Mid-term Report

NIUS (Physics) PROJECT

Year: 2019 – 2020,   Batch: 16,   Camp: 16.2

Title of the project: Study of two-photon decay and its implication on nuclear structure

Name of the student: Kunal Verma
Affiliation: Indian institute of Science Education and Research(IISER), Mohali
S.A.S Nagar, Sector 81,Knowledge City
Punjab-140306

Name of the Mentor: Dr. Rudrajyoti Palit
Affiliation: Department of Nuclear and Atomic Physics, T.I.F.R. Mumbai

Name of the HBCSE Co-mentor: Dr. Rajesh Khaparde

Acknowledgement:

This work was supported by the National Initiative on Undergraduate Science (NIUS) undertaken by the Homi Bhabha Centre for Science Education, Tata Institute of Fundamental Research (HBCSE-TIFR), Mumbai, India.

Kunal

Date: 25/01/2020   Signature of the NIUS student:

Gamma ray-matter interaction and detectors for decay processes

Kunal Verma
IISER Mohali

1 Radioactive Decay and Radiation

Radioactive decay in nuclear processes is simply described as the pprocess in which an unstable nuclei loses energy by emitting radiation to achieve a lower energy state with a higher stability. In many processes, the decay from excited nuclear state results in a nuclear transmutation resulting in a daughter nucleus containing a different number of protons or neutrons. Some of the processes (not an exhaustive list) are-

- **Alpha Decay**
  Heavy nuclei which are energetically unstable against the spontaneous emission of an α-particle (^{4}He nucleus). The energy releasd is shared between an alpha particle and the recoil nucleus such that each alpha particle apprears with the same energy.

- **Beta Decay**
  β decays are a common source of fast electrons and they occur either as β^- (n $\rightarrow$p + e + $\bar{\nu}$) or β^+ decay (p $\rightarrow$n + e^- + ν). The nucleus appears with a very small recoil energy.

- **Electron Capture**
  The nucleus captures an orbiting electron which causes a proton to convert into a neutron (p + e^- $\rightarrow$n).

- **Spontaneous Fission**
  in spontaneous fission processes, the nuclear unstability causes the nucleus to split into 2 or more daughter nuclei which results in emission of energetic heavy charged particles.

But there are some other processes also, in which the nucleus loses energy without nuclear transmutations such as -

- **Internal Conversion**
  Internal conversion in a process in which an excited nucleus electromagnetically inteacts with one of the orbital electrons of th atom and emits a high-energy electron to reach a lower energy state.

- **Gamma Rays**
  Gamma rays are electromagnetic radiation produced in almost all decay processes. After decay, many nuclei become excited decay products and eventually go to their respective ground states by emitting EM radiation in form of γ-rays. They also possess a much higher penetration power compared to α or β particles. Gamma rays are produced by a number of astronomical processes in which very high-energy electrons are produced. Such electrons produce secondary gamma rays by the mechanisms of bremsstrahlung, inverse Compton scattering and synchrotron radiation.

Most of our discussuon from now will mostly be regarding gamma radiatio, its interaction with matter, and its detection mechanisms.

2 Interaction of Gamma Rays with matter

Gamma rays usually have a very high penetrating power and need large amounts of shielding material to attenuate their energy. When gamma rays interact with matter, the absorption of gammar rays shows an exponential decay of intensity with distance from incident surface. All in all, gamma radiation, according to it's energy, interacts with matter in three ways: the photoelectric effect, Compton scattering, and pair production.

- **Photoelectric Effect** A photon undergoes an interaction with the absorber atom in which the energy of the photon is completely absorbed and used to eject a photo electron (not the free electrons) with the most probable electrons being of that of K shell which are ejected. th energy of the photo- electron is given by

  $$E_{e^-} = h\nu - \phi_{work}$$

  It is the predominant mode of interaction of gamma rays of low energy.

- **Compton Scattering** Compton scattering which occurs due to scattering of a photon with a charged particle (usually electron) which results in the decrease of energy of a photon when it is deflected mby some angle θ and the electron being deflected at some angle ϕ. If the initial frequency of the photon is ν and the final frequency after collision as ν', then

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0c^2}(1 - cos\theta)}$$

The interaction process of Compton scattering is most common for energies typical of radioisotope sources.

- **Pair Production** When gamma ray energies exceeds energies around 1.02 MeV, the process of pair production is possible. In pair production, when the gamma ray approaches the nucleus, the gammay ray disappears and there is creation of electron-positron pair. The process must conserve both energy and momentum. However, all other conserved quantum numbers (angular momentum, electric charge, lepton number) of the produced particles must sum to zero.

3 Method of Detection

In the previous section, we discussed how gamma rays interact with matter. These theoretical results can be used in modelling detectors which can be used to monitor the activity of the radioactive sources. The electrical signals generated by such light-matter interactions are an excellent source to obtain information about the gamma radiation. One of the possible ways is by using Scintillator detectors and then amplifying the signal produced by them into gamma ray spectrums.

- **Scintillator Detectors**
  Scintillators are materials which show the property of luminescence when excited by ionizing radiation. The material, when struck by an incoming particle, absorbs its energy and re-emits the absorbed energy in the form of photons. There are usually two types of scintillator materials-(1) Organic Scintillators and (2) Inorganic Scintillators.

  (1)Organic Scintillators Organic scinitillators are aromatic compunds containing benzene ring in the crystals linked in various ways and have symmetry properties asscoiated with the structure. They are very durable but their response is anisotropic which means they need to be collimated. The fluorescence mechanism in organic materials results from transitions in the energy levels of a single molecule.

(2)Inorganic Scintillators Inorganic scintillators are usually crystals and the scintillation mechanisms in these are mostly dependent on the nature of crystal lattice. In pure crystals, absorption of energy can elevate electrons from the valence band to the conduction band leaving a gap in the valence band. However, the return of an electron to the valence band with the emission of a photon is an inefficient process. Thus, small amount of activator impurities are added to the crystal.

- **Photo-Multipler Tube**

  A scintillator detector is always coupled to an electronic sensor known as a photomultiplier tube. PMTs absorb the light emitted by the scintillator and re-emit it in the form of electrons via photo electric effect. The two major components of a PMT are *photocathode* and an *electron multiplier*. The photocathode is used to convert the incident incident photons to photoelectrons and the elctron multiplier amplifies the weak electron signal to a detectable value.

  (1) Photocathode

  Photo cathode is a device that is used to convert the incident photons from the scintillations produced to photoelectrons. The photoemission process consists of three steps: (1) the absorption of incident photon and transfer of energy to the elctron, (2) the migration of electron to the surface and (3) escae of electron from the surface.

  In step 2, some of the energy will be lost through electron-electron collisions in the migration process. So, there should be enough energy for the photon to overcome the work function of the photocathode material. Also, since the work function of each material is different we can define an efficiency of the photocathode material-

  $$\text{Quantum Efficiency} = \frac{\text{No. of Photoelectrons emitted}}{\text{No. of incident photons}}$$

  (2)Electron Multiplier

  The multiplier tube of the PMTs based on the phenomenon of secondary electron emission. Electrons from the photodiode are accelerated and are made to strike the surface of an electrode, called a *dynode*. Contrary to photoelectric effect, the electrons within the dynode are excited by passage of energetic electrons rather than photons.

The secondary electron yield is a sensitive function of incident electron energy. The overall multiplication factor for a dynode materil is given by

$$\delta = \frac{\text{No. of secondary electrons emitted}}{\text{No. of primary incident electron}}$$

. If α is the fraction of photoelectrons collected by the multiplier structure and if N stages of multiplication are involved, then the overall gain ζ is given as

$$\text{overall gain}(\zeta) = \alpha\delta^N$$

4 Analysing the data obtained from spectroscopy

As we have discussed in the above sections, the detection of gamma rays is commonly done using Scintillator detectors coupled with PMTs and electron multiplier which improve the quality of the signal obtained. . Another aspect of such an experiment would be to actually use the data obtained to obtain conclusions and real world information which actually provides some valuable insight into the physics of such phenomenon.

As the central part of our project, we were given the task to create a peak detection model using a computer code such that it detects the peaks of a given gamma ray spectrum. For verification purposes, we were given a spectrum of ^{137}Cs and our program was successfully able to detect the peaks. The program first detects all those points which are larger than its adjacent left and right values, then sets two filters to further reduce the number of points which are acually peaks. The two filters are-
(1) the points should be a local maxima within a window size of 2b. (b is the input you would give for the window size).
(2) the area of the graph within the interval (x-b,x+b) should be less than or equal to a Gaussian that could be constructed in that particular window. This ensures that the peak is atleast thinner than a gaussian.

The following page presents the gamma ray spectrum of ^{137}Cs, the peaks detected on the spectrum and the program that is used to detect the peaks in the spectral data-

FinalPeakProgram

[21]:
```
import pandas as pd
import numpy as np
import matplotlib.pyplot as pl
#Reading the spectrum intensity data onto x
f=np.array(pd.read_csv('137Cs.asc').transpose())[1][:]
x=list(f)

def numint(l): # Function for numerical integration with interval length 1.
    return sum(l)-(l[0]+l[1])/2

#Function for peak detection. b is the window length of numbers for calculating␣
↪the local maxima. l and a are obtained from data file only.
def peak(l,a,b):
    x=[]
    y=[]
    for i in range(len(l)):
        if i>b:
            if l[i-1]<l[i] and l[i]>l[i+1]: # First check. Number is greater␣
↪than the left and right counterpart.
                if max(l[(i-b):(i+b)])==l[i] and numint(l[(i-b):(i+b)])<np.
↪var(l[(i-b):(i+b)])*np.sqrt(np.pi*2): #Filter conditions:(1)local maxima␣
↪and(2) area of spectrum in the window should be less than or equal to the␣
↪area of a gaussian of the variance within the window.
                    x.append(l[i])
                    y.append(a[i])
    return x,y


a=np.arange(0,len(x))
pl.plot(a,x)
pl.xlabel("Frequency Channel")
pl.ylabel("Intensity/Count")
window=int(input("Enter desirable window length (20-30 works the best- usual␣
↪spread of a peak): \n"))
pl.plot(peak(x,a,window)[1],peak(x,a,window)[0],'ro',label='Peaks')
pl.legend()
pl.show()
```

```
Enter desirable window length (20-30 works the best- usual spread of a peak:
20
```