



LINKÖPINGS UNIVERSITET

IFM – The Department of Physics, Chemistry and Biology

LAB 26

Analysis of γ spectrum

NAME	
PERSONAL NUMBER	
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APPROVED	

I. OBJECTIVES

- To understand features of gamma spectrum and recall basic knowledge of radioactivity;
- To become familiar with some basic techniques used for measuring γ -rays;
- To understand how NaI (Tl) scintillator and high-purity germanium detectors work;
- To identify an unknown radioactive source from analysis of the γ -ray spectrum.

II. BACKGROUND

1. Gamma source

In radioactive decay, the gamma rays can be created when an unstable (excited) nucleus returns to a ground state by emitting an excess energy as an electromagnetic wave. The gamma rays are often produced along with other products such as alpha α or beta β particles. A frequency of gamma rays is above 10^{19} Hz. It is important to understand a difference between the origin of gamma rays and X-rays. Although both of them have the range of frequencies overlapping, gamma rays comes from the nuclei of radioactive atoms while X-rays are emitted by electrons.

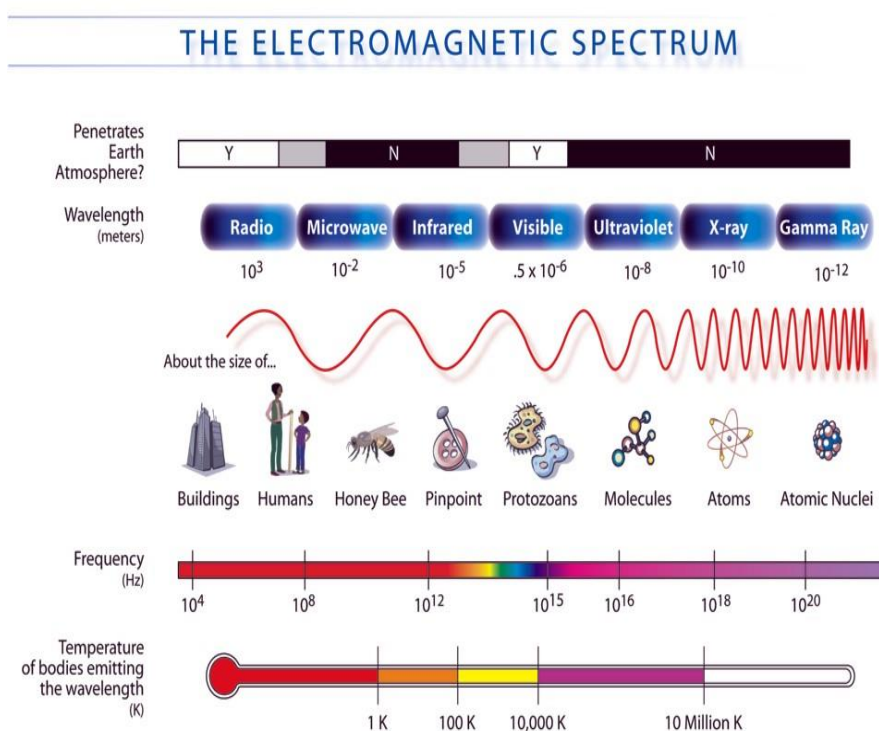


FIG 1. The electromagnetic spectrum

From: <http://mynasadata.larc.nasa.gov/science-processes/electromagnetic-diagram/>

2. Nuclei instability

Radioactive atoms have unstable nuclei which can switch to more stable state through a radioactive decay process. Now the question is why the radioactive nucleus are unstable? To understand this let's recall the four basic forces in nature:

- gravity;
- electromagnetic force;
- strong nuclear force;

- weak nuclear force.

In order to explain instability of radioactive nuclei we just focus on two of them. The Coulomb force (electrostatic force) is known as the repulsive force between particles of same charge or the attractive force between particles of opposite charge. Nucleus consist of two particles: proton and neutron in which proton has positive charge and neutron is neutral. Therefore, the protons will repel each other in a nucleus due to the Coulomb force while no Coulomb force exists between the neutrons. There must be a stronger force which keeps them together in a nucleus. That force is called the strong nuclear force which acts over a very short range for both protons and neutrons. This force is very strong in a short distance of $\sim 10^{-15}$ m and decreases rapidly to zero with an increase of the distance. So at higher distances the Coulomb force is dominant. In order to overcome the Coulombs force between the protons nucleus needs neutrons which contribute to the strong nuclear force. If there are no neutrons, no nucleus can be formed, except the case of hydrogen having only 1 proton. So the condition for stable nucleus is the right balance of protons and neutrons. If the balance is broken, the nucleus are unstable and can decay by suitable process to get the right balance which makes sure that a post-decayed nucleus are more stable. Another case making a nucleus unstable is that a nucleus is too large to be able to stay together. The solution now is to get rid of nucleons to reduce the size of nucleus. In nature, a nucleus can reduce its size by getting rid of nucleons by emitting alpha particle or splitting into two smaller nuclei.

Fig 2 shows the nuclear landscape dependence between number of protons (Z) and number of neutrons (N) plot. The black squares represent the stable nuclei, the yellow region shows the known and unstable nuclei, and the green region describes the unknown and unstable nuclei. The red vertical and horizontal lines show the magic numbers, reflecting regions where nuclei are very stable. Therefore, from Fig 2, we can observe the tendency of decay process of unstable nuclei. By decaying, unstable nuclei try to get closer to *“the line of stability”* (black squares).

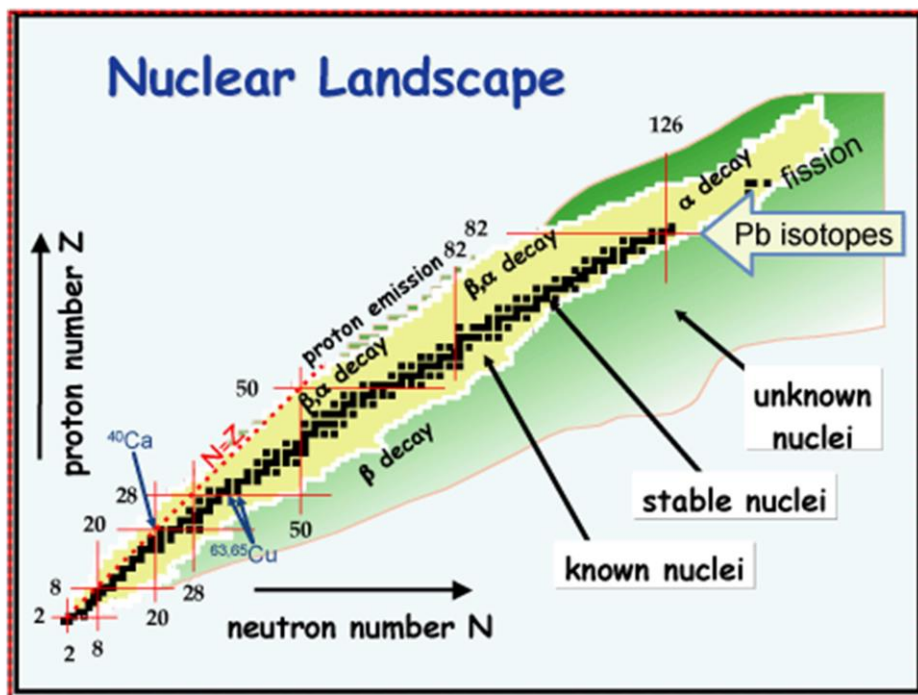
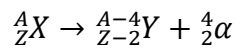


FIG 2. The chart of nuclides
From: <http://www.phy.ornl.gov/hribf/science/abc/>

3. Type of decay

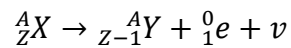
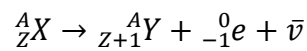
* Alpha Decay

An atom nucleus (parent atom) transforms into another atom nucleus (daughter atom) by emitting an alpha particle which is considered as the nucleus of He atom. Therefore, the new atom nuclei has a mass number 4 less and an atomic number 2 less than the parent atom.



* Beta Decay

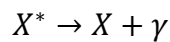
In the case of beta decay, a beta particle (electron or positron) is emitted from the parent atom. The daughter atom has an atomic number 1 more (electron) or 1 less (positron).



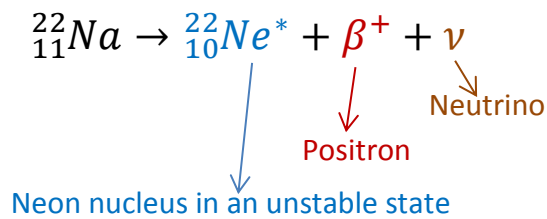
Where ν , $\bar{\nu}$ are neutrino and antineutrino, respectively; ${}^0_{-1}e$ is an electron; 0_1e is a positron.

* Gamma decay

In gamma decay, a nucleus just jumps from higher energy state to a lower energy state by emitting electromagnetic radiation (gamma photon).



* Decay of ${}^{22}\text{Na}$



After the beta decay β^+ , ${}^{22}\text{Na}$ nucleus is transformed into an unstable ${}^{22}\text{Ne}$ nucleus. The relaxation of this Ne nucleus to ground state gives rise to a gamma photon emission at **1.27458 MeV** (also see Fig. 3). Positron will immediately find electron and be annihilated. This process is called pair annihilation.

* Decay of ${}^{137}\text{Cs}$

Similar to the case of ${}^{22}\text{Na}$, ${}^{137}\text{Cs}$ decays to excited ${}^{137}\text{Ba}$ nuclei by β^- decay and then ${}^{137}\text{Ba}$ relaxes to the ground state by emitting the 0.66165 MeV gamma ray (see Fig. 2).

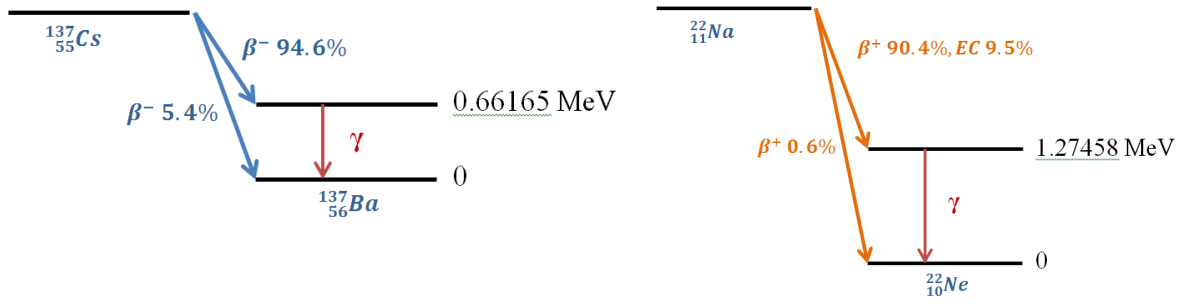


FIG 3. Decay schemes of ^{137}Cs and ^{22}Na

4. Gamma interaction with matter

It is essential to have a background of the basic processes how photon interacts with matter in order to understand how gamma ray detector works. There are three main processes which occur at the detector and allow us to infer the energy of the γ -ray:

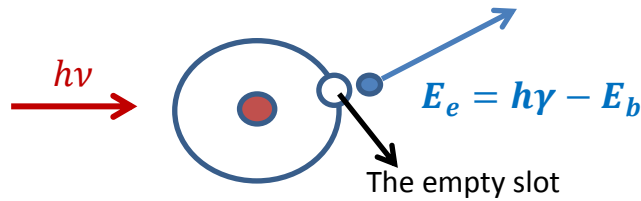
- The photoelectric effect
- The Compton scattering
- The pair production

4.1. The photoelectric process:

In the photoelectric process a photon gives all of its energy to a bound electron in an atom and the electron is subsequently ejected from the atom with the kinetic energy (E_e) equal to the difference between the incident photon energy and the binding energy (E_b).

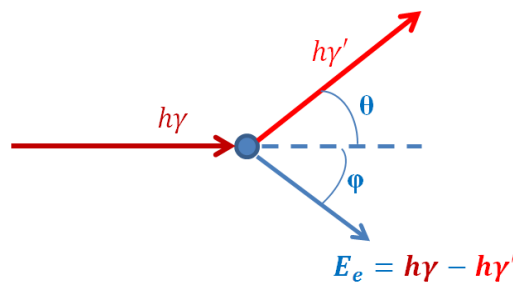
$$E_e = h\gamma - E_b$$

This process allows to measure the energy of the incident photon transferred to the electron and gives rise to well-defined peaks in a spectrum which are known as full-energy photopeaks (FEP). In the ideal case in which there is only photoelectric process we will obtain a very sharp FEP (see Fig. 4)



One event may happen here. Free electron leave an empty slot which is soon filled by electron rearrangement. As a result, the energy equal to E_b will be released in the form of characteristic X-ray or an Auger electron.

4.2. The Compton scattering



Due to the Compton scattering process an incident photon transfers part of its energy to a free or loosely bound electron via collision process depending on the angle between the direction of the incident and scattered photons. The scattered photon leaves the detector and the detected energy is the kinetic energy of the electron. The energies of the scattered photon and electron are given by:

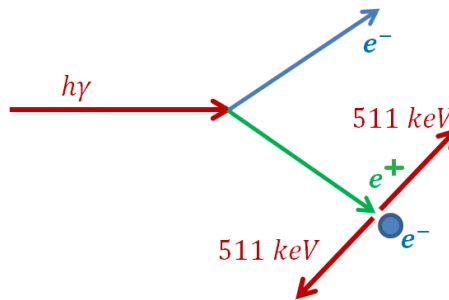
$$E_{\gamma'} = \frac{E_{\gamma}}{1 + E_0(1 - \cos\theta)} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{511\text{keV}}(1 - \cos\theta)}$$

$$E_e = E_{\gamma} - E_{\gamma'} = E_{\gamma} - \frac{E_{\gamma}}{1 + E_0(1 - \cos\theta)} = E_{\gamma} - \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{511\text{keV}}(1 - \cos\theta)}$$

Where E_{γ} is the incident γ -photon energy, $E_{\gamma'}$ is the scattered γ' -photon energy, E_e is the electron energy, E_0 is $\frac{E_{\gamma}}{m_e c^2}$ ($= \frac{E_{\gamma}}{511\text{keV}}$) and θ is the scattering angle for the γ' -photon. From the relationships above, this process yields the continuum observed in the spectrum known as the Compton distribution by which recoiling electron energy extends from zero energy ($\theta=0^\circ$) up to a maximum energy ($\theta=180^\circ$) when the photon is completely backscattered. This maximum energy that can be imparted to an electron produces **the Compton edge** and hence the minimum energy of the scattered photon gives rise to **the backscatter peak**.

4.3. The pair production

In the production of a positron-electron pair in the electric field of an atom, the incident photon must have energy of at least the rest mass of these two particles (1.022 MeV) since it takes that much energy to create electron and positron. The unstable positron will annihilate with a free electron yielding two γ -photons of 511 keV each.



5. Spectrum component

When analyzing a gamma spectrum it is important to understand that the energy we measure is the kinetic energy of the electron obtained from the gamma photon. Gamma rays entering the detector can undergo any of the possible interaction processes described before. Since the gamma rays moves at speed of light and the detector size is in the range of centimeters, no matter what interaction processes gamma photon go through in the detector, it happens so fast that it is impossible to distinguish between separate processes. It just gives a single pulse in the detector output signal. All we can measure is how much energy gamma photon lost in the detector.

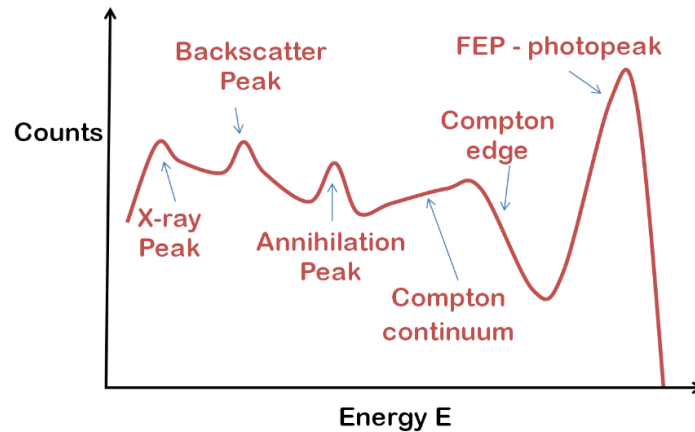
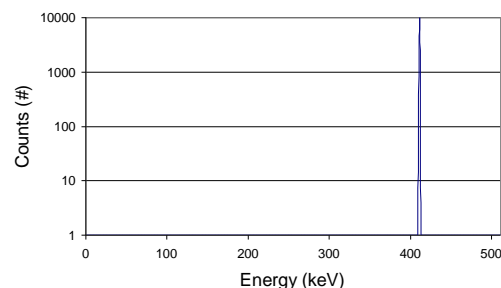
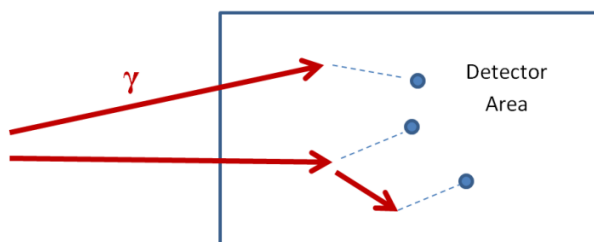


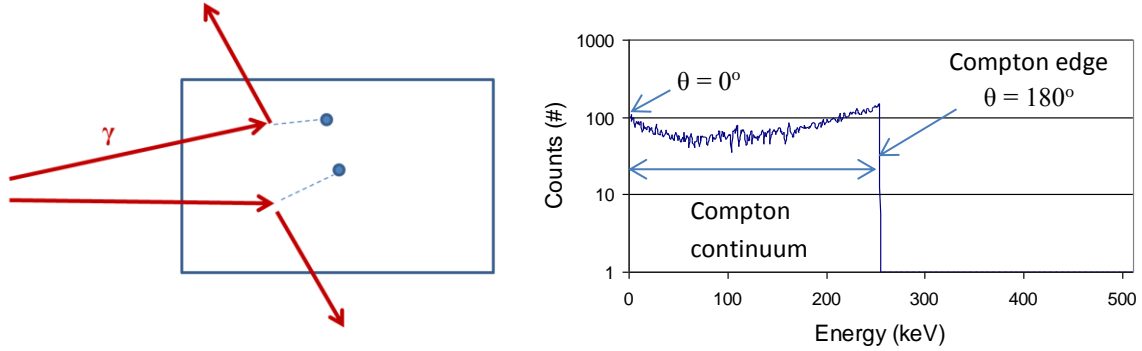
Fig. 4. Typical gamma ray spectrum for the source emitting single gamma photon in a radioactive decay process

5.1. Full energy peak (FEP)

A full energy peak (FEP) appears when the incident gamma ray is absorbed completely by the detector. Basically at all cases then gamma ray losses all the energy contribute to the FEP no matter what interaction processes it went through. One of the particular cases is absorption by the photoelectric effect, then gamma photon is fully absorbed by the electron in the detector. But it also could be the case than gamma photon is scattered via Compton scattering and when absorbed by the photoelectric effect. In the ideal detector which is infinitely big, all incoming gamma photons lose all its energy and contribute to the FEP. However real detectors has limited size and only the certain fraction of incoming gamma photons lose all the energy and contribute to FEP.

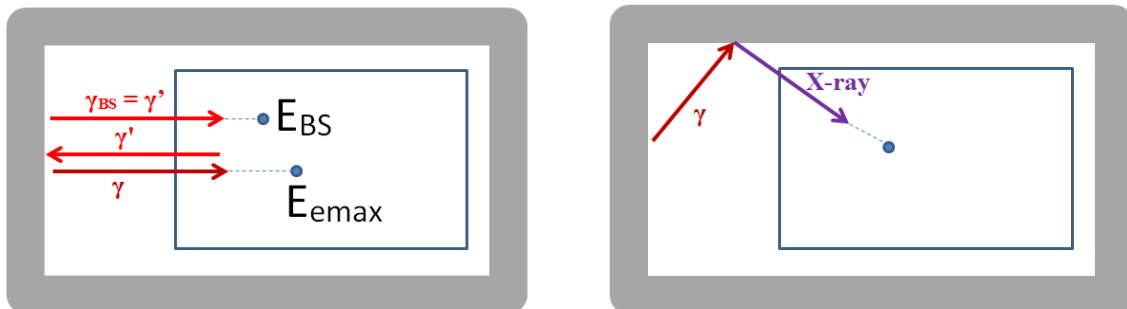


5.2. Compton edge and Compton continuum



If the Compton scattering occurs, the scattered gamma photon can (usually the case, since gamma ray interaction cross section with material is very low) leave the detector and the amount of the detected energy is the kinetic energy transferred to the electron. Depending on the scattering angle, the detected energy varies from the minimum value ($\theta = 0^\circ$) to the maximum value ($\theta = 180^\circ$) and thereby we get the Compton continuum in a measured spectrum. The Compton edge represents the maximum energy given to the electron. Usually the Compton edge does not appear very sharp in the spectrum due to limited spectral resolution of the detector. The other reason is a multi-Compton scattering, when gamma photon is scattered several times before it escapes the detector (due to low interaction cross section it does not happen often).

5.3. Backscattering peak



A backscattering peak appears in the spectrum due to the interaction of gamma rays with materials outside the detector. The backscattered gamma photons, scattered at angles around 180 degrees, can reach the detector and be absorbed. The backscattering peak appears at energies equal to backscattered photon energy. Following the energy conservation principle, the sum of the Compton edge energy and the backscattering energy must be equal to the original gamma photon energy:

$$E_\gamma = E_{\gamma'} + E_{\text{emax}} = E_{\text{BS}} + E_{\text{emax}}$$

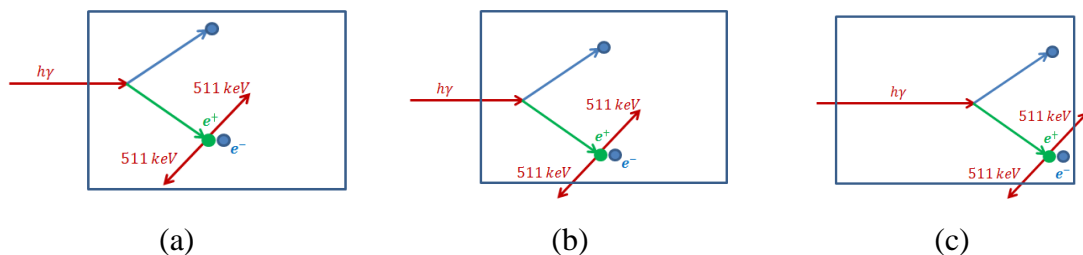
5.4. X-ray peak

The gamma source can ionize the surrounding materials. Gamma photons can remove tightly bound inner shell electrons (the lowest energy states) in atoms that results in electron vacancies in the atom shell. The electron in a higher energy states can fill this vacancy by emitting a characteristic X-ray.

5.5. Annihilation peak

When the gamma ray with an energy greater than the two electron masses of 1022 keV passes near a nucleus, a pair production in which one electron and one positron are created can occur. The positron is unstable, it will soon lose its kinetic energy and find an electron to annihilate. Consequently, two opposite moving 511 keV gamma photons are produced in which only one can move to the detector if the annihilation happens outside the detector. Therefore, we can see a peak in gamma spectrum at the energy of 511 keV. If a gamma ray enters the detector, causes pair production and consequently an annihilation inside the detector, we have three cases which need to be considered:

- (a): Both of 511 keV gammas interact with the detector \rightarrow together with the kinetic energies of the electron and the positron (before annihilation), we get a full energy peak (FEP). All energy of gamma photon is absorbed.
- (b): One of the annihilation photons escapes from the detector \rightarrow this means the detected energy decreases by 511 keV \rightarrow we can see the photopeak called *the first escape peak* at the energy of **FEP – 511 keV**.
- (c): Both of them escape from the detector \rightarrow Similar to the above case, we can see the photopeak called *the second escape peak* at the energy of **(FEP – 1022 keV)**.



5.6. Sum peak

In a single decay process, it is possible to have two or more photons arriving at the detector at the same time. Such events give rise to a so-called **sum-peaks**. Sum-peaks can be observed for highly active isotopes.

6. Detector

6.1. NaI (Tl) scintillation detector

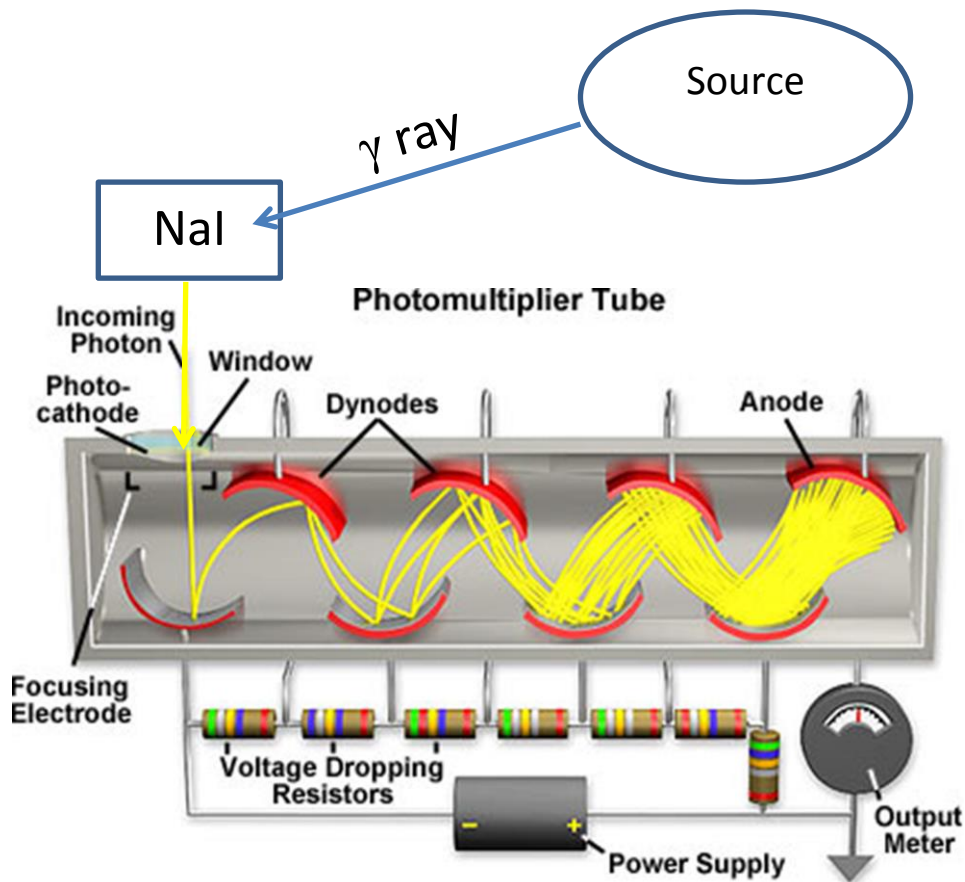


FIG 5. Schematic diagram of a NaI (Tl) scintillation detector

From: <http://micro.magnet.fsu.edu/primer/digitalimaging/concepts/photomultipliers.html>.

In this experiment a sodium iodide (activated with thallium) scintillation detector is used for measuring gamma spectrum. The interaction of γ -rays with the sodium iodide crystal produces electrons with high kinetic energy. These electrons move in sodium iodide crystal and gradually lose their energy by transferring it to the surrounding electrons that generates a number of lower energy photons. As a result, a light is produced in NaI crystal. The intensity of light (or number of photons) depends on the kinetic energy of electrons and thereby on the energy of the incident gamma ray. Photocathode absorbs the light coming from NaI crystal and emits electrons through the photoelectric process into the photomultiplier tube. These electrons are then multiplied by a system of electrodes called dynodes. Each dynode is biased at higher voltage than the previous one, see Fig. 5. This process gives rise to a pulse of current at the external circuit connected to the photomultiplier tube, which can be converted to a pulse in voltage. These pulses are fed into a linear amplifier for further signal processing and then a multichannel analyzer (MCA) which sorts the pulses with respect to magnitude of the voltage, e.g., larger pulses go into higher numbered channels. The channel number is therefore proportional to γ -ray energy (\propto - proportional):

Gamma ray energy \propto electron kinetic energy in NaI crystal \propto number of photons produced in NaI \propto Number of photons produced in photocathode \propto Number of electrons reaching the anode in photomultiplier tube \propto Voltage pulse in external electrical circuit \propto MCA channel number.

6.2. High-purity germanium detector

Although a scintillation detector has high efficiency, its energy resolution suffers from the statistical fluctuation in all energy conversion steps in the detector, particularly, in the process of the multiplication of the photoelectrons in the photomultiplier tube. Unlike scintillation detectors, a semiconductor detector provides a much higher energy resolution since the energy conversion is achieved in a more direct way, i.e., the amount of the energy lost by the original incident γ -photon in the detector is proportional to the measurable electrical signal. A semiconductor detector is just a large diode consisting of n-p junction connected in reverse bias. When photons interact within the depletion region between p- and n-layers, at the reverse bias across the diode, electron-hole pairs are created. Gamma photon transfers all or part of its energy to the electron, which loses its kinetic energy gradually due to interaction with surrounding electrons and produces a large number of electron-hole pairs (~ 2.95 eV per pair in Ge at 80 K). The number of electron-hole pairs produced in this process depends on the amount of energy given to the electron by the gamma photon. The produced pairs are collected at the electrodes due to the applied voltage, resulting in a pulse of the current. In a similar manner to the scintillation detector, this pulse is fed into further electronic pulse processing systems and then a MCA.

A semiconductor detector requires a liquid nitrogen cooling in order to reduce the number of thermally excited electron-hole pairs in the detector and hence the signal noise. Semiconductor detectors for measuring γ -radiation are usually made of high-purity germanium detector because of its high absorption efficiency of high energy photons whereas those made of silicon are mainly used for detection of X-rays. Indeed, a germanium detector has a typical resolution of some tenths of a percent of 1 MeV. This superior energy resolution is mainly due to more direct measurement of gamma ray energy, since Ge detector uses less energy conversion steps compared to the scintillator detector.

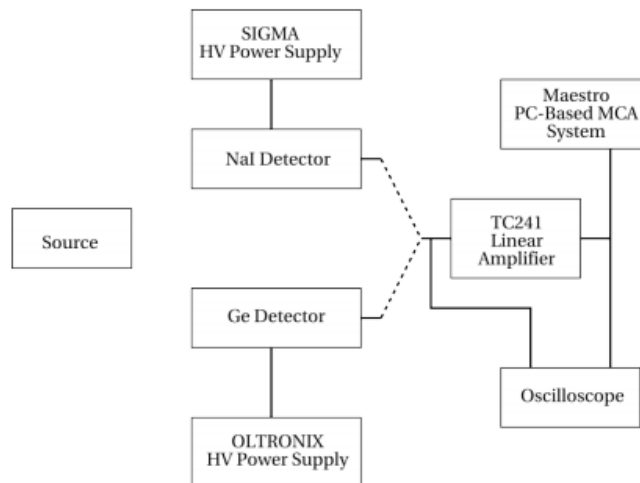
III. EXPERIMENT

Experiment 1: Study the multichannel analyzer using a scintillation detector – Calibration of the multichannel analyzer

In this exercise, you will learn how to calibrate the multichannel analyzer by studying the gamma spectra of ^{137}Cs and ^{22}Na using a NaI (Tl) scintillation detector. The main task is to find the correct calibration function.

Quest 1: Startup

1. Set up the electronics in the arrangement shown in Figure 4. Connect the NaI detector to its high voltage power supply (SIGMA) and to the linear amplifier (TC241). Check all connections. Make sure the input of the linear amplifier is set on negative polarity and that the course gain is at 200. Set the high voltage supply to 0 V.
2. Turn on the oscilloscope, the preamplifier and a power supply for the detector.
3. Start the computer and open MAESTRO-32 MCA program, see Appendix.
4. Place the ^{137}Cs source in front of the NaI detector.
5. Increase the high voltage to 1000 V.



*** Quest 2: Acquire ^{137}Cs and ^{22}Na (or sample including ^{22}Na and ^{137}Cs) spectra**

- Study the shapes of pulses on the oscilloscope screen (signal before and after the linear amplifier) and give your comments about what you observe on the screen of the oscilloscope.
- Acquire the ^{137}Cs spectrum for a long enough period of time so the peak position can be easily determined. Identify different peaks in obtained gamma spectrum.
- Repeat the measurement and adjust the coarse/fine gain controls of the linear amplifier such that the 0.66165 MeV photopeak for ^{137}Cs appears slightly below the middle of the gamma spectrum. It assures that FEP for ^{22}Na (1.274 MeV) also appears in accessible spectral range. If that photopeak is already at the specified position, you do not need to change the coarse/find gain. Once an optical gain parameters are set, do not change them, except the case than you switch to another detector, then you have to adjust these parameters again. In any case adjusting of the gain parameters means calibrating again.
- Save the ^{137}Cs spectrum under the name: "Cs_NaI"
- Replace the ^{137}Cs source with the ^{22}Na source. Acquire the spectrum for the ^{22}Na source and plot it.
- Save the ^{22}Na spectrum under the name: "Na_NaI"

*** Quest 3: Calibrate the multichannel analyzer**

- Recall the plots of ^{137}Cs and ^{22}Na in the same window by using "**compare**" in **File** menu. The x-axis is now in channel unit, so we need to convert the channel unit to the energy unit (eV)
- Determine the known peaks of ^{137}Cs and ^{22}Na from the decay scheme
- Click the unknown peak and then choose **Calculate → Calibration**. In the calibrate window, put the energy corresponding to that peak in **keV** unit. Do the same for the rest two peaks. Before starting calibrating do not forget to remove old calibration (click **Destroy calibration**)
- Then you are done with the calibration save the data file again. Calibration parameters will be saved in the data file.

NOTE: calibration parameters are saved in a data file not in a software memory, thus every time you load a new data file, as a result new calibration parameters are loaded from the data file as well.

*** Quest 4: Analysis of the spectrum**

- Try to identify all peaks in the spectrum.

Notice: When quest 4 is finished, you have to decrease the high voltage to 0V and turn off the power in order to prepare for the next experiment.

Experiment 2: Study of the Ge-detector

In this exercise, you will learn how to acquire the gamma spectra of ^{137}Cs and ^{22}Na by using the Ge-detector. You will learn what are the advantages of Ge-detector compared to the scintillation detector.

*** Quest 1: Startup**

- Connection of the Ge-detector.
 - Check a log of the detector to make sure that the liquid nitrogen has been refilled.
 - Connect the GE-detector to the amplifier instead of the NaI-detector.
- Place the ^{137}Cs source in front of the detector.
- Turn on the high voltage power supply (OLTRONIX) and increase the voltage to 1 kV.

*** Quest 2: Acquire ^{137}Cs and ^{22}Na spectra and do calibration**

- Study the shapes of the pulses on the oscilloscope (before and after the linear amplifier) and give your comments about what you observe on the screen of the oscilloscope.
- Acquire the ^{137}Cs spectrum for a long enough period of time so the peak position can be determined.
- Repeat the measurement and adjust the coarse/fine gain controls of the linear amplifier such that the 0.66165 MeV photopeak for ^{137}Cs appears slightly below the middle of the gamma spectrum. It assures that FEP for ^{22}Na also appears in accessible spectral range.
- Save the ^{137}Cs spectrum under the name: "Cs_Ge"
- Replace the ^{137}Cs source with the ^{22}Na source. Acquire the spectrum for the ^{22}Na source and plot it.
- Save the ^{22}Na spectrum under the name: "Na_Ge"
- Do calibration as in the experiment 1. Before do calibration, you have to remove the already done calibration in the experiment 1 by choosing **Calculate → Calibration → Destroy Calibration**.
- When calibration is done, do not forget to save your data file.
- Determine the energy of each peak and discuss the shape of peak in comparison with the same peak using the NaI detector.

Experiment 3: Study of the Ge-detector

Use the calibrated system at the experiment 2 part to measure the gamma spectrum of an unknown sample and try to identify which elements it is.

*** Quest 1: Acquire the spectrum of an unknown source**

- Use the gain calibration settings of the system from experiment 2.
- Acquire a spectrum for an unknown source for a period of time long enough that all interesting peaks can be easily identified.
- Determine the energy for as many photopeaks as you can.
- Save the unknown spectrum.

* Quest 2: Identify the unknown source

- To identify the unknown source, the most convenient way is to use the standard table of γ -ray energy. In the software, there is a library of γ -energy accessed by choosing **Service** → **Library** → **Select Peak**.

- Summarize the data and give the name of the unknown source.

Notice: When quest 2 is finished, you have to decrease the high voltage to 0V and turn off the power and put the source back in the box.

IV. PREPARATORY ASSIGNMENTS

1. Describe schemes of alpha, beta and gamma decays, use only equations to explain.
2. Calculate the energy of a scattered photon E_γ and energy of an electron E_e , when a γ photon of energy 662 KeV makes collisions with a stationary electron at an angle of 0° and 180° .
3. Give a reason why the radioactive nuclei are not stable. It means why radioactive nuclei emits alpha, beta and gamma radiation.
4. You could be asked about the scintillation and Ge detector, so you must to understand how these detectors work.
5. You must know the function of photomultiplier tube (PMT) and multichannel analyzer (MCA), at least in short.
6. Look and understand the decay scheme of ^{137}Cs and ^{22}Na .

Reference

[1]: The previous version of compendium for Lab 26 in TFFM08 (Analysis of γ spectrum)