Gamma ray spectroscopy using Inorganic scintillators

Alpana[1], Dmitrii Kyshtymov[2], Samadhan Kamble[3]

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[1]: IISER, Pune, India
[2]: BINP, Novosibirsk, Russia
[3]: IIT, Madras, India

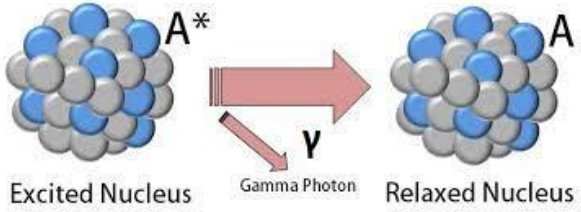
Outline of the talk

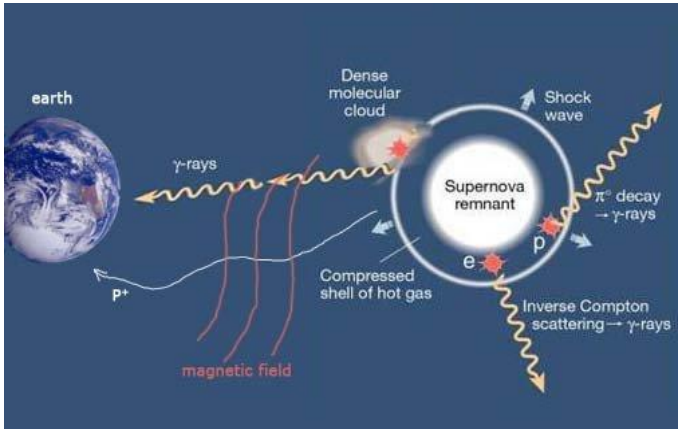
- Motivation & sources of Gamma radiation
- Interaction of photons with matter
- Different detectors to detect gamma radiation
- Basic principle of scintillators - Inorganic & organic & PMTs
- Experimental setup for gamma ray spectroscopy
- Results
  - Identifying different photo peaks & observation in the gamma spectrum of Cs-137.
  - Comparison of energy resolution as a function of energy for NaI(Tl) & $LaBr_3$:Ce crystal.

- Conclusions

Motivation

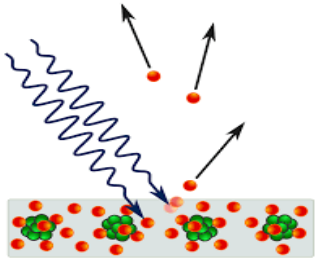
- Gamma ray spectroscopy - precise measurement of gamma photon energies.
  - Can establish nuclear energy structures
  - Identification of radioactive elements
  - Positron emission tomography (PET) & radiation therapy to treat tumours - applications in medical fields.
- Sources: **Radioactive elements, Nuclear fission, Neutron capture, supernova remnant, neutron pulsars and etc…**
  - We will be focusing on Gamma rays from radioactive sources.

