preset Limits...**   allows you to preset the acquisition time (use the 'Live Time = ' box)
>
> **Start, Stop, Clear**   (should be self-explanatory)

The marker can be moved by clicking at the desired location. The number reported beside 'Marker:' in the bottom left of the window is the channel number corresponding to the marker location.

To obtain the total counts over a range of channels, a Region of Interest (ROI) must be defined. This is done, using the mouse, as follows:

• Move the marker to the left-hand limit of the desired ROI (channel 0 for this lab).

• Click and drag with the left mouse button so that the rectangle that forms brackets the desired range of channels (0 to 2044 for this lab). Right-click and select 'Mark ROI'. The desired ROI should fill with colour.

• The 'Gross Area:' number reported in the bottom left of the window is the total number of counts between the marker limits (i.e. total number of counts in the ROI).

Procedure and Experiment:

NOTE: For reliable results, the high voltage supply/pulse amplifier should be turned on half an hour before measurements are to be taken.

1. The spectrometer must be calibrated. This is done using the sources whose gamma ray energies are given in the following table.

Source	Energy of emitted gamma ray (keV)
^{22}Na	511, 1275
^{54}Mn	835
^{57}Co	122
^{109}Cd	88

Acquire the gamma ray spectrum for the ^{22}Na source.

For each gamma ray peak, define an appropriate ROI that brackets the gamma ray peak and record the peak channel number. When defining the ROI's, note that you can use the 'Zoom In' button, , to expand the region containing the peak.

Calibration is done as follows:

*   Place the marker in the ROI of the peak

*   In the **Calculate** menu, select **Calibration...**

*   Enter the appropriate energy (in keV) in the **Calibration (Energy)** box and click on **OK**

*   If prompted, enter the units as **keV**

Go to the **Acquire** menu and select **Clear**.

Repeat the above steps for the other calibration sources.

Once the calibration procedure has been completed, clear the ROI's by going to the **ROI** menu and selecting **Clear All**.

As a check of the linearity of the system's response, plot by hand the energy calibration curve, i.e. plot gamma ray energy vs. peak channel number. The equation of this line allows manual conversion from channel number to energy.

2. Study of Source with closely spaced gamma ray energies (^{133}Ba)

    Acquire the spectrum for ^{133}Ba. For each observable peak, record the energy and the number of counts at the peak energy. (To accurately determine the peak location, define a ROI around the peak.)

    According to the 56th edition of the CRC Handbook of Chemistry and Physics, the energies and relative intensities of the gamma rays emitted by ^{133}Ba are as follows:

Energy (keV)	Relative Intensity
80	5
276	1
302	3
356	10
382	2

    Compare the tabulated energies and relative intensities with the experimentally determined energies and peak counts. Do some energies seem to be missing? Are there 'extra' peaks? Comment.

3. Study of ^{137}Cs

    Acquire the gamma ray spectrum for ^{137}Cs. Identify as many features as possible, in particular determine the gamma ray energy, the FWHM of the peak, the Compton edge, and the 180° backscattering peak energy. Compare with the accepted gamma energy of 662 keV. Calculate the expected energy of the Compton edge and compare with the value determined experimentally. Calculate the expected energy of a peak due to 180° backscattering of gamma rays. If the peak was visible on the spectrum, compare its experimental energy with the theoretical value.

4. Study of ^{60}Co

    Acquire the ^{60}Co gamma ray spectrum. Determine the energies of the two peaks and compare with the accepted values of 1173 and 1332 keV.

5. Measurement of Unknown Source

    Acquire the gamma ray spectrum of the unknown source. Determine the energies of the gamma rays corresponding to the observed peaks. Do any of the observed peak energies match the energy of a peak from a source used previously? If so, which one(s)?

6. Calculate the resolution (FWHM (in keV)/peak energy) for the gamma rays from ^{109}Cd, ^{22}Na, ^{54}Mn, and ^{137}Cs. As stated previously, simple theory predicts that the resolution should vary inversely as the square root of the peak energy. Do your measurements agree with this prediction? (Plot resolution versus $1/\sqrt{E}$.)

7. Study of ^{133}Ba with different detector/analyzer system

    Ask the instructor to show, and explain the operation of, the lithium drifted germanium (GeLi) detector system. Ionization caused by the passage of radiation into the detector produces a voltage pulse that is directly related to the energy deposited in the detector by the radiation. Since there is no 'electron multiplication' stage the resolution of this system is quite good.

Acquire the spectrum for ^{133}Ba. Measure the energies and peak counts of all observable peaks. Compare the energies and heights of the experimental gamma ray peaks with the accepted energies and relative intensities.

References:

Ajzenberg-Selove, Nuclear Spectroscopy, Part A, QC 784
Bleuler, Experimental Nucleonics, QC 784
Curran, Luminescence and the Scintillation Counter, QC 787
Fretter, Introduction to Experimental Physics, QC 41
Halliday, Introductory Nuclear Physics, QC 173
Melissinos, Experiments in Modern Physics, QC 33
Siegbahn, Beta and Gamma Ray Spectroscopy, QC 771