SU QuarkNet Workshop 2012 — Lab Activity 2
GAMMA SPECTROSCOPY

Laboratory Goals

1. Learn about radioactivity, radiation sources, and emission spectra.
2. Learn how to use a photomultiplier tube and a Multi-Channel Analyzer as a scintillation spectrometer.
3. Observe total absorption peaks and Compton spectra by detecting gamma-rays from ^{137}Cs and ^{60}Co decays.
4. Determine the gamma spectrum from natural background radiation.
5. Measure energy resolution of the spectrometer.

1. INTRODUCTION: GAMMA DECAYS

Gamma-rays are emitted by certain transitions between an unstable nucleus and one with a lower energy state. These are electromagnetic transitions, so the charge Z does not change. Similarly so for the mass A of the nucleus. However other quantum numbers do change. Two examples of gamma decays in nuclei are ^{137}Cs and ^{60}Co.

As shown in Figure 1, $^{137}_{55}$Cs decays principally by the β^- process. In 94.7% the β^- decay occurs to the excited state of $^{137}_{56}$Ba. The maximal electron energy is 0.514 MeV. This excited state of Ba decays in a matter of milliseconds to the ground state of this nucleus by emission of 0.662 MeV γ-ray. This is our principal line. The rest of the time (6.5%), $^{137}_{55}$Cs decays directly to the ground state of Ba via another β^- decay (the maximal energy of these electrons is 1.176 MeV). In addition to these nuclear transitions, atoms participating in the change of the nucleus can be excited and subsequently emit X-rays. This process produces a monochromatic X-ray line of energy 32 keV.

As shown in Figure 2, $^{60}_{27}$Co practically always decays by β- (with the maximal electron energy 0.314 MeV) to the excited state of $^{60}_{28}$Ni (99.9%). The latter always decays by γ-transition to a lower excitation, which in turn decays again by γ-emission to the ground state of $^{60}_{28}$Ni. Energies of the gammas emitted in the γ-cascade process are 1.173 MeV and 1.332 MeV. These are our principal lines for this decay.
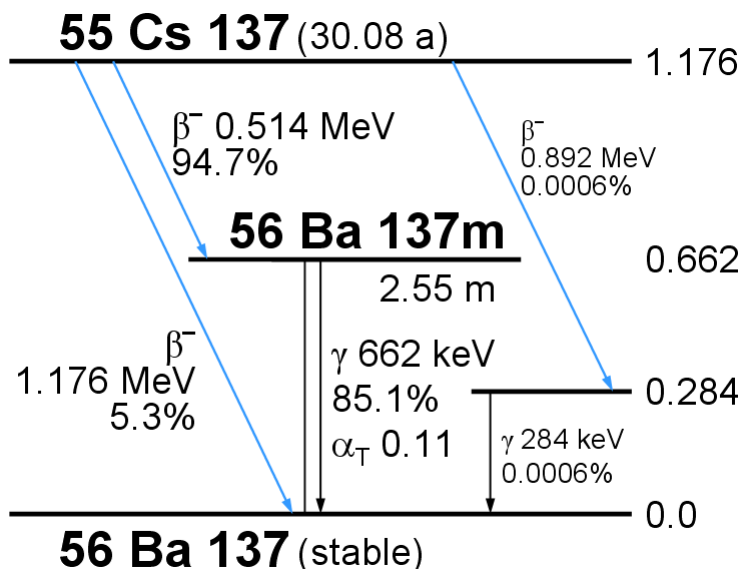
55 Cs 137 (30.08 a)   1.176

β⁻ 0.514 MeV
94.7%   β⁻
                             0.892 MeV
                             0.0006%

56 Ba 137m   0.662
2.55 m

β⁻
1.176 MeV   γ 662 keV
5.3%   85.1%   0.284
                 α_T 0.11   γ 284 keV
                               0.0006%

                                                           0.0
56 Ba 137 (stable)

Figure 1. Energy level diagram for 137Cs decays. The various decay modes
(β±,γ) are shown, along with their emission energies and branching
probabilities. From [2]. Here a = yr, m = metastable, and αT =
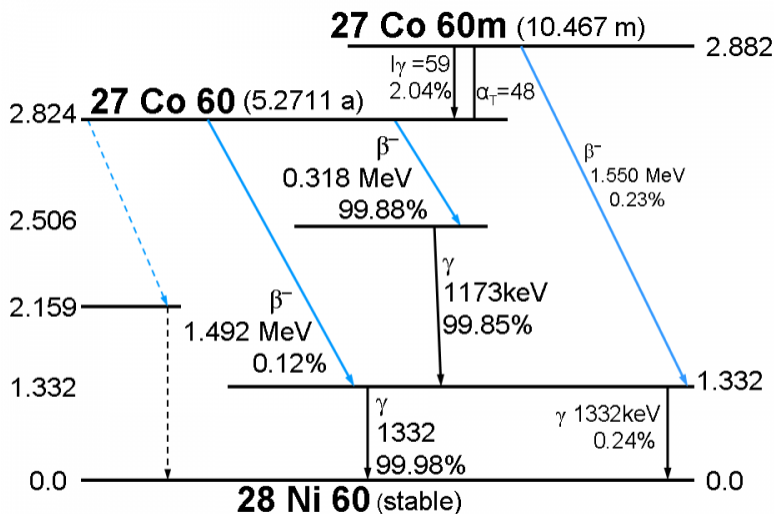electron capture (EC).

                    27 Co 60m (10.467 m)   2.882
                    I_γ =59│
                    2.04% │α_T=48
2.824 **27 Co 60** (5.2711 a)
                         β⁻
                    0.318 MeV   β⁻
                    99.88%   1.550 MeV
2.506   0.23%

                         β⁻   γ
2.159 ───────   1.492 MeV 1173keV
                         0.12%   99.85%

1.332 ──────────   1.332
                              γ
                              1332   γ 1332keV
                              99.98%   0.24%
0.0 ──────────   0.0
      28 Ni 60 (stable)

Figure 2. Energy level diagram for ⁶⁰Co decays. From [2]. Annotations here
follow those of the previous diagram.

2. SCINTILLATION DETECTORS

The range of γ-rays in a material is usually much longer than that for charged particles. Low density detectors, such as gas tubes in Geiger-Müller counters, routinely used for detection of α or β radiation, have very low detection efficiency for gamma rays. Solids have sufficient density to absorb photons using even small size detectors. In gaseous detectors, ionization charge released in the absorption of nuclear radiation is easily collected via an electric field applied to the detector. In conductors, the ionization charge cannot be detected on top of the ordinary electric current flowing whenever electric field is applied. In insulators, electrons cannot move at all. Semiconductors offer one possibility for construction of solid state detectors for nuclear radiation. Another type of solid state detector is offered by scintillating materials. No external electrical field is required. In the scintillators, part of the energy absorbed by the material is turned into secondary photon radiation of much smaller energy than that of nuclear radiation. The scintillation photons are emitted by electrons excited in atoms, molecules or crystals. The important feature of scintillation photons is that they cannot be easily re-absorbed by the material. This happens when the electron de-excites to an energy level which is usually not populated in the material (typically, a level created by impurities added to the material). Thus, scintillation photons escape the original material and are detected in an auxiliary detector attached to the scintillator.

The PhotoMultiplier Tube (PMT) is the most common detector of scintillation radiation. Scintillating photons incident at the photocathode of the PMT liberate electrons via the photoelectric effect. These electrons are then accelerated by the electric field created between the cathode and the first dynode. Kinetic energy of the accelerated electrons in used to liberate even more electrons when they strike this dynode. The first dynode is followed by another one and the multiplication process is repeated. Usually several stages of dynodes are used. Eventually, electrons reach the anode— the electrode at the highest positive potential. Thus, photomultiplier allows not only detection of the scintillation photons but also provides large signal amplification. For example, a 10-dynode PM can produce 10^7 electrons at the anode, compared to one electron at the photocathode. In this case, we would say that the tube has a gain of 10^7. There is a fairly large spread about a peak value, but gains of 10^6–10^7 are typical.

All types of nuclear radiation can be detected with scintillation detectors. Interactions of gammas are more probable in high Z materials. Organic scintillators (e.g. Anthracene, and certain types of plastic) have low Z values and therefore are used to enhance charged particle signals over γ-rays. Inorganic crystals are used for detection of gammas (e.g. NaI, CsI). The scintillation in crystals is usually obtained by doping the crystal with small amounts of some impurities to create the energy levels needed. For example, doping with Tl is indicated by NaI(Tl), or CsI(Tl).

3. SCINTILLATION SPECTROMETER

Scintillators can be used not only to count nuclear radiation (like Geiger-Müller counters), but also to measure energy of the radiation. A device used to measure particle energy (here gamma energy) is called the spectrometer. An approximately constant fraction of energy absorbed by the material is turned into scintillation photons. Since the energy needed to emit one scintillating photon is always the same, **the total number of scintillation photons is proportional to the absorbed energy**. The number of electrons liberated by the scintillation photons on the photocathode of the PMT is again proportional to the number of photons. Since every electron emitted by the photocathode goes through the same multiplication process in the system of dynodes, the total output from the photomultiplier is linearly proportional to the number of primary electrons, and thus to the energy absorbed by the scintillator material. Hence, the total charge produced on the output of the PM can be used to measure energy deposited by the nuclear radiation in the detector. If the radiated particle stops in the detector, its total kinetic energy is measured.

In order to make the measurement, the charge signal from the PMT is usually integrated in a preamplifier and then the voltage signal is amplified and shaped in an amplifier. The amplification is usually precisely linear to preserve direct proportionality to the absorbed energy.

The spectrometer (apparatus designed to measure particle energy) is completed by a device allowing analysis of voltage pulse heights (PHA = Pulse Height Analyzer). The simplest device of this kind is called Single Channel Analyzer (SCA). It consists of a double discriminator. The incoming voltage signal is discriminated at two different voltage values. The output signal is logical in nature. No signal is set if the input signal did not pass any of the discrimination thresholds, or passed both of them. Thus, the positive output, in a form of a standard pulse in height and duration, is set only if the pulse height happens to fall in between the two discriminator thresholds. In practice, one adjusts the lower discriminator threshold and the voltage window (the difference between the upper and the lower thresholds). The SCA is usually followed by a scaler, which allows for counting the number of pulses within the SCA window in a preset time interval. Counting must be repeated many times to compare frequency of various energy depositions in the detector.

A Multi Channel Analyzer (MCA) can be used to analyze the distribution of various pulse heights in a single time interval. The MCA detects changes in the input voltage over time. Local voltage maximum is detected by the initial rise followed by the drop of voltage. The maximum voltage is then turned into a number (called a "channel number") which is proportional to the voltage value. This conversion is performed by the so-called Analog-to-Digital Converter (ADC), which is built into the MCA. The MCA counts how many times each number occurred and displays the results in a form of a histogram. The horizontal axis corresponds to the channel number, thus to the pulse height or the detected energy. The vertical axis gives a number of counts in each channel. One can think of MCA as a large number of SCAs, counting at the same time with the same voltage windows and adjacent discriminator thresholds. Image all these SCAs strung together end-to-end in pulse height. The voltage window (also called "bin size") is equal to the total voltage range covered by MCA divided by the number of channels.

4. GAMMA ENERGY SPECTRA

If all the γ energy is absorbed in the scintillator, the spectrometer will produce a pulse with the height proportional to the incident photon energy. Even if the incident gammas are monochromatic (i.e. have the exact same energy), the pulse heights corresponding to the total absorption of different γ-rays will differ slightly because of the fluctuations in the scintillation process, in the conversion to PMT electrons and in the amplification process.   The monoenergetic γ-ray will produce a peak on the MCA histogram. The width of this peak will depend on the size of these fluctuations. This width usually is a feature of the spectrometer rather than of the gamma ray, and it is called "resolution" of the spectrometer. Resolution in absolute (energy) units usually increases with photon energy. Relative resolution, i.e. ratio of the resolution to the photon energy, usually decreases with photon energy. .

In small size scintillation detectors the photon energy is totally absorbed only in some fraction of all events. This fraction is a function of the detector size and of the gamma energy. Low energy gammas (<0.1 MeV) have a high probability for interaction with matter by the photoelectric effect. In a single collision with an atom, the photon is totally absorbed and its energy is turned into kinetic energy of the electron (minus binding energy of the electron which can be neglected here). The electron kicked off in this process has a very short range in a dense material of the scintillator and quickly loses all its kinetic energy in Coulomb scattering with other atomic electrons. Some fraction of the energy transferred to the atoms in this process is emitted in a form of scintillation photons. Since all the photon energy is absorbed a peak will be produced in the pulse height spectrum. This peak is called "photopeak" or "total absorption peak". The probability for photoelectric effect is proportional to Z^4 of the material.

At intermediate photon energies (0.1-1.0 MeV, depending on the material) Compton scattering becomes more probably than the photoelectric effect. Compton scattering is a pure kinematic collision between a photon and an atomic electron. The photon never gives up all its energy. The energy of the scattered photon depends on the angle between the incoming and the outgoing photon (θ):

$$E'_\gamma = E_\gamma \frac{1}{1 + E_\gamma / m_e (1 - \cos\theta)}$$

Energy gained by the electron can be calculated from

$$E_e = E_\gamma - E'_\gamma$$

The maximal energy transfer from the photon to the electron occurs when the photon is back-scattered ($\cos\theta = -1$):

$$\min(E'_\gamma) = E_\gamma \frac{1}{1 + 2E_\gamma / m_e}$$
.

Energy of the Compton electron is measured in the detector, which in this case is maximized.

$$\max(\mathrm{E_e}) = \mathrm{E}_\gamma - \min(\mathrm{E}'_\gamma)$$.

For forward photon scattering, $\cos\theta = +1$, $E'_\gamma = E_\gamma$ and $E_e = 0$. The energy spectrum of Compton electrons stretches from zero up to the maximal value. Even when photon energy is such that Compton scattering dominates over other processes, the total photon energy can be still absorbed by the scintillator because the photon may interact more than once in the material. In particular, when photon loses a lot of energy in the Compton collision the outgoing photon is much softer and has much higher probability to be totally absorbed in the photoelectric effect. Multiple Compton scattering is also possible. In a small scintillating detector, photons will produce the total absorption peak and a flat spectrum from the first Compton scattering ending by an enhancement at the $\max(E_e)$ given above (so called "**Compton edge**"). There will be a minimum in intensity for energy depositions in between the Compton edge and the total absorption peak. The intensity does not go totally to zero in this region, because of multiple Compton scattering. In a large scintillation detector, photon escape after the first Compton scattering is rather unlikely, and therefore the total absorption peak will be more intense on the expense of the Compton spectrum intensity. Also the Compton edge will be smeared by secondary Compton interactions. The Compton process may produce yet another interesting structure in the measured absorbed energy spectrum if some photons can interact in the material *surrounding* the scintillator. Then the scintillator measures the Compton scattered photon beam on top of the direct photon beam. The probability for Compton scattering peaks somewhat for the backscattering in the *surrounding* material, which produces the peak in the measured energy spectrum if the scattered photon is then totally absorbed in the scintillator (so called "**back-scattering peak**"). The probability for the Compton interaction does not depend on Z.

When photon energy exceeds twice the electron's rest mass energy, $2m_e$ (=1.022 MeV), a third type of photon interaction with matter is possible—pair production. In this process, the gamma is *completely absorbed* and its energy is turned into a creation of electron-positron pair. Above a few MeV, this process completely dominates over Compton scattering. Both electron and positron lose their kinetic energy and stop. Note that the kinetic energy of the pair is equal to $E_\gamma - 2m_e$ and not to E_γ. The fraction of gamma energy trapped in the electron mass cannot be detected in the scintillator. However, the stopped positron annihilates with an atomic electron and produces two photons each of energy equal to the electron mass. Thus, the energy left in the electron mass is recovered by destroying one of the atomic electrons. If both annihilation photons are absorbed the total energy absorbed in the detector is $E\gamma$, and thus the total absorption peak is produced. If one annihilation photon escapes the detector, the measured energy equals $E_\gamma - 2m_e$ ("single escape peak"). If both annihilation photons are missed the double escape peak is observed $E_\gamma - 2m_e$. The probability for pair production depends on Z^2 of the material.

For further information, see Krane [1], sections 7.1, 7.3, 7.6.

5. APPARATUS

The setup for this experiment is shown in Figure 3. Before taking data, check that the connections are correctly made. You will be asked to change the configuration inside the dark box several times to take different spectra.

<div style="border: 2px solid red;">

SAFETY PRECAUTIONS:

- Handle the PMT carefully. Avoid scratching the entrance window.
- Do not exceed 900 V high voltage on the PMT.
- Handle the NaI(Tl) and CsI crystals with care. They can crack under mechanical stress or mechanical shock.
- *Only the instructor should handle the radiation sources !!!*
- *Before you turn on any high voltage ask the instructor to approve the setup.*
- *Never open the dark box when the HV is ON !!!*

</div>

1. Make sure the high voltage is set to OFF before opening the dark box.

2. Check to see that the (red) High Voltage Cable that is connected to the photomultiplier tube is connected to the corresponding HV cable on the outside of the dark box. Do the same for the (black) Signal Cable.

3. Arrange the PMT, scintillator and source on the block supports provided. They should be centered coaxially for these measurements. Consult with the instructor for precautions in handling these elements.

4. Connect, if not already connected, the HV Cable from the dark box to the back of the Power Supply. Then connect, if not already connected, the Signal Cable from the dark box to the input of the Spectroscopic Amplifier.

5. Make sure that the settings in the actual amplifier correspond to the settings on the diagram. The input signal is positive. Set the output to bipolar shape. Set the gain on the amplifier to 300.

6. Connect a new (black) Signal Cable to the Bipolar Output on the Amplifier. Then connect that to the slot on the back of the 'Ancient Computer' (or to the input on the oscilloscope, depending on the experiment you are doing).

7. Double Check to make sure that everything's set up correctly! Turn on the power switch (to the right), and wait for the Stand-by (white) light turns on. Now you're ready to turn on the HV.

8. Turn the HV switch to the right to turn it on. Then, slowly turn up the Output Voltage to 900V. First, start with turn the leftmost dial to the 500V setting. Then, increment the next dial until it reaches 400V. These together make 900V in total.
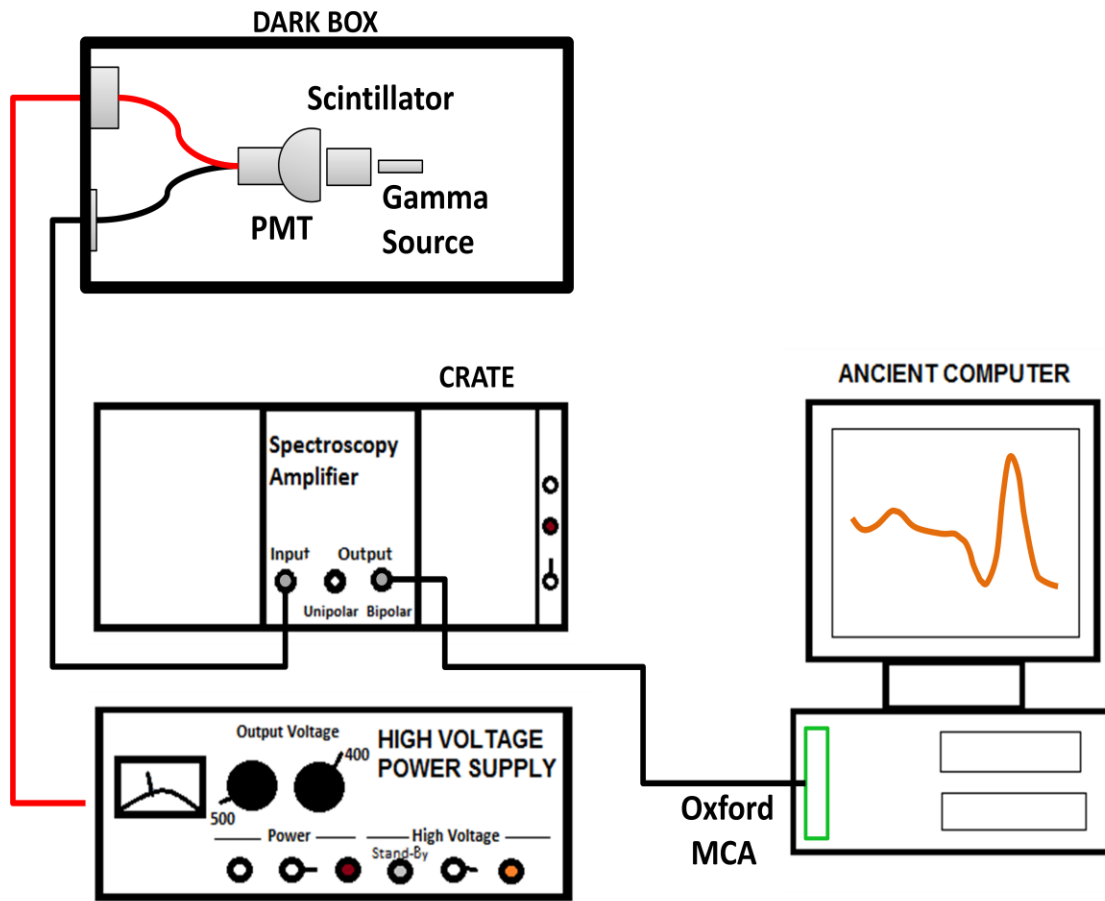
Figure 3. Setup for gamma-ray spectroscopy measurements.

6. EXPERIMENTS

Experiment I. Observation of Scintillation Signals on the Oscilloscope

Configure the setup with the CsI scintillator and ^{137}Cs source. (*Make sure HV is turned off before opening the box to check.*)

1. Take the black signal cable and connect to the oscilloscope.

2. Observe the signal and its shape. Trigger on the negative edge of the signal. Note its amplitude, rise time and fall time. Sketch this in your logbook. Different pulse heights correspond to different absorbed energies. You should see crowding of the signal at the pulse height corresponding to full absorption peak of the 0.662 MeV gammas emitted by the ^{137}Cs source.

3. Remove the source and find the signal again. How is it different?

Repeat this exercise with 800 V high voltage. Note the differences.

Repeat this exercise looking at the output of the Amplifier. Note the differences in the signal shape and amplitude. Sketch again in your logbook. Estimate the gain of the amplifier based on your measurements. The overall gain of the full system is a product of the PM gain and of the amplifier gain.

Repeat this exercise using the NaI(Tl) scintillator. What are differences do you observe?

Experiment II. The ^{137}Cs Energy Spectrum with the Multi-Channel Analyzer

Configure the setup with the CsI scintillator and ^{137}Cs source.

Obtain the energy spectrum for this arrangement.

Make a drawing of the spectrum displayed on the screen. Try to interpret what you are seeing in terms of the previous pulse height measurements. Note the widths of the peaks also.

Interpret the spectrum in terms of the physics processes that are involved. You should see total absorption peaks for 0.662 MeV and 0.032 MeV gammas. You might not see the low energy peak, due to the threshold of the MCA. Use these two peaks to calibrate the MCA horizontal scale in keV (see MCA manual). Alternately, use the single peak and the zero pulse height (less accurate). Using this calibration read from the spectrum energy of the Compton edge and of the backscattering peak. Compare the measured values with theoretical calculations presented in the introduction.

You can save the spectra on the disk and transfer it to Excel to do additional analysis. You will have to save the file twice, as an asc-file and an ans-file. Consult the instructor on this.

Take a spectrum without the source, and save. This will be the background spectrum. Perform a subtraction to see the real signal spectrum.

Repeat for NaI(Tl) scintillator and ^{137}Cs. Explain the differences.

Experiment III. The ^{60}Co Energy Spectrum

Configure the setup with the CsI scintillator and ^{60}Co source. Use the energy calibration obtained from CsI here (you may have to remake the calibration).

Take an energy spectrum for ^{60}Co.

Make a drawing of the spectrum obtained.

Interpret the spectrum in terms of the physics processes that are involved. Measure the energies of all peaks observed. Do the measured energies agree with your expectations? Measure the energy of the Compton edge and of the backscattering peak if you see them. Compare them to the expected values from the higher energy photon. Counting for a longer time you should be able to see a weak line corresponding to the total absorption of both gammas at the same time. As the lifetime of the intermediate Ni state is short (0.7 ps) compared to the time resolution of the spectrometer (~μs), absorption of these two separate photons can be observed as a single event. Does the measured energy equal the sum of individual photon energies?

Experiment IV. Determine the Resolution of the Spectrometer

Study the spectrometer resolution in a function of gamma energy. Measure the FWHM of full absorption peaks, and plot $\sigma E/E$ as a function of γ energies E (σ = FWHM/2.36). Use the photopeaks observed in the ^{60}Co and ^{137}Cs spectra. Plot the FWHM estimated "by eye." You can use either the MCA built in functions: ROI, FWHM (see manual) or use Excel offline. Does relative resolution improve with photon energy?

Experiment V. Obtain a Gamma Spectrum from the Walls

Configure the setup with the CsI scintillator and ^{60}Co source. Using the calibration obtained from the ^{137}Cs and/or ^{60}Co spectrum, take a photon spectrum without any source. You will need to do this for approximately one hour.

The spectrum you obtain results from several sources: radioactivity from the walls, cosmic rays, phototube noise, and any residual activity in the CsI crystal. You can isolate the first two sources from the latter two by surrounding the phototube and crystal with enough absorber. If you have time, you can try to get 2-4" of lead around the scintillator. Then take a spectrum for an equal amount of time. You can subtract the spectra and see what radioactivity is arising from outside sources. You can also find out what peaks are present, by looking at a gamma decay table online. Are these peaks consistent with the resolution expected for photons as measured in the previous section? Can you can identify what nuclei are the parents?

Thorium Series (4n)[*]

Nuclide	Historical Name	Half-life	Major radiation energies (MeV) and intensities[†]		
			α	β	γ
$^{232}_{90}Th$	Thorium	1.14×10^{10}y	3.95 (24%) 4.01 (76%)	- - -	- - -
↓					
$^{228}_{88}Ra$	Mesothorium I	6.7y	- - -	0.055 (100%)	- - -
↓					
$^{228}_{89}Ac$	Mesothorium II	6.13h	- - -	1.18 (35%) 1.75 (12%) 2.09 (12%)	0.34c# (15%) 0.908 (25%) 0.96c (20%)
↓					
$^{228}_{90}Th$	Radiothorium	1.910y	5.34 (28%) 5.43 (71%)	- - -	0.084 (1.6%) 0.214 (0.3%)
↓					
$^{224}_{88}Ra$	Thorium X	3.64d	5.45 (6%) 5.68 (94%)	- - -	0.241 (3.7%)

↓ $^{220}_{86}Rn$	Emanation Thoron (Tn)	55s	6.29 (100%)	- - -	0.55 (0.07%)
| ↓ $^{216}_{84}Po$	Thorium A	0.15s	6.78 (100%)	- - -	- - -
↓ $^{212}_{82}Pb$	Thorium B	10.64h	- - -	0.346 (81%) 0.586 (14%)	0.239 (47%) 0.300 (3.2%)
| ↓ $^{212}_{83}Bi$ ↓	Thorium C	60.6m	6.05 (25%) 6.09 (10%)	1.55 (5%) 2.26 (55%)	0.040 (2%) 0.727 (7%) 1.620 (1.8%)
64.0% 36.0% ↓ | $^{212}_{84}Po$ |	Thorium C'	304ns	8.78 (100%)	- - -	- - -
| ↓ | $^{208}_{81}Tl$ | | | | |___|	Thorium C''	3.10m	- - -	1.28 (25%) 1.52 (21%) 1.80 (50%)	0.511 (23%) 0.583 (86%) 0.860 (12%) 2.614 (100%)
↓ $^{208}_{82}Pb$	Thorium D	Stable	- - -	- - -	- - -

* This expression describes the mass number of any member in this series, where n is an integer.

Example: $^{232}_{90}Th$ (4n) ....4(58) = 232

† Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series. Complex energy peak which would be incompletely resolved by instruments of moderately low resolving power such as scintillators.

Data taken from: Lederer, C.M., Hollander, J.M., and Perlman, I., Table of Isotopes (6th ed.; New York: John Wiley & Sons. Inc., 1967) and Hogan, O.H., Zigman, P.E., and Mackin, J.L., Beta Spectra (USNDRL-TR-802), [Washington, D.C., U.S. Atomic Energy Commission, 1964]).

7. REFERENCES

[1] Kenneth S. Krane, Introductory Nuclear Physics, John Wiley & Sons (1988).

[2] Nucleonica wiki [`http://www.nucleonica.net/wiki/`].

This document is based on the laboratory write-up by S. Stone, for the SU course PHY344 Experimental Physics (2005). Additional contributions to this write-up by: R. Mountain, E. Cowan, and S. Blusk, for the SU QuarkNet Workshop (2012).