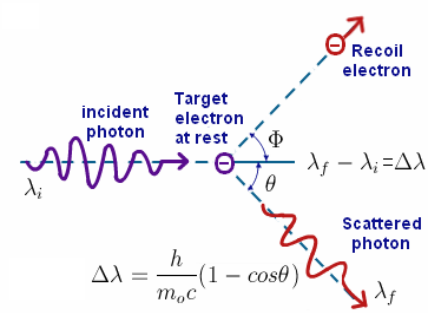


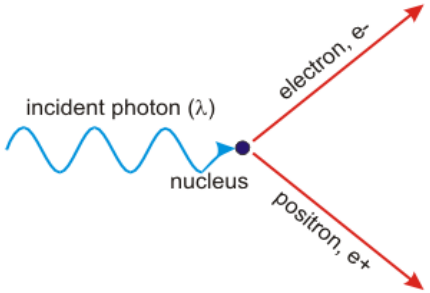


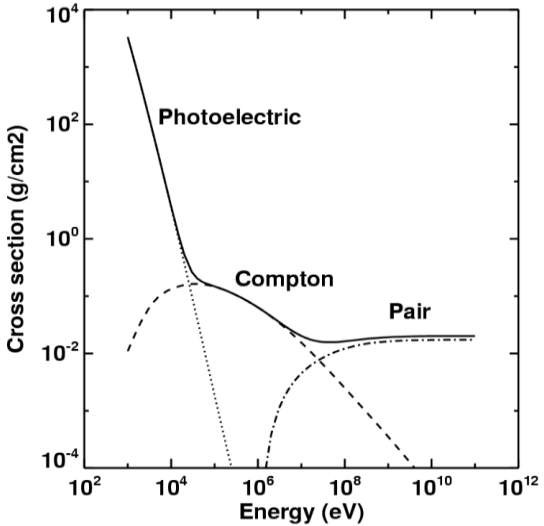
- **How to detect Gamma rays? -** Can be observed by their effect on the matter.
  - That effect on the detecting matter can be converted to a signal which corresponds to the energy of the photons.

Interaction of photons with materials









- Photons interact with material via,
  - Photoelectric effect (PEE) (< few hundred keV)
    - High Z dependence of the cross section
  - Compton scattering (CS)
    - (few hundred keV < E_{photon} < 5 MeV)
  - Pair production (PP) **(> 5 MeV)**

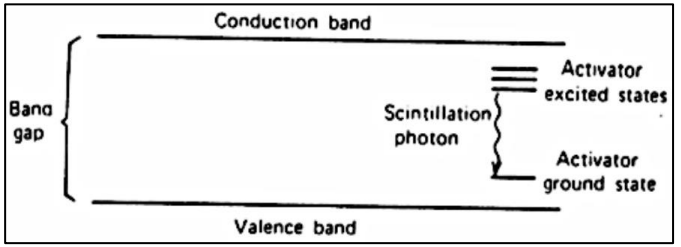
- **PEE -** give peak of total energy absorption of gamma ray and use of high Z material increase the photo peak efficiency.
- **CS γ-ray** suffers multiple scatterings unless and until it gets absorbed through photoelectric process or escapes the detector.
  - First contributes to the photopeak, the second gives rise to a continuous Compton background.
- **e^-/e^+ from PP** - go through either coulomb scattering or e^+ annihilation results into single/double escapes peak.

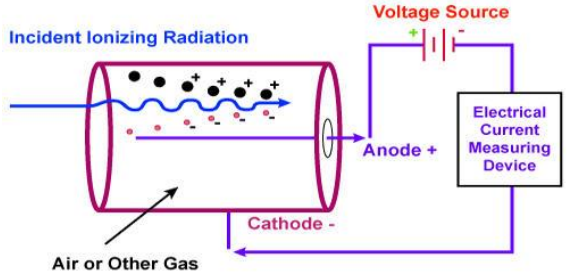
Different detectors for Gamma ray detection

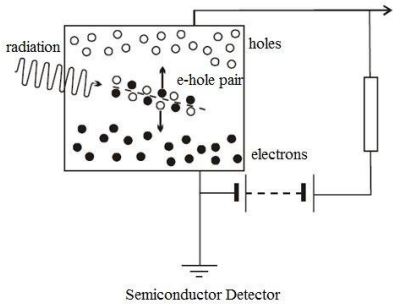
- Scintillators: Inorganic scintillators with good resolution in the range of few keV to higher E.
  - Worse resolution of organic scintillators, less light output.

- Gaseous detectors:
  - Can not detect directly the photons, convert to charged particles via some interaction.

- Solid state detectors : Silicon and Germanium detectors
  - Pure Ge has better efficiency and light output as compared to Si.
  - More photons/MeV as compared to Inorganic scintillators & Si - hence better resolution.
    - For high energy gamma detection, need larger pure Ge crystal.
      - Very costly and not feasible to make.







Today we will be discussing the two organic scintillators - NaI(Tl) & $LaBr_3$:Ce

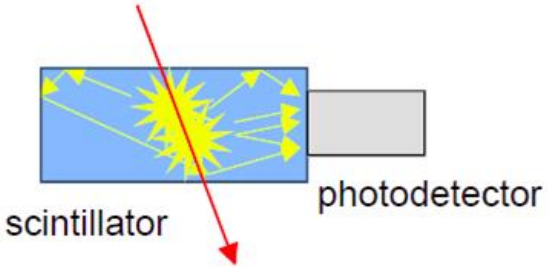
Experimental method and the setup

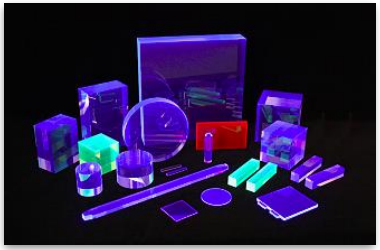
Scintillation detectors

Scintillation is a luminescence induced by ionizing radiation in transparent dielectric media.

Two main components:

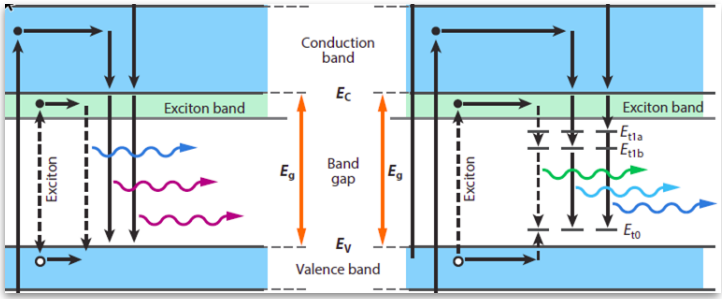
- Scintillator
- Photo sensor & multiplier





Scintillator types

- Organic
- Inorganic
  - ✓ NaI:Tl
  - ✓ LaBr3:Ce



Band levels-Inorganic crystals

Advantages:
- Good efficiency
- Good linearity
- Radiation tolerance

Disadvantage:
- Relatively slow
- Crystal structure needed (small and expensive)

Photodetector

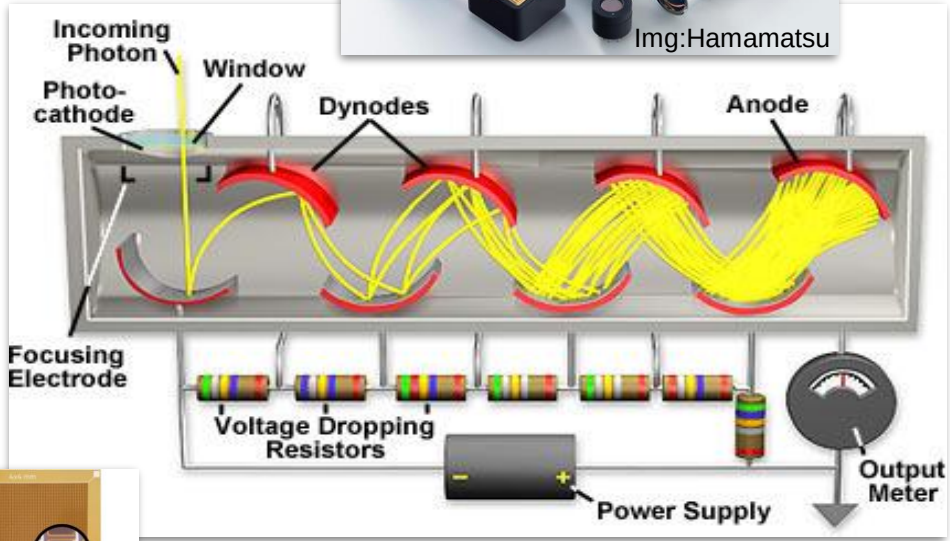
- Convert light into detectable electronic signal (photoelectric effect)
- Standard requirement: high sensitivity (Quantum Efficiency = $N_{pe}/N_{photons}$)

Photo-multiplier tubes (PMT's)

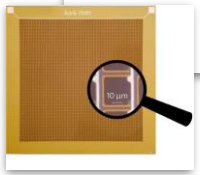
A PMT combines a photