JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE INTEREST PROGRAMME

Radiation Protection and the Safety of Radiation Sources

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1. Radiation protection and dosimetry

1.1. Radiation protection

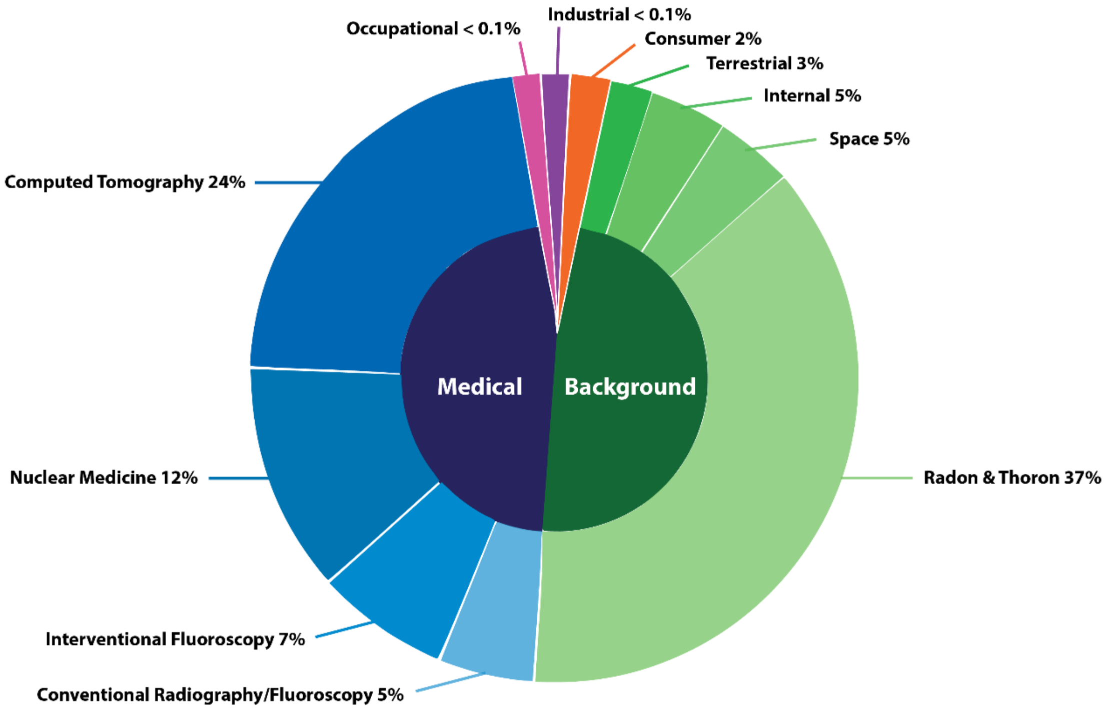


Figure 1. Sources of Radiation Exposure

The ICRP and the IAEA recommend the individual dose must be kept as low as reasonably achievable, and consideration must be given to the presence of other sources which may cause simultaneous radiation exposure to the same group of the public. Also, allowance for future sources or practices must be kept in mind so that the total dose received by an individual member of the public does not exceed the dose limit.

Radiation protection sets examples for other safety disciplines in two unique respects:

- First, there is the assumption that any increased level of radiation above natural background will carry some risk of harm to health.
- Second, it aims to protect future generations from activities conducted today.

1.2. Dosimetry

Dosimetry refers to the science by which radiation dose is determined by measurement, calculation, or a combination of measurement and calculation. The technical name for radiation dose is absorbed dose, it is the amount of radiation energy that is deposited in tissue divided by the mass of the tissue. The absorbed dose is the most important physical factor that influences the response of tumors and the rest of the body to radiation.

The absorbed dose refers to the amount of energy deposited in matter and its biological effect on living tissue, and should not be confused with activity, measured in units of curie or becquerel. Exposure to a radioactive source will give a dose which is dependent on the activity, time of exposure, energy of the radiation emitted, distance from the source and shielding. The dose equivalent is then dependent upon the additional assignment of weighting factors describing biological effects for different kinds of radiation on different organs.

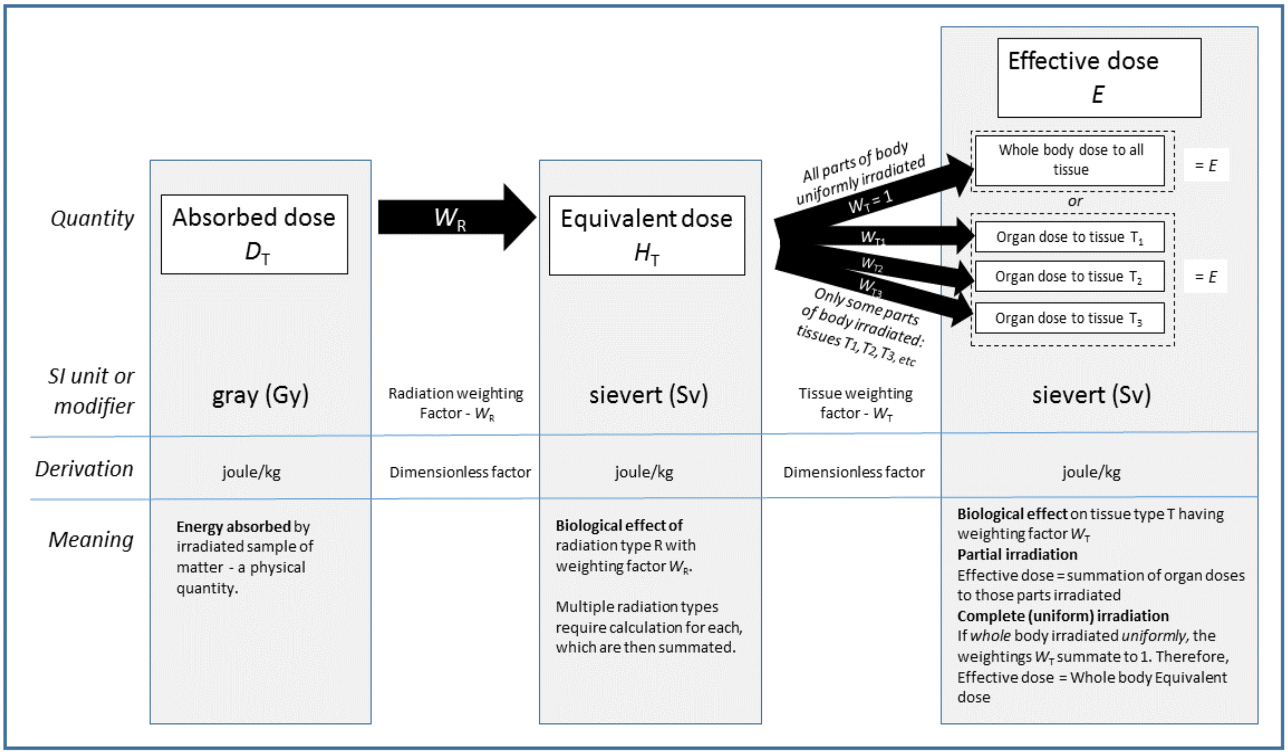


Figure 2. Ionizing radiation – protection dose quantities in SI units

2. Scintillation detectors and Photomultiplier tube (PMT)

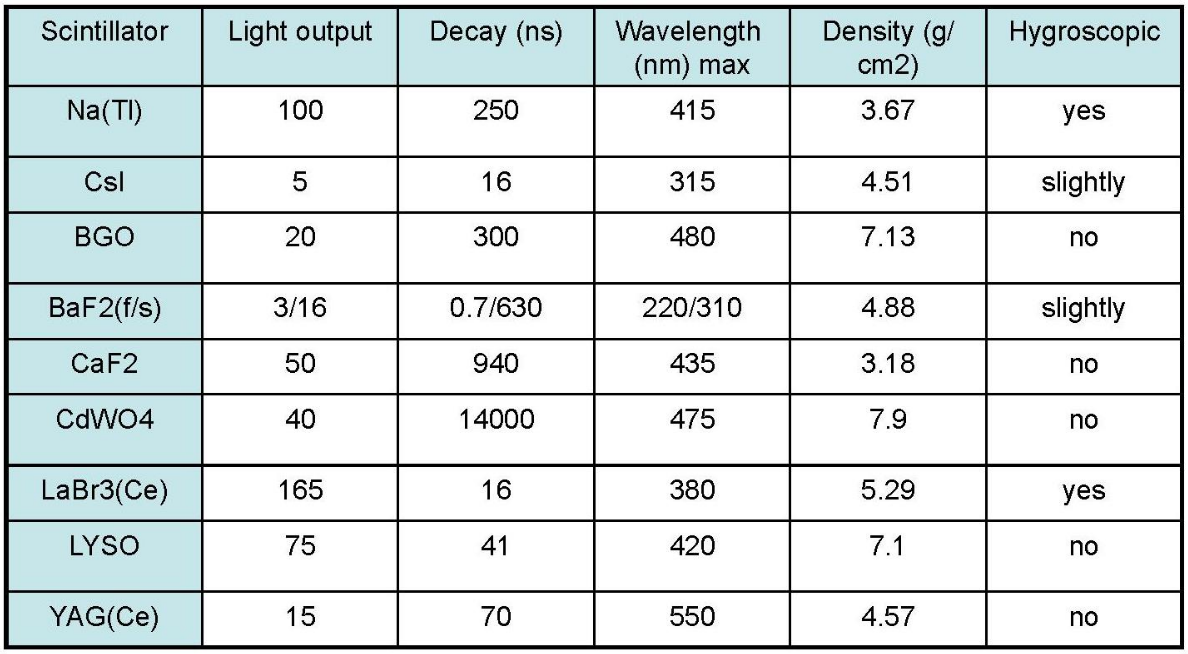
2.1. Inorganic scintillators

BGO – Bismuth Germanate ($Bi_4Ge_3O_{12}$):

- Wavelength range: 375- 650 nm
- Crystals diameter: 75- 300 mm max lengths
- Applications: PET, HEP, NP, space and medical physics
- Highly effective gamma ray absorber

NaI (Tl) – Sodium Iodide (Thallium):

- Wavelength range: 325- 550 nm
- Crystals diameter: 150- 400 mm max lengths
- Applications: TOF measurements, Positron lifetimes studies, PET, HEP and NP



Scintillator	Light output	Decay (ns)	Wavelength (nm) max	Density (g/ cm2)	Hygroscopic
Na(Tl)	100	250	415	3.67	yes
CsI	5	16	315	4.51	slightly
BGO	20	300	480	7.13	no
BaF2(f/s)	3/16	0.7/630	220/310	4.88	slightly
CaF2	50	940	435	3.18	no
CdWO4	40	14000	475	7.9	no
LaBr3(Ce)	165	16	380	5.29	yes
LYSO	75	41	420	7.1	no
YAG(Ce)	15	70	550	4.57	no

Figure 3. Scintillator properties of crystals

2.2. Photomultiplier tube (PMT)

A scintillating material (usually an inorganic crystal or doped plastic) emits light when its atoms are ionized or excited. This ionization can be caused by charged particles or by neutral particles that interact in the scintillator. In typical applications a single incoming particle will produce hundreds of scintillation photons, each photon will interact in the photocathode layer approximately 25% of the time to produce a single photoelectron, via the photoelectric effect. This electron accelerates in the electric field and hits the first dynode, where it produces N (about 2-4) electrons by secondary emission. These electrons accelerate to the next dynode and ending with the anode. At each stage, the gain is $\sim$ N, so if there are M acceleration stages, the overall gain in number of electrons is approximately M^N, with typical total gains being in the range 10^7 to 10^9.

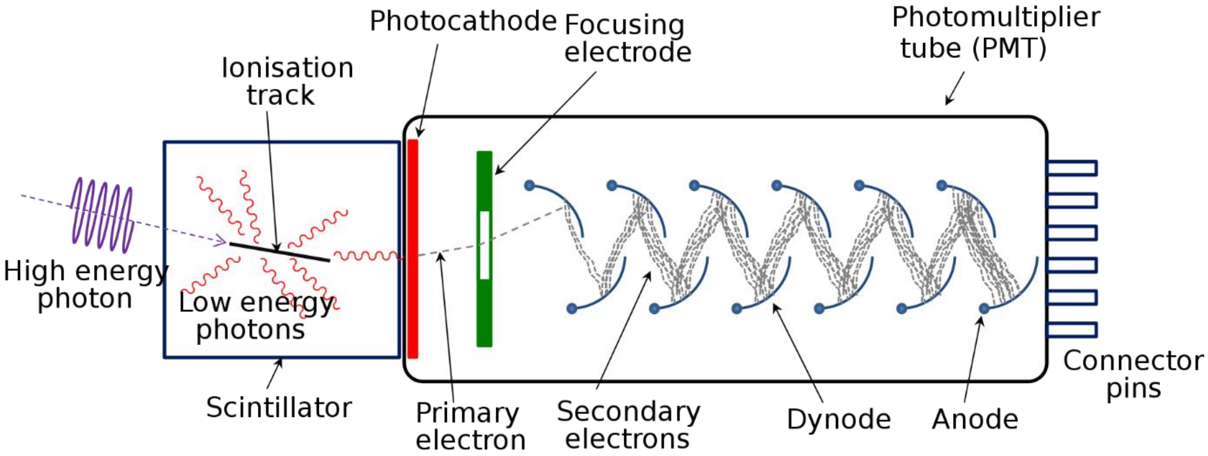


Figure 4. A photomultiplier tube scheme

TASK 1. RELATION BETWEEN THE RESOLUTION AND APPLIED VOLTAGE FOR BGO

The energy resolution of a detector measures its ability to distinguish gamma-rays with close energies. The better the energy resolution, the better it can separate two adjacent energy peaks, which allows identifying different decays or radionuclides in the spectrum. Resolution is obtained from the peak full width at half of the maximum height (FWHM) divided by the location of the peak centroid H_0 or :

$$\text{Resolution} = \frac{\text{Sigma}}{\text{Mean}} \times 2.35 \qquad (1)$$

Voltage	Mean	Sigma	Resolution (%)
1200	1.627	0.436	62.996
1300	1.386	0.277	46.977
1400	1.917	0.280	34.283
1500	2.997	0.395	30.948
1600	4.420	0.536	28.519
1700	6.053	0.662	25.722
1900	10.491	1.032	23.115
2000	13.313	1.121	19.797

Table 1. Resolution of BGO detector corresponding to applied voltage derived from mean and sigma using equation (1).

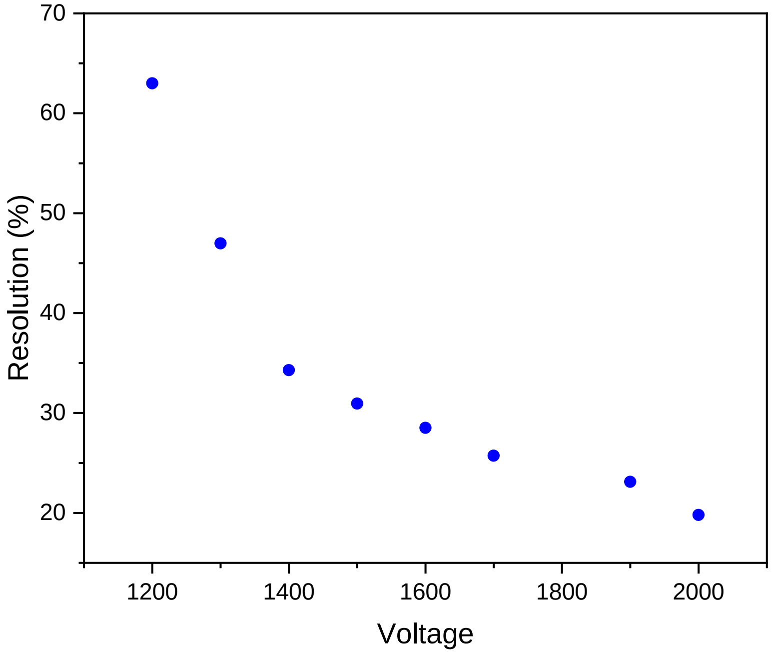


Figure 1. The relation between the resolution and applied voltage for BGO scintillation detector.

TASK 2. ENERGY CALIBRATION FOR BGO DETECTOR

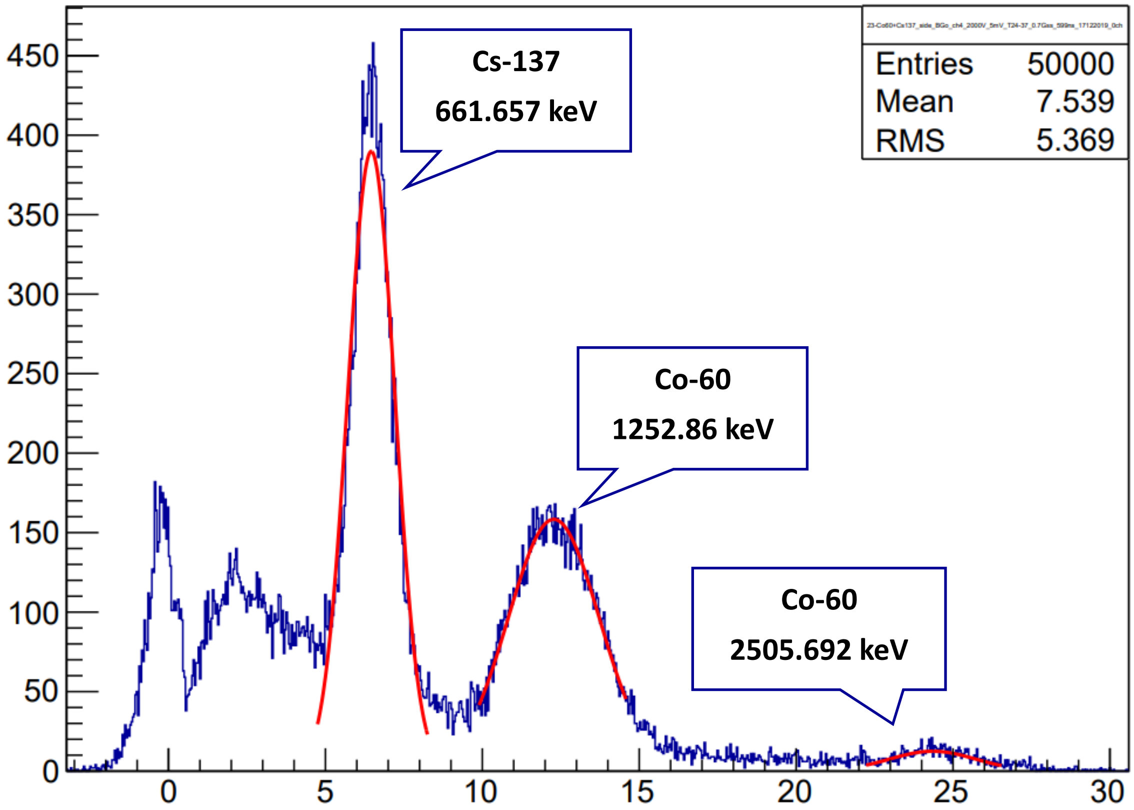


Figure 2. Cs-137 and Co-60 spectrum from measurements with BGO detector at 2000 V

Equation of the calibration curve for BGO detector:

$$102.88301x - 4.16376 = y$$

Where

x = channel,

y = energy in keV of unknown source peaks.

Table 2. Channel and energy of corresponding peaks of Cs - 137 and Co - 60

Isotope	Channel	Energy (keV)
Cs - 137	6.44116	661.657
Co - 60	12.2631	1252.86
	24.3806	2505.692

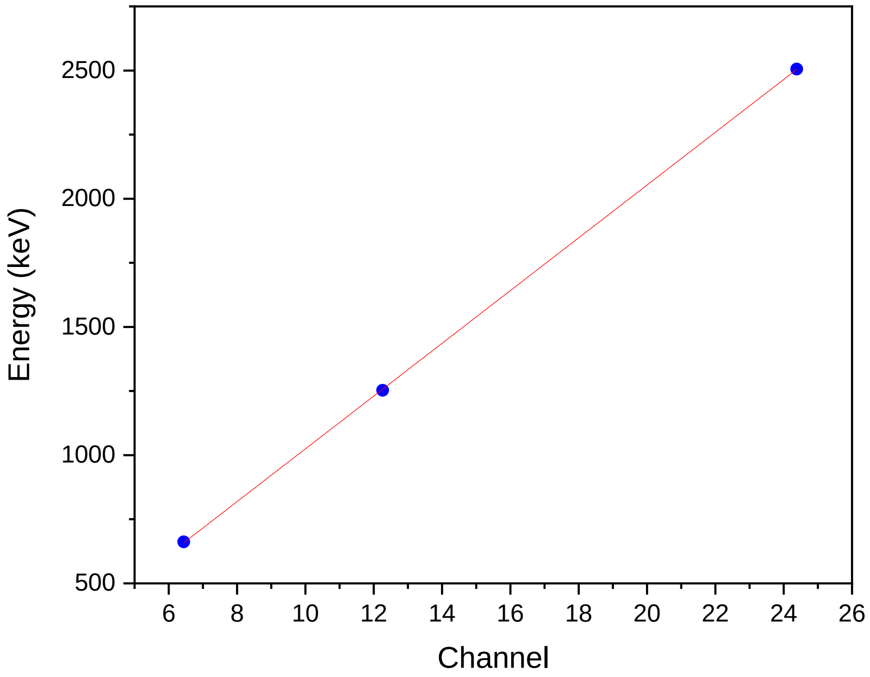


Figure 3. Energy calibration for Co-60 and Cs-137 spectrum resulting from measurements with BGO scintillation detector

2.1. Identification of unknown energy

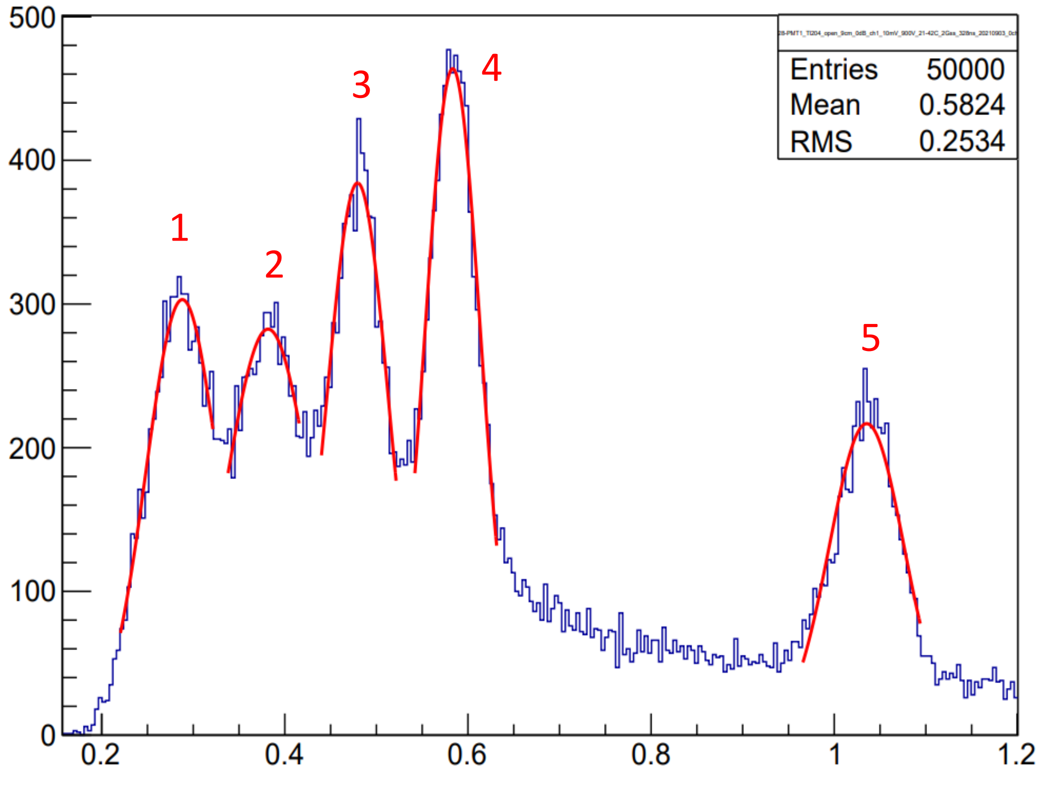


Figure 4. Ra-226 gamma spectrum

Steps to determine the energy of a peak:

1. We get the spectrum of unknown energy

2. We make Gauss fitting and find Channel (Mean)

3. From energy calibration we can determine energy peak of an unknown source by using equation from calibration of BGO detector:

$$y = 102.88301x - 4.16376$$

For example, the energy of peak 1 :

$$\begin{aligned} \text{With } x \text{ (Channel) } &= 0.289, \\ y \text{ (Energy) } &= 102.88301 \times 0.289 - 4.16376, \\ y &= 25.551 \text{ keV} \end{aligned}$$

Table 3. Energy of 5 peaks in Ra-226 gamma spectrum with corresponding channels

Peak	Channel	Energy (keV)
1	0.289	25.551
2	0.382	35.173
3	0.478	45.042
4	0.583	55.776
5	1.034	102.254

TASK 3. RELATION BETWEEN THE RESOLUTION AND APPLIED VOLTAGE FOR NaI

Table 4. Resolution of NaI detector corresponding to applied voltage derived from mean and sigma using equation (1).

Voltage	Mean	Sigma	Resolution (%)
900	23.660	0.619	6.145
1000	40.682	0.921	5.317
1100	65.897	1.481	5.280
1200	98.708	1.813	4.318
1300	137.516	2.397	4.097

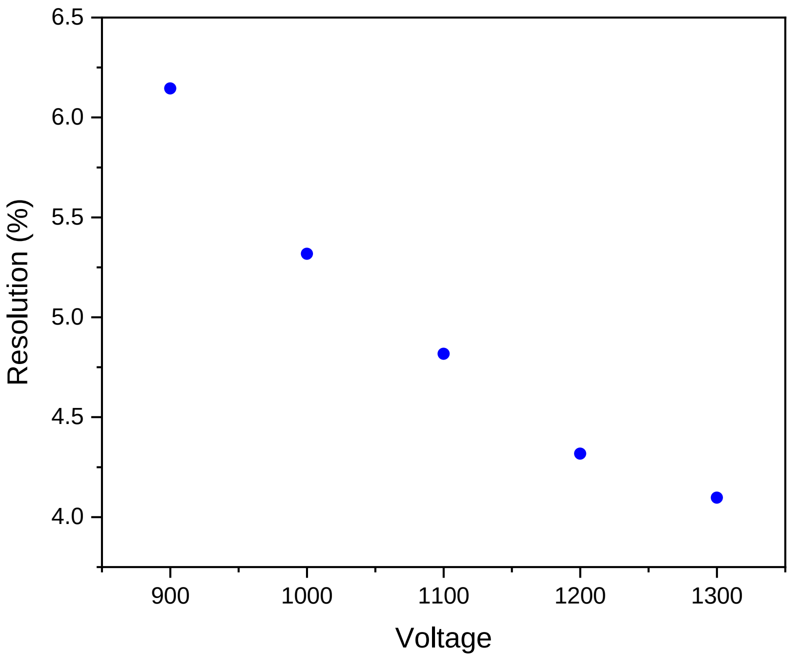


Figure 5. The relation between the resolution and applied voltage
for NaI scintillation detector

TASK 4. ENERGY CALIBRATION FOR NaI DETECTOR

4.1. Energy calibration

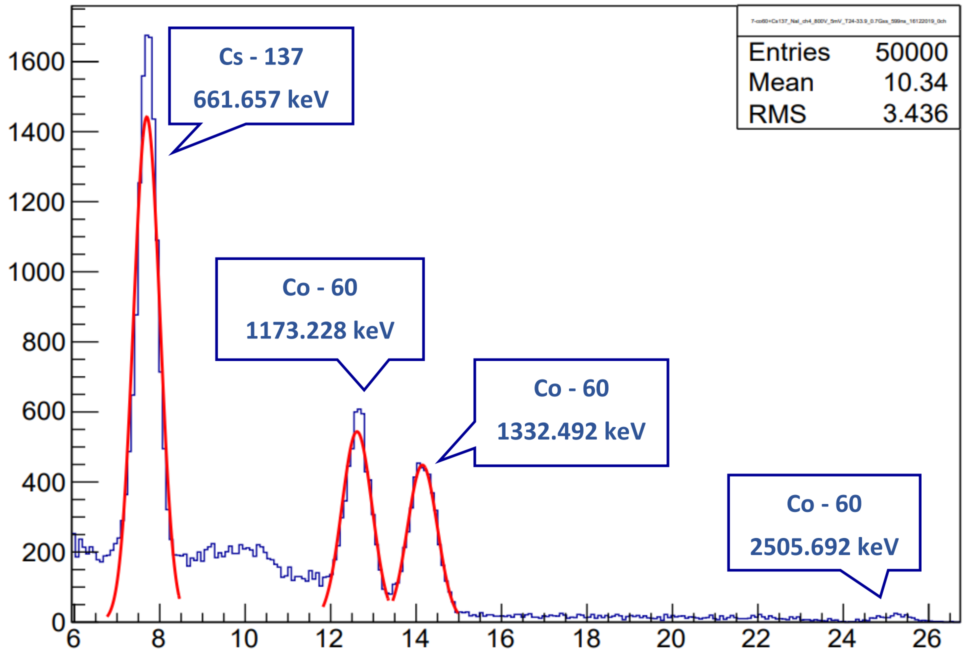


Figure 6. Cs-137 and Co-60 spectrum from measurements with NaI detector at 800 V

Table 5. Channel and energy of Cs-137 and Co-60 peaks from measurements with NaI detector at 800 V

Isotope	Channel	Energy (keV)
Cs – 137	7.695	661.657
Co - 60	12.625	1173.228
	14.149	1332.492
	25.193	2505.692

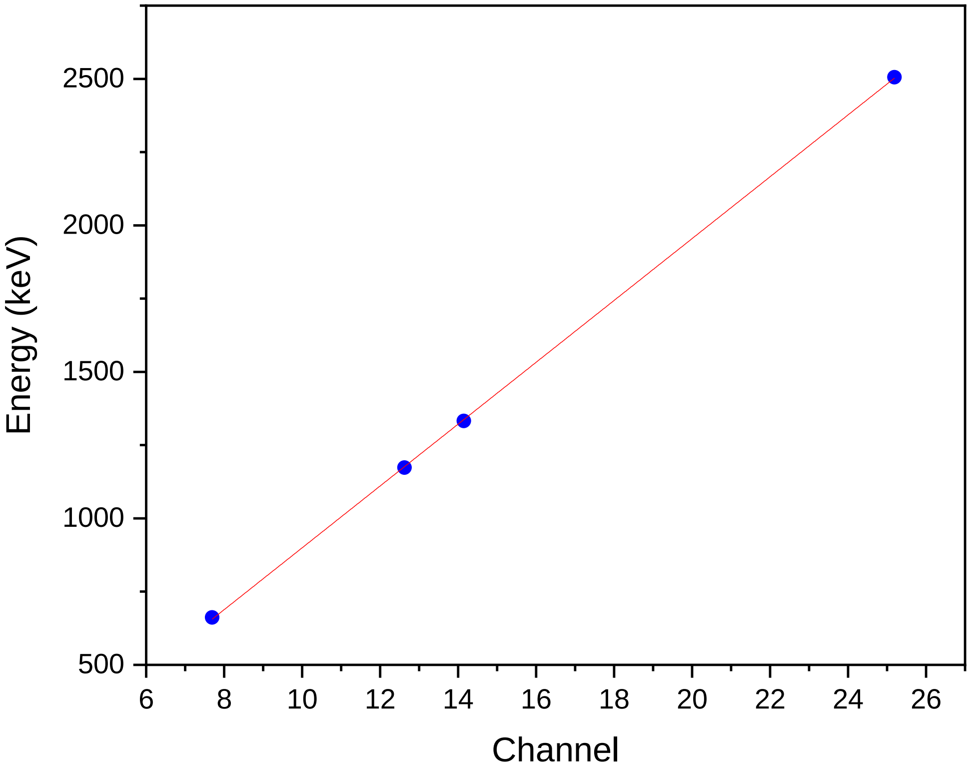


Figure 7. Energy calibration for Co-60 and Cs-137 spectrum resulting from measurements with NaI scintillation detector

Equation of the calibration curve for NaI detector:

$$105.53656x - 155.85538 = y$$

Where

x = channel,

y = energy in keV of unknown source peaks.

4.2. Identification of unknown sources

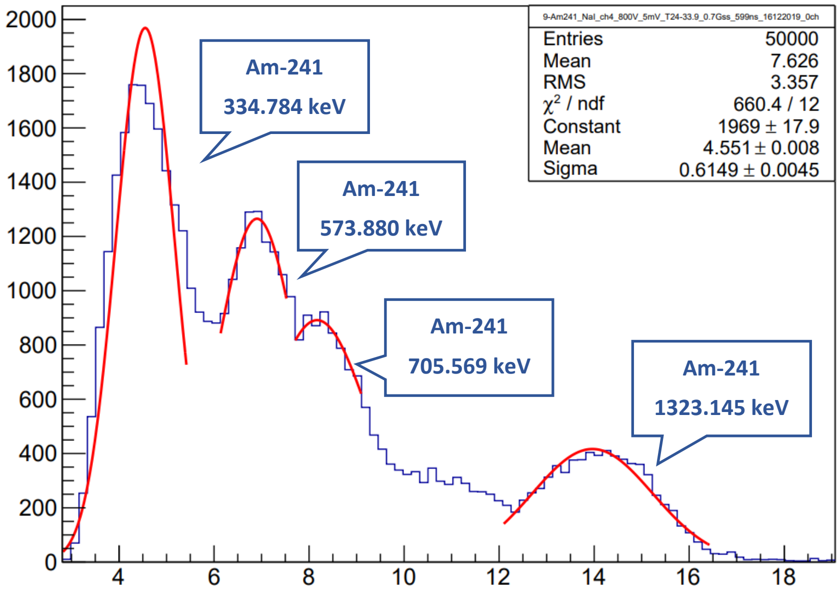


Figure 8. Am-241 gamma spectrum

Steps to determine the energy of a peak:

1. We get the spectrum of an unknown source

2. We make Gauss fitting and find Channel (Mean)

3. From energy calibration we can determine energy peak of an unknown source by using equation from calibration of NaI detector:

$$y = 105.53656x - 155.85538$$

For example, the energy of peak 1:

$$\text{With } x \text{ (Channel)} = 4.649,$$

$$y \text{ (Energy)} = 105.53656\ 4.649 - 155.85538,$$

$$y = 334.784 \text{ keV}$$

Therefore, the unknown source is Am-241

Peak	Channel	Energy (keV)
1	4.649	334.784
2	6.915	573.880
3	8.162	705.569
4	14.014	1323.145

Table 6. Energy of 4 peaks in Am-241 gamma spectrum with corresponding channels

TASK 5. ATTENUATION COEFFICIENT

The attenuation coefficient is a constant that describes the fraction of absorbed or scattered incident photons in a beam per unit thickness of a material. The equation for calculating the attenuation coefficient is as follows:

$$\mathrm{I} = \mathrm{I}_0 \mathrm{e}^{-\mu x}$$

Where x = absorber thickness,

I = intensity transmitted through an absorber of thickness x,

I_0 = intensity at zero absorber thickness,

μ = linear attenuation coefficient.

There are two main features of the linear attenuation coefficient:

- Increases as the atomic number of the absorber increases.
- Decreases (for all materials) with the energy of the gamma rays.

Experimental equipment:

- Detector: BGO scintillation detector
- Voltage: 2000 V
- Source: Cs-137, E_{Cs}= 661 keV
- Attenuation material: Cu, Al

5.1. ATTENUATION COEFFICIENT OF ALUMINUM (Al)

Thickness (cm)	I/I_0
0	1
0.15	0.75573
0.3	0.71623
0.45	0.70569
0.75	0.68596
0.9	0.67155
1.08	0.66103
1.26	0.63939

Table 7. The aluminum (Al) shield thickness necessary to reduce the intensity of a beam to the desired level

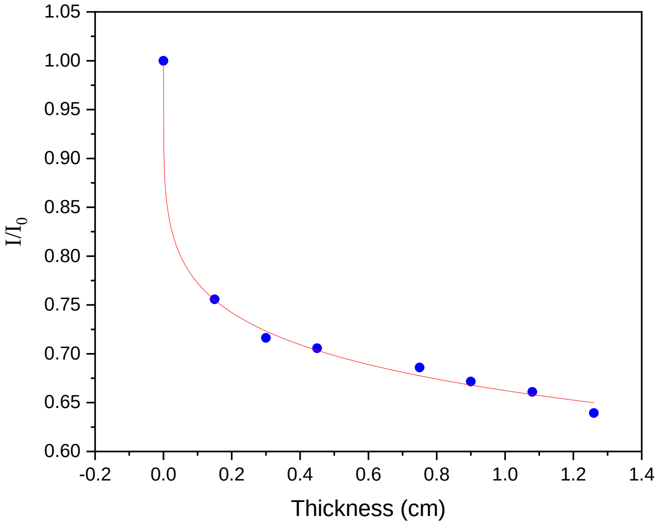


Figure 9. Determination of linear attenuation coefficient for Al using BGO scintillation detector with the radiation source Cs-137 (661 keV)

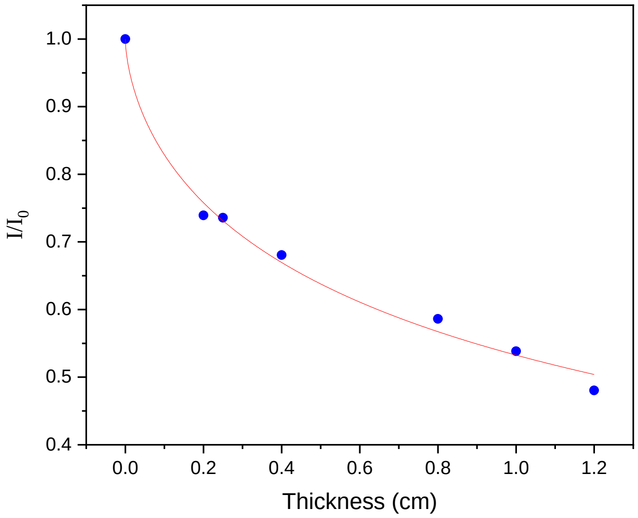
The attenuation coefficient of aluminum (Al) was determined to be *0.23828 ± 0.01725* cm^{-1}.

5.2. ATTENUATION COEFFICIENT OF COPPER (Cu)

Thickness (cm)	I/I_0
0	1
0.2	0.73931
0.25	0.7357
0.4	0.68065
0.8	0.58611
1	0.53827
1.2	0.48042

Table 8. The copper (Cu) shield thickness necessary to reduce the intensity of a beam to the desired level

Figure 10. Determination of attenuation coefficient for Cu using BGO scintillation detector with the radiation source Cs-137 (661 keV)



The attenuation coefficient of copper (Cu) was determined to be *0.23828 ± 0.01725* cm^{-1}.

TASK 6. ALPHA RANGE IN AIR

6.1. Alpha range in air by experiment

Range is the distance that a particle travels from its source through matter. It is dependent upon a number of variables such as the particle type, its energy and the medium through which it travels. Range applies especially to charged particles, i.e. electrons and alpha particles. This is because when charged particles pass through matter their energy is absorbed by the medium hence slowing them down.

Experimental equipment:

- Alpha source: Pu-239
- Energy of He: 5.5 MeV
- Detector type: plastic
- Applied volt: 2000V

Distance (cm)	Counts/sec
0	440
0.5	390
1	360
1.5	340
2	320
2.5	300
3	280
3.5	260
3.8	260
4	260

Table 9. Number of counts per second of source at different distances from the detector

From the value in table 9, it shows that the counts per second decreases until it reaches a point where the numbers of counts are consistent. We conclude that the range of alpha in the air is about 3.5 cm.

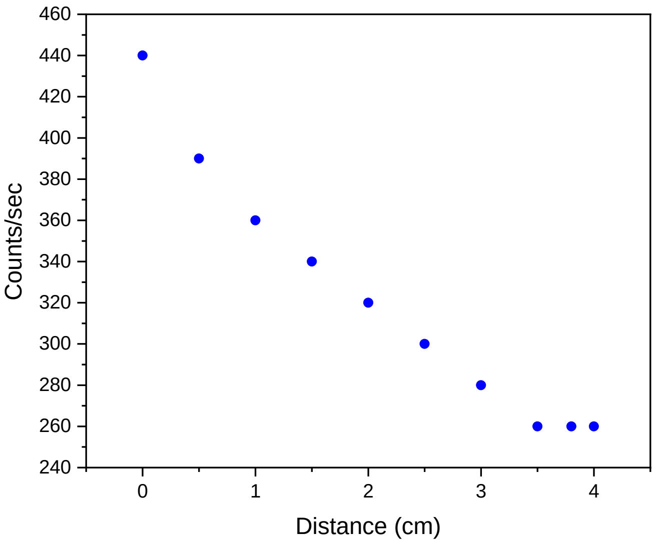


Figure 11. The range of alpha particles resulting from measurements with plastic detectors at 2000 V and Pu-239 (5.5 MeV)

6.2. Alpha range in air by SRIM simulation (Monte Carlo)

Figure 12. Depth for alpha radiation in 5 cm air

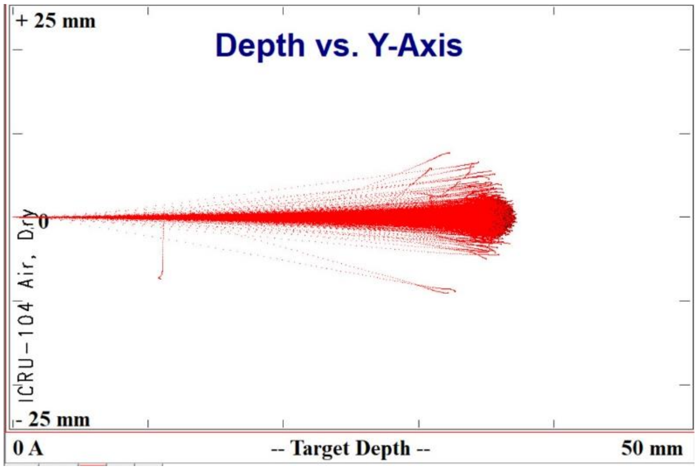
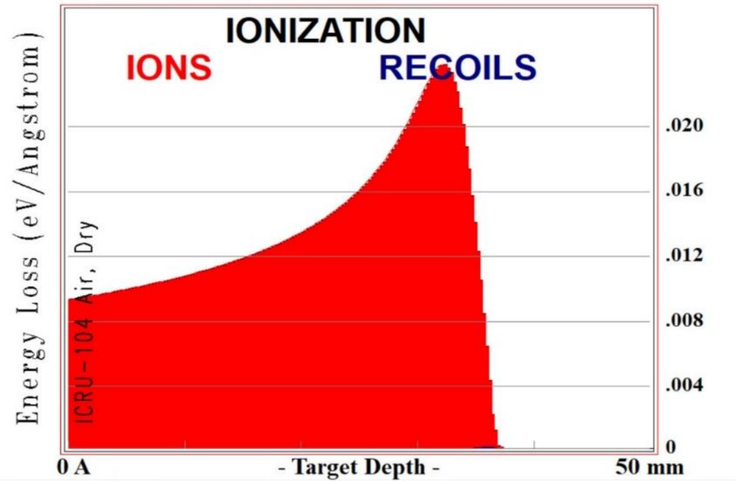


Figure 13. Ionization power of alpha particles in air at 5 cm



The intensity of the alpha radiation decreases with the distance rapidly. It is possible to describe this process with an exponential function. Alpha particles lose their energy due to the interaction with particles of the air. This distance is the range of alpha particles in the air. The value of the range of alpha particles in the air is between 3 cm and 4 cm.

TASK 7. PIXEL DETECTOR

7.1. Characteristics

- It is an advanced detector similar to a digital camera
- It consists of 3 parts:
  1. Sensor (Si)
  2. Electronic chip
  3. USB
- The size of the sensor: 1.5×1.5 cm
- It has 256×256 pixels (65,536 pixel)
- The pixel size is 55 µm×55 µm
- High resolution detector
- Used for the registration different types of radiation (x- rays, gamma radiation, electrons, neutrons and charged particles).

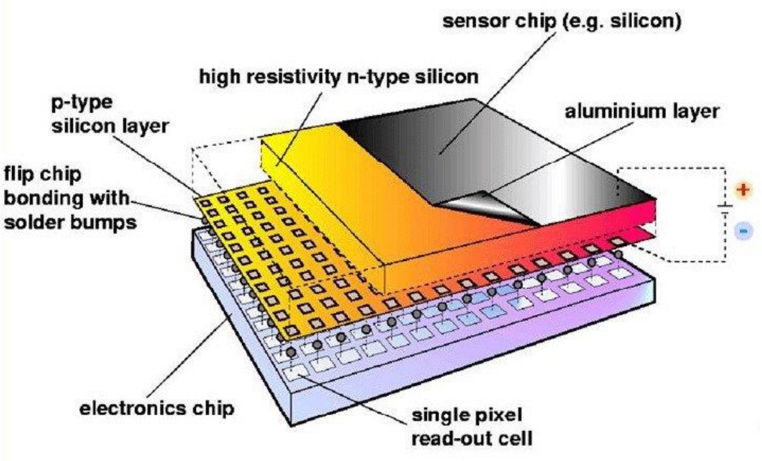


Figure 14. Hybrid pixel detector

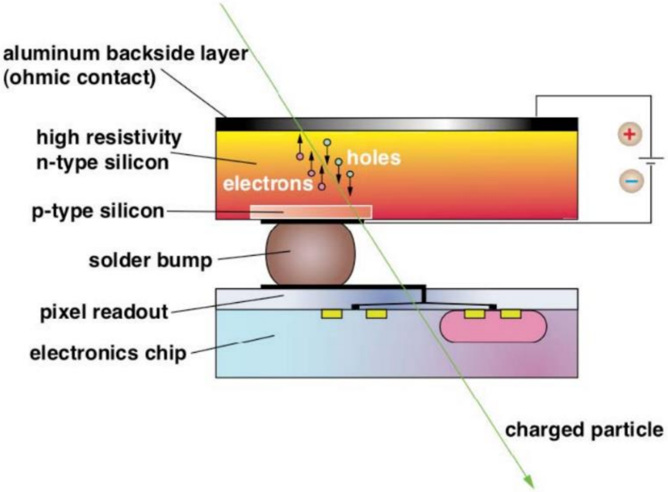


Figure 15. Hybrid pixel detector - cross Section

7.2. Determination of alpha particles range in air using pixel detector

The range of alpha particles with (Am-241) energy about 4 MeV in air using pixel detector

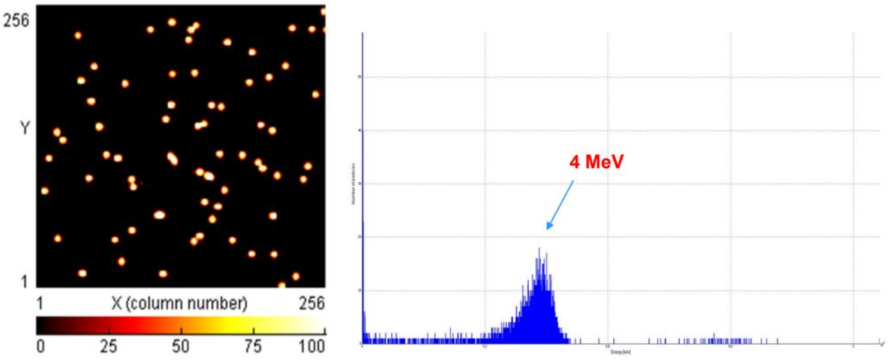


Figure 16. Absorption of alpha particle energy in the air at 0 cm

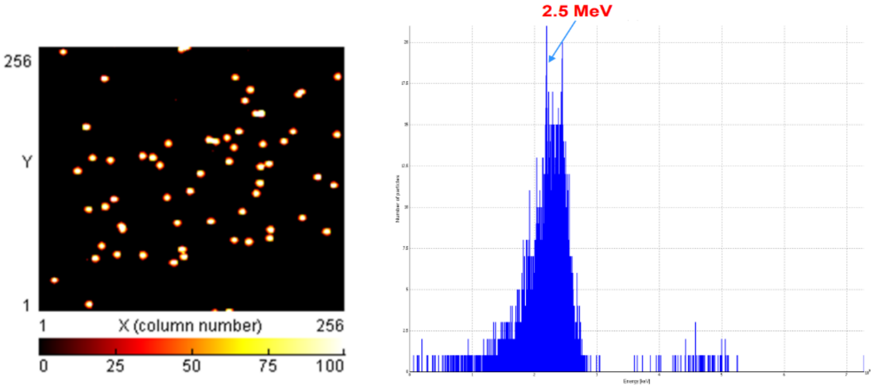


Figure 17. Absorption of alpha particle energy in the air by moving the alpha source away by 1 cm

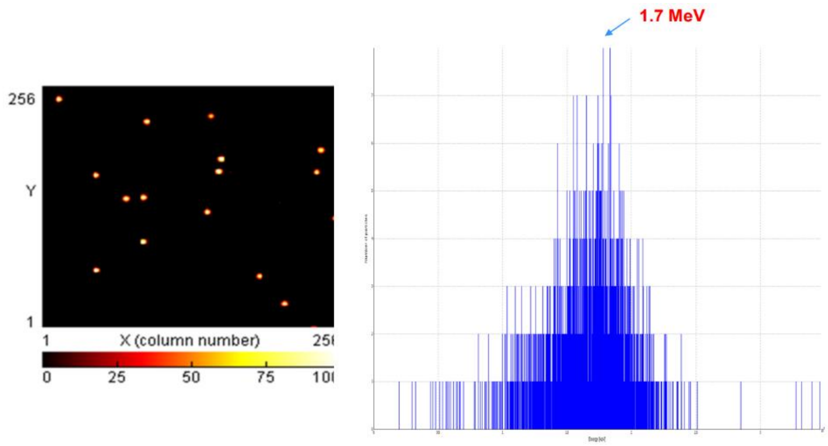


Figure 18. Absorption of alpha particle energy in the air by moving the alpha source away by 2 cm

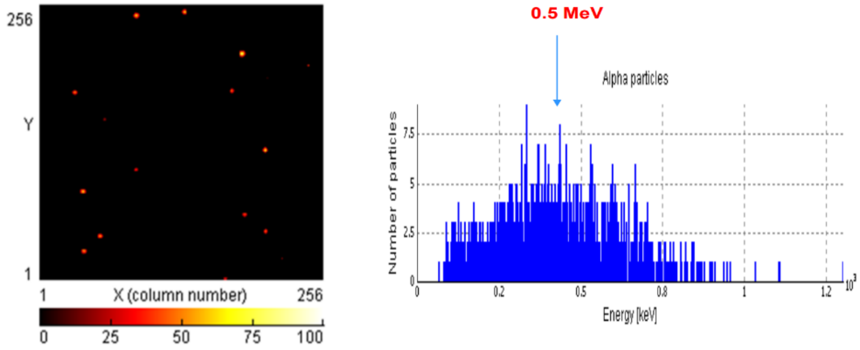


Figure 19. Absorption of alpha particle energy in the air by moving the alpha source away by 2.5 cm

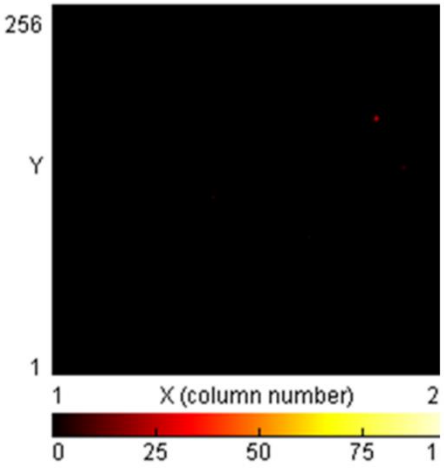


Figure 20. Absorption of alpha particle energy in the air by moving the alpha source away by 3 cm

At 3 cm distance from the source there are no alpha particles detected. Maximum of alpha particle range is 3 cm.

CONCLUSIONS

- Different types of radiation sources, and detection of radiation.
- Limit dose and recommended radiation protection protocol
- Radioactivity and naturally occurring radioactive materials NORM.
- Energy calibration of some scintillation detectors (BGO and NaI) by using standard sources.
- Identify of unknown source by using energy calibration curve.
- Calculation of resolution for different scintillation detectors.
- Determination of alpha range in air using pixel and plastic detectors.
- Determination of attenuation coefficient for different materials .
- Assessment the ranges and energy of alpha particles using Monto Carlo simulation SIRM software.

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