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**ABSTRACT**

An attempted work had been made on the basic principle that when a radiation interacted with the detector material, it was absorbing by the material and emitting flash of light, i.e, scintillation. The Thallium doped Sodium Iodide scintillation had been used. In that crystal the thallium acted as an activator.

To measure the spectrum of several standard gamma emitters using NaI(Tl): (Thallium doped Sodium Iodide), scintillation counter coupled with modular electronics, multichannel analyzer and software. A given scintillation material was used to convert the energy of ionization into visible photons. The scintillation so produced may be directed to PMT (Photomultiplier tube) which converted it into electrical signal. The amplitude of the signal was a measure of the incident gamma radiation energy. A Geiger counter merely determined count rates for radiation, gamma spectroscopy had ability to determine both the count rate as well as the energy of radiation. A detector could identify an unknown radioisotope by identifying features on the gamma spectrum and comparing them to known spectra. The spectra of different source would be measured. Those spectra analyzed and the features that distinguish them from other spectra identified. The gamma rays interact with matter by several processes. Some of those processes were photoelectric absorption, Compton scattering, pair production, coherent scattering, photonuclear reactions etc.

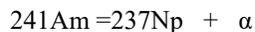
**KEYWORDS:** Gamma – ray Spectroscopy, NaI(Tl) detector, Compton scattering, pair production, coherent scattering, photonuclear reactions, voltage power supply and some devices.

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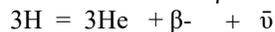
**INTRODUCTION**

Nuclear radiations originated in the atomic nucleus as a result of radioactive decay of the excited nucleus. Those radiations might be divided broadly into three categories viz., charged particle radiation, neutral radiations and electromagnetic radiation. The charged particle radiation include protons, alpha particles etc. Example of neutral radiations are neutrons, neutrinos and example of electromagnetic radiation are X–ray and gamma rays [3,4,15].

In case of  $\alpha$  decay:



In case of  $\beta$  decay:



In case of  $\gamma$  decay:



Though, X–ray and  $\gamma$ –rays both are electromagnetic radiation, the basic difference between these two was in their origin. The gamma rays basically originate during the decay of excited nuclei. The X–rays are produced by de–excitation of atomic bound states while  $\gamma$ –ray are emitted from the nucleus, in general the X–ray has lower energies than  $\gamma$ –rays. The energy spectrum of the gamma rays was a measure of energy levels of the nuclear states as well. The basic objective of the gamma spectroscopy was to measure the energy and number of photons [4, 5].

In photoelectric absorption process of gamma ray photon undergoes an interaction with an absorber atom in which the photon completely disappeared. In its place, an energetic photoelectron was ejected by the atom from one of its bound shells. The interaction took place with the atom as whole and couldn't take place with a free electron. For gamma ray of sufficient energy, the most probable origin of photoelectron was the most tightly bound or K – shell electron [8, 9]. In the low energy region, discontinuities in the curve or the “absorption edges” appear at gamma ray energies that corresponds to binding energies of the electrons that corresponds to binding energies of the electrons in various shells

of the absorber atoms[2]. The sharp edges lying highest in energy corresponding to the binding energy of K-shell electrons. For gamma ray energies slightly above the edge, a photon was just sufficient to undergo a photoelectric interaction with a K-electron ejected from the atom. Similar absorption edges occur at low energies for L, M, ... Electron shells of the atoms respectively [7].

Compton Scattering took place between the incident gamma ray photon and a free or weakly bound electron (i.e.  $E_\gamma \gg E_b$ ) in the absorbing material. In Compton scattering, the incoming gamma ray photon was scattered through an angle  $\theta$  with respects to its original direction. The photon transfers a portion of its energy to the electron (assumed to be at rest), which was known as recoil electron[1, 13, 14].

Gamma ray with energy at least 1.022MeV could create an electron and positron pair when it was under the influence of strong E.M. field in the vicinity of nucleus. The electron and positron from pair production were rapidly slowed down in the absorber. After losing its kinetic energy, the positron combines with an electron in an annihilation process, which releases two gamma rays of energy 0.511MeV as a secondary product of the interaction[16,17].

These collisions gave rise the atomic electrons into excited states. The excited state then decayed with the emission of photon in the visible part of electromagnetic spectrum. Those photons were then detected by a photomultiplier tube. The intensity of light produced was basically a measure of the initial energy rays.

## THEORY

The photoelectron appeared with an energy given by:

$$E_e = h\nu - E_b \dots \dots (1)$$

Where  $E_e$  electron energy,  $E_b$  is the binding energy of the photoelectron in its original shell,  $h$  is plank constant and  $\nu$  is the frequency of photon.

The probability of photoelectric absorption depended on the gamma ray energy, the electron binding energy and the atomic number of the atom. The probability of photoelectric absorption was given approximately by the equation below

$$\tau \propto Z^n / E_\gamma^{3.5}, \quad (n = 4 - 5) \dots \dots (2)$$

Where  $Z$  is the atomic number in various shell and  $E_\gamma^{3.5}$  is gamma rays energy in 3-5 shell.

As all angles of scattering were possible, the energy transferred to the electron could vary from zero to a large fraction of the gamma ray energy. It could be shown by writing simultaneous equations for conservation of momentum and energy. The energy of the scattered photon is given by:

$$E' = h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0c^2} (1 - \cos\theta)} \dots \dots (3)$$

Where,  $E'$  is energy of scattered photon,  $\nu'$  is frequency of scattered photon and  $m_0c^2$  is the rest mass energy of the electron (0.51MeV)[1].

The probability of Compton scattering per atom of the absorber depended on the number of atoms available as scattering targets and therefore increases linearly with  $Z$ .

Resolution of a spectrometer was a measure of its ability to resolve two peaks that were fairly close together in energy. It depend on several factors, viz. on the number of photons emitted in each event, the number of photons that stroked the photocathode, the number of photoelectrons released per photon hitting on the photocathode, the number of photoelectrons that stroked the first dynode, the multiplication factor of the photomultiplier tube etc. the parameters required for % resolution are shown in Table .3. The response function should have a Gaussian shape as  $N$  is typically a large number. In those case Gaussian function was written as:

$$G(H) = \frac{A}{\sigma\sqrt{2\pi}} \exp \left[ -\frac{(H-H')^2}{2\sigma^2} \right] \dots \dots (4)$$

Where:  $\sigma$  is width parameter that determines FWHM of any Gaussian shape through the relation  $FWHM = 2.35\sigma$ ,  $A$  is area under the curve and  $H'$  is centroid of the peak[18].

The responses of detectors were generally linear, so that the average pulse amplitude  $H' = k\sqrt{N}$ : where  $k$  is the proportionality factor. The standard deviation ( $\sigma$ ) of the peak in the pulse height spectrum was then  $\sigma = k\sqrt{N}$  and was its  $FWHM = 2.35 k\sqrt{N}$ . the resolution due to only statistical fluctuation in the number of charge carriers as:

$$R_{\text{poisson limit}} = \frac{FWHM}{H'} = \frac{2.35k\sqrt{N}}{kN} = \frac{2.35}{\sqrt{N}} \dots \dots (5)$$

Now a careful measurement show that R could be lower by a factor as large as 3 or 4 than the minimum predicted by the statistical argument above. The total number of charge carriers' couldn't be described by Poisson statistics & was defined as:

$$F = \frac{\text{observed variance in } N}{\text{Poisson predicted variance } (=N)} \dots\dots\dots(6)$$

Because the variance was given by  $\sigma^2$ , the equivalent expression to equation (4.5) is given by:

$$R_{\text{poisson limit}} = \frac{2.35k\sqrt{N}\sqrt{F}}{kN} = 2.35\sqrt{\frac{F}{N}} \dots\dots\dots(7)$$

Again the Fano factor can be written as:

$$F = \frac{\text{observed statistical variance}}{E/\varepsilon} \dots\dots\dots(8)$$

Where,  $\varepsilon$  was the ionization energy.

Now from the equation (4.5) and (4.6), we can write easily that:

$$R = \text{const} \frac{1}{\sqrt{E}} \dots\dots\dots(9)$$

Therefore,  $R \propto \frac{1}{\sqrt{E}}$

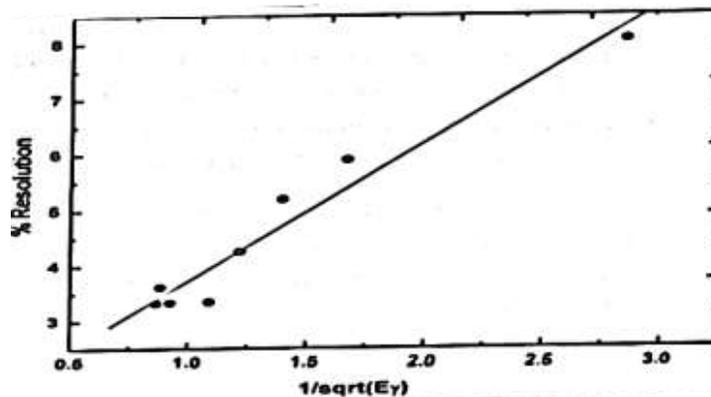


Fig. 1. The measured % resolution vs.  $1/\sqrt{E\gamma}$ .

Fig. 1 shows that the resolution was directly proportional to inverse of the square root of energy.

**EXPERIMENTAL METHOD**

In the Fig(2). a block diagram containing the main component of the NaI(Tl) gamma – ray spectrometer were given as  $\gamma$  – ray source, Na(Tl) Scintillator as sample, PMT(photomultiplier tube), pre-Amplifier, high voltage, amplifier, MCA( multichannel analyzer) and computer coupled to freedom. The possess of each part can be illustrated below in experimental method.

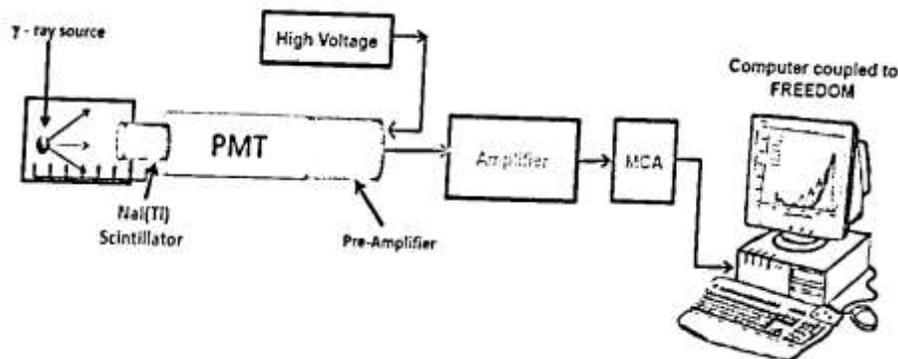


Fig. 2 a typical block diagram of NaI(Tl) scintillation spectrometer

Scintillation detectors use the material that could emit light when energetic particles / radiation interacted with its molecules and transferred energy, in the NaI(Tl) scintillators, the thallium acted as an activator, creates special sites at which the normal energy band structure was modified from that of pure crystal. As shown in fig.2.

The refractive index of the material should be near to the glass to permit efficient coupling of scintillation light to a PMT. That photomultiplier tube converted these scintillations into electrical pulses, which could be analyzed and counted electronically to probe the incident radiation[8].

A charged particle passing through the detection medium would produce a large number of electron–holes pairs created by the elevation of electrons from valence band to conduction band.

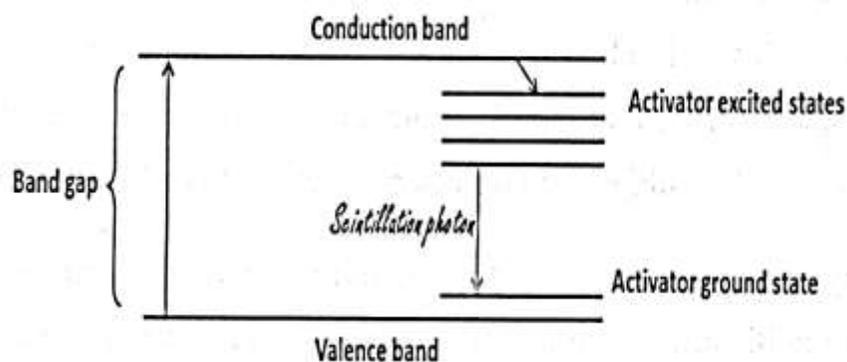
If the activator site that was transition to an excited configuration within an allowed transition to the ground state its de – excitation would occur very quickly and high probability for the emission of corresponding photon.

Typical half – lives for such excited states were 50–500ns. As the migration time for the electrons was much shorter, all the excited impurity configuration were formed essentially at once would subsequently de – excited with the half – life that were characteristic of the excited state. It was decay time of those states that, determined the time characteristic of emitted scintillation lights[11, 12].

The photomultiplier tubes (PMT) converted extremely weak light output of a scintillation pulse into a corresponding electrical output without adding a large amount of noise. PMT were sensitive in the UV, visible and near infra–red regions of electromagnetic spectrum. The basic function of a pre–amplifier was to amplify the weak signals from the detector and drive it through the cable that connects the pre–amplifier with the rest of the equipment. At the same time it must add the least amount of noise possible. Pre–amplifiers are mounted close to the detector so as to minimize cable length. In this way, pick up of stray electromagnetic fields was reduced and cable capacitance, which decreases the signal–to–noise ratio, was used mainly to present the correct impedances to the detector and the electronics and to shape the subsequent output pulse[17,18].

The amplifier serves two main purposes i.e. amplified the signal from the pre – amplifier and shapes it to convenient form for further processing. If pulse height information was desired, strict proportionality between input and output amplitude must be preserved (linear amplifier).

Multichannel Analyzer (MCA) was a sophisticated device which sorts out incoming pulses according to the pulse height and keeps count of number at each pulse height in a multichannel memory. The content of each channel could then be displayed on a screen or printed out to give a pulse height spectrum.



*Fig. 3. Energy band structure of an activated crystalline scintillators*

Fig.(3). illustrated that, the positive holes would quickly drift to the location of an activator site and ionized it as the ionization energy of activator would be less than that of a lattice site Electron could drop into the activator site, creating a neutral configuration that could have its own set of excited energy states.

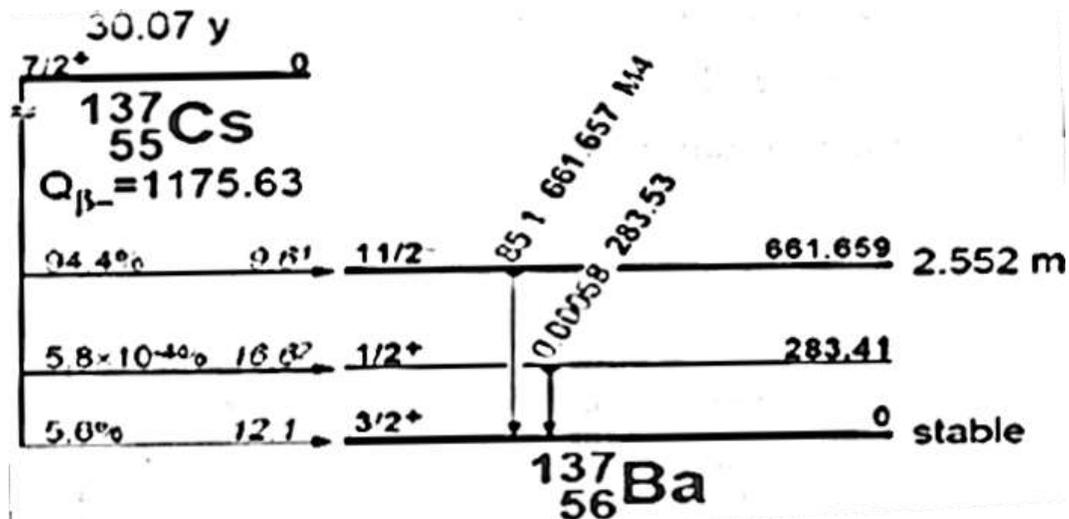
## RESULTS AND DISCUSSION

A detailed description of NaI(Tl) gamma ray spectrometer set up used had been already described.

The standard gamma ray sources used are listed in table1, along with their spectroscopic properties viz. decay modes,  $\gamma$  – ray energies, half-livesetc[2].

**Table1. The  $\gamma$  – rays sources with their spectroscopic properties.**

| $\gamma$ – ray sources | Decay mode | $\gamma$ -ray energy(MeV) | Nominal activity ( $\mu$ Ci) | Half – life |
|------------------------|------------|---------------------------|------------------------------|-------------|
| $^{57}\text{Co}$       | $\beta^+$  | 0.123                     | 2.1                          | 273 days    |
| $^{133}\text{Ba}$      | $\beta^+$  | 0.360                     | 3.20                         | 7.5 years   |
| $^{22}\text{Na}$       | $\beta^+$  | 0.511 1.280               | 3.4                          | 2.6 years   |
| $^{137}\text{Cs}$      | $\beta^-$  | 0.662                     | 3.05                         | 30 years    |
| $^{60}\text{Co}$       | $\beta^-$  | 1.172 1.332               | 3.13                         | 5.3 years   |
| $^{54}\text{Mn}$       | $\beta^+$  | 0.835                     | 2.0                          | 312 days    |



**Fig.4. The measured  $\gamma$  – ray spectrum of  $^{137}\text{Cs}$**

A typical decay scheme of  $^{137}\text{Cs}$  source is shown in Fig.4. The radioactive source  $^{137}\text{Cs}$  was one of the standard sources having single gamma ray energy and was generally used for calibration of the spectrometer. As could be seen from the decay scheme of  $^{137}\text{Cs}$ , it decayed by  $\beta^-$  emission. About 6% of the times it decayed directly to the ground state of  $^{137}\text{Ba}$  and rest of the time to the short lived intermediate state of approximately 2.6m minutes life time that decayed by emitting about 662 keV gamma ray. The decayed may be represented as:  $^{137}\text{Cs} = ^{137}\text{Ba} + \beta^- + \nu$ . The high voltage applied to the photomultiplier tube was set to 500 volts. Further the settings of the amplifier etc. were done to get a good spectrum of the  $^{137}\text{Cs}$  source for 662keV gamma ray. The amplifier gain control and the applied voltages were set to get the photo peak of 662keV at nearly 30 – 40% of the full scale of the analyzer. The counts were accumulated to the turn of 2 – 3 thousand at peak position.

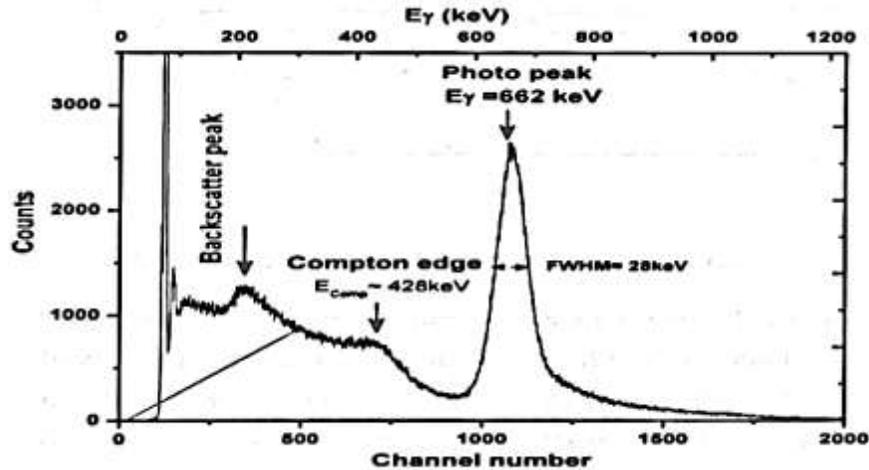


Fig. 5. The measured  $\gamma$  – ray spectrum of  $^{137}\text{Cs}$

The measured gamma ray spectrum of  $^{137}\text{Cs}$  was shown in Fig.5. a close examination of spectrum clearly indicated the photo – peak, Compton edge, backscattering peak along with low energy background. The gamma spectrum was fitted using peaks fitting software. The width of  $^{137}\text{Cs}$  gamma ray (662keV) was found to be  $\approx 28\text{keV}$ .

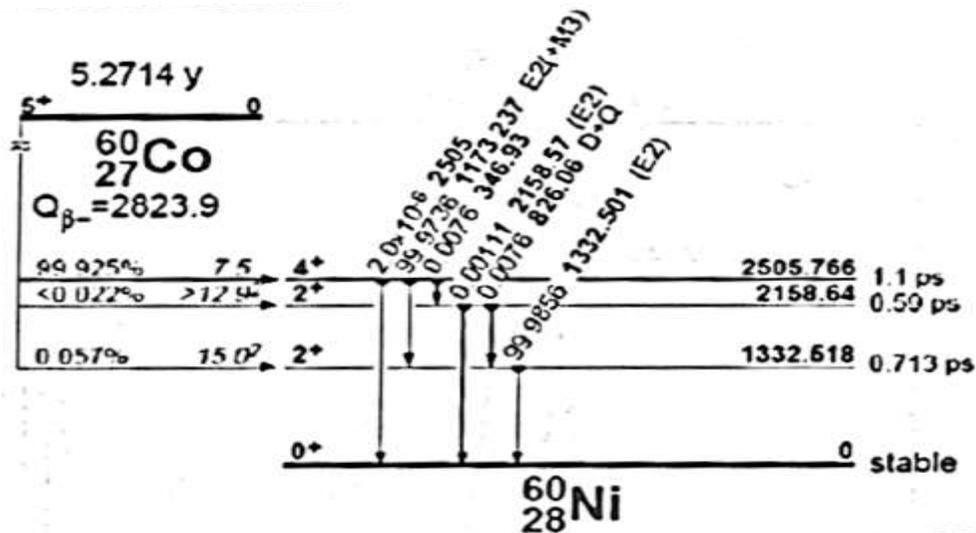


Fig. 6. Typical decay scheme of  $^{60}\text{Co}$

Fig .6. shows that the  $^{60}\text{Co}$  nucleus decayed ( $T_{1/2} = 5.27\text{years}$ ) by  $\beta^-$  emission to the excited state of  $^{60}\text{Ni}$  and about 0.12% of the time to the 1332keV level of  $^{60}\text{Ni}$ .The 2.505MeV level decayed to 1.332MeV level emitting the gamma ray of 1.1732MeV energy. the 1.332MeV level then went to ground state by emitting 1.332MeV gamma ray and the  $^{60}\text{Co}$  source was very good example of gamma ray cascade

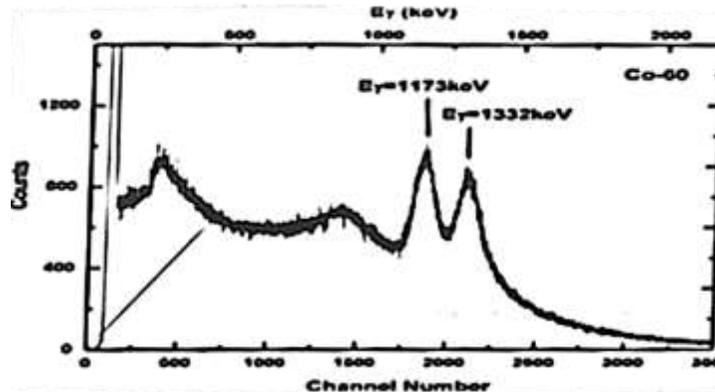


Fig. 7. Typical measured  $\gamma$  – ray spectrum of  $^{60}\text{Co}$

Fig. 7 shows the the measured  $\gamma$  – ray spectrum. A close observation to the measured  $^{60}\text{Co}$  spectrum clearly indicated two well separated photo peaks corresponding to 1.173MeV and 1.332MeV gamma energies. Further, the Compton edge as well as backscattered peak along with the low energy background parts was also observed. The width (FWHM) of the two peaks were found 38.47KeV (for 1.171MeV) and 43.47keV (for 1.332MeV) respectively.

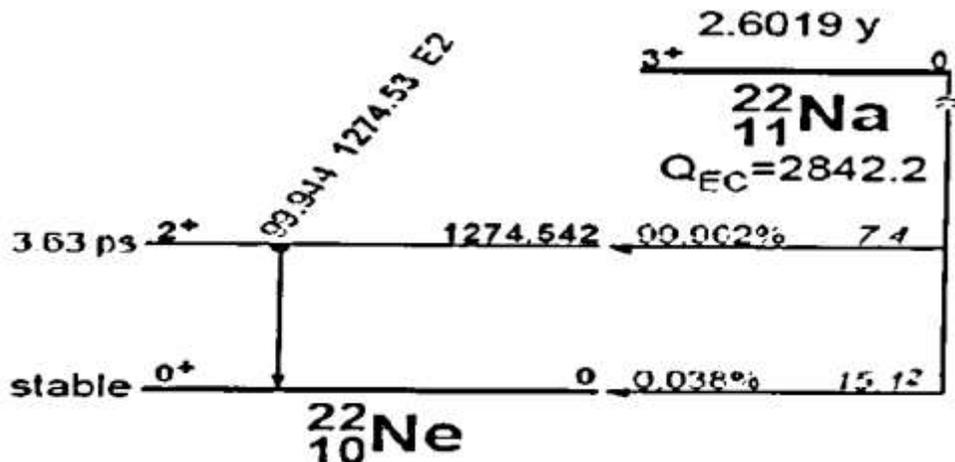


Fig. 8. Typical decay scheme of  $^{22}\text{Na}$

Fig .8. shows that a typical decay scheme of  $^{22}\text{Ne}$ , the radioactive source  $^{22}\text{Na}$  is similar to  $^{137}\text{Cs}$  source, where there was a  $\beta^+$  transition leading to the excited state (1274.5keV) of  $^{22}\text{Ne}$ , which decayed to ground state emitting 1274keV gamma ray. The basic difference between the two was that  $^{22}\text{Na}$  was a positron emitter (not electron). The  $^{22}\text{Na}$  nuclides for about 10% of the time decay by electron capture (EC) leading to 1274keV excited state of  $^{22}\text{Ne}$  and then emitted 1274keV gamma ray..In the case when  $^{22}\text{Na}$  decayed by positron emission, the positrons annihilate with the electrons in the source itself or in the source covering:  $e^+ + e^- = \gamma + \gamma$

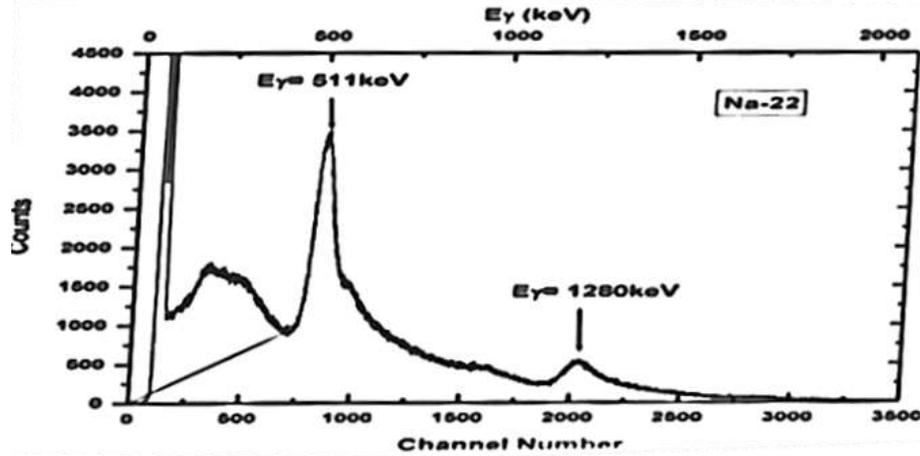


Fig. 9. The measured  $\gamma$  – ray spectrum of  $^{22}\text{Na}$

The Fig.9. shows that a typical measured gamma ray spectrum of  $^{22}\text{Na}$ , due to that annihilation process, two gamma rays were emitted in the opposite direction with  $E_{\gamma} = m_0c^2 = 511\text{keV}$  each. As such,  $^{22}\text{Na}$  source spectrum showed two gamma lines, one from nuclear decays (1274keV) and the other (511keV) due to positron annihilation.

In the same fashion, observed gamma ray spectrum of  $^{57}\text{Co}$ ,  $^{54}\text{Mn}$ ,  $^{133}\text{Ba}$  might be correlated to their respective decay schemes.

When gamma ray spectrum of any radioactive source was measured, one observes a large background surrounding the peak and in particular at low energies. As such, it was important to analyze the background spectrum as well [13,14,15].

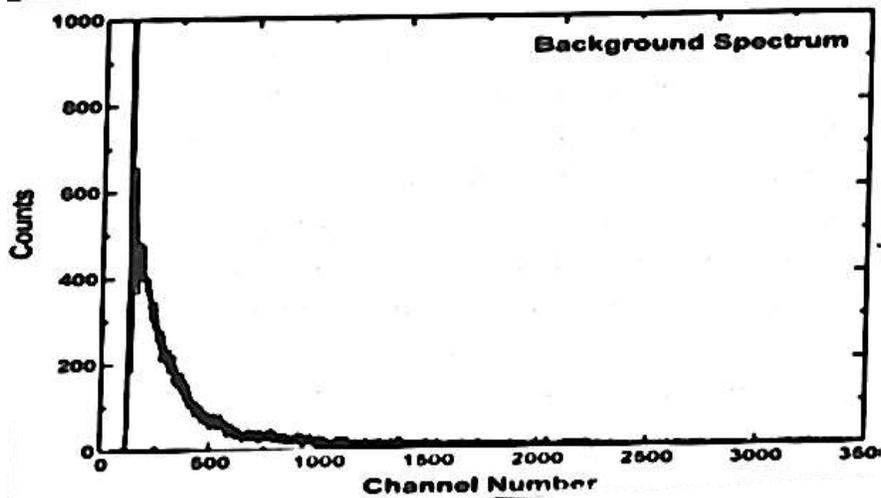


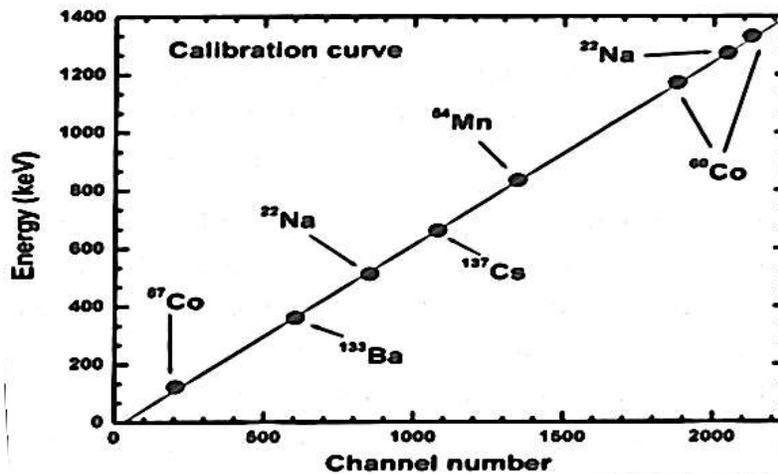
Fig.10. the measured  $\gamma$  – ray spectrum of background radiations recorded in the laboratory

Fig.10 shows that a typical background spectrum was recorded by keeping all the radioactive sources from the detector set up. The measured background spectrum.

After recording that spectrum, other standard sources were taken and their gamma ray spectra was also plotted keeping all the experiment parameter same. The corresponding data of pulse height and the gamma ray energy etc. of the peaks were noted as given in Table.2.

*Table (2)calculated the resolution of the detector for all the peaks*

| Source            | Energy (kev) | Channel number | FWHM (channels) | Peak area |
|-------------------|--------------|----------------|-----------------|-----------|
| <sup>133</sup> Ba | 360          | 605            | 35.6            | 112887    |
| <sup>57</sup> Co  | 123          | 205            | 16.5            | 180047    |
| <sup>137</sup> Cs | 662          | 1080           | 46.0            | 208425    |
| <sup>54</sup> Mn  | 835          | 1346           | 45.1            | 36150     |
| <sup>22</sup> Na  | 511          | 853            | 44.3            | 205284    |
|                   | 1274         | 2045           | 74.2            | 42370     |
| <sup>60</sup> Co  | 1172         | 1877           | 62.7            | 56013     |
|                   | 1332         | 2126           | 70.9            | 46114     |



*Fig.11. Energy calibration curve of the spectrometer*

Fig . 11. shows a plot of gamma ray energy vs. channel number was plotted.Using the data in Table .2. such a linear plot could be described by an equation of the form:

$$E_{\gamma} = m (\text{Channel number}) + b$$

Where,  $E_{\gamma}$  is the gamma ray energy expressed in MeV, (m) is the slope of the calibration line in MeV / channel and (b) is the intercept on the energy axis at channel number 0 expressed in MeV. It was found that for the present calibration line  $m=17.0266\text{keV/Channel}$ , while the intercept  $b = 0.631\text{keV}$ [2].

The statistical noise arises from the fact that the charge, Q generated within the detector by a quantum of radiation but by not a continuous process. An estimate could be made of the amount of inherent fluctuation by assuming that the formation of each charge carrier was a Poisson process. Under this assumption, if a total number N, of a charge carrier was generated on an average, then standard deviation of  $\sqrt{N}$  characterize the inherent statistical fluctuations in that number. If thos were the only source of fluctuation in the signal

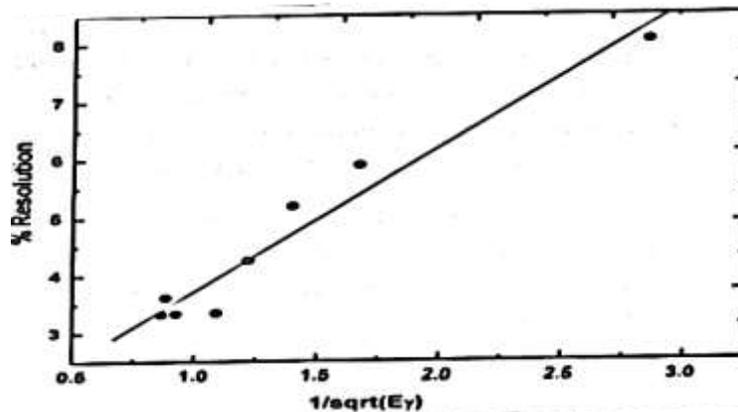
*Table.3. The table for plotting the percentage resolution.*

| Source            | $\gamma$ – Energy (keV) | $1/(\sqrt{E_\gamma})$ | % Resolution |
|-------------------|-------------------------|-----------------------|--------------|
| <sup>133</sup> Ba | 360                     | 1.67                  | 5.89         |
| <sup>57</sup> Co  | 123                     | 2.85                  | 8.05         |
| <sup>137</sup> Cs | 662                     | 1.22                  | 4.26         |
| <sup>54</sup> Mn  | 835                     | 1.09                  | 3.35         |
| <sup>22</sup> Na  | 511                     | 1.399                 | 5.2          |
|                   | 1274                    | 0.884                 | 3.62         |
| <sup>60</sup> Co  | 1172                    | 0.925                 | 3.34         |
|                   | 1332                    | 0.867                 | 3.33         |

The % resolution of the for each gamma peaks is calculated from the following equation:

$$\% \text{ Resolution} = \frac{\delta E}{E} \times 100\% \quad \dots\dots\dots(11)$$

where,  $\delta E$  is the full width of the peak at half of the Maxima(FWHM), measured in terms number of channels and ‘E’ is the channel number at the centroid of the peak.



*Fig. 12. The measured % resolution vs.1/√Eγ.*

Fig .12. shows the resolution was directly proportional to inverse of the square root of energy. Percentage resolution was also plotted against  $1/\sqrt{E_\gamma}$  as shown in Fig.24. Mathematically, the above plot might be represented by equation of the form:

$$\% R = \alpha + \beta / \sqrt{E} \quad \dots\dots\dots(12)$$

Where, the parameter  $\alpha$  and  $\beta$  depend on the properties of the scintillator and the mechanism of photon production. The values of  $\alpha$  and  $\beta$  parameters are found to be 1.25934 and 2.47275 respectively.

The operating voltage of a PMT's was typically of the order of 1000volts as given by the manufacturer. The gain of the PMT strongly depends on that voltage. Therefore, the gain could be conveniently controlled by changing the operation voltage. An attempt had been made in the present work to obtain the variation of gain of the PMT with the increase of the applied high voltage.

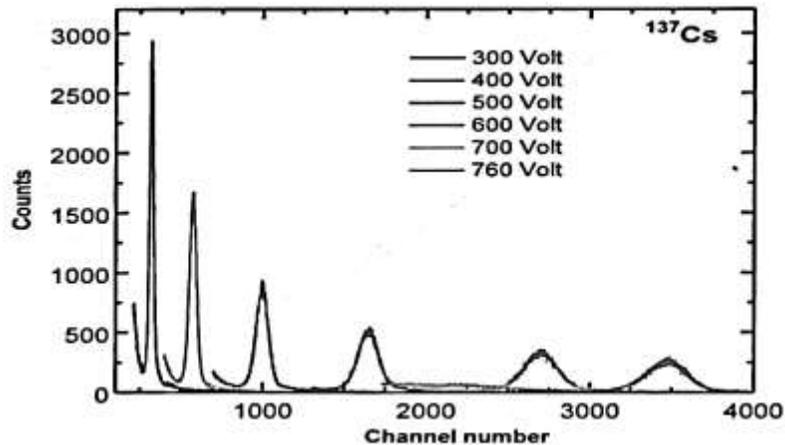


Fig.13. Typical plot showing the dependence of gain applied voltage

Fig .13. shows a typical plot indicating that variation shift in the 662 keV photo peaks of the <sup>137</sup>Cs source as could be seen from that figure, the gain increased with the increase in applied voltage. Further, the FWHM had also been found to increase with voltage. The broadening in the photo peak was not desirable as it worsens the resolution spectrometer. As such, while working with a scintillation spectrometer a compromise had to be made between the gain and the resolution so that the measurements might be completed satisfactorily.

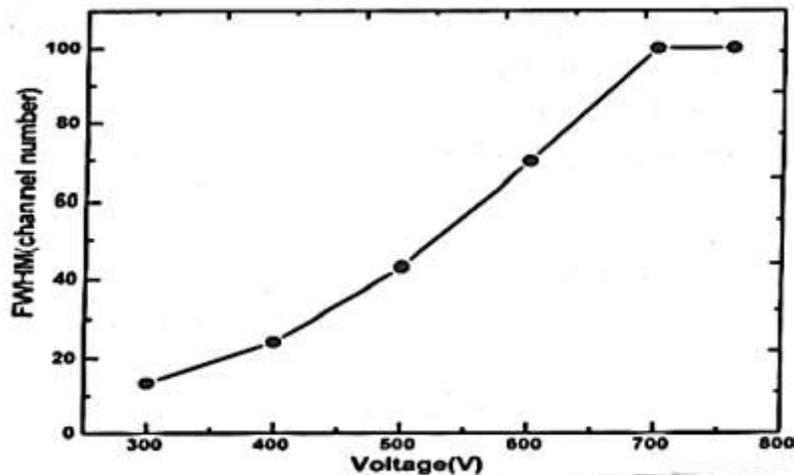


Fig. 14. Effect of operating voltage on FWHM of peak

Fig .14. shows a plot of peak channel number shift (for 662 keV gamma ray) with applied voltage as could be seen from this figure that with the increase in voltage the pulse height (channel number) increased. The corresponding FWHM values is also shown in fig.14. Were found to attain a constant value from 700 – 800volts. As such, it was desirable to use nearly the same applied voltage as suggested by manufacture because of those reason.

## CONCLUSIONS

The workreported many gamma ray spectra of various standard gamma ray sources had been recorded employing the MCA and associated electronics. The spectra had been analyzed to obtain various important information. The features of the measured gamma spectrum e.g. the photo peak, Compton edge, the annihilation peak, the backscattered peak, background spectrum etc. had been identified. The background spectrum indicatedthat there were natural background radiation which were bombarding us were our daily life. As such, in order to get exact analysis of gamma spectrum,

attempt should be done to minimize their effect in the measured spectra. The energy resolution of the spectrometer had also been determined as a function of gamma ray energy. The activity of unknown radioactive source had been determined using relative method found to agree reasonably well with that supplied by the manufacturer.

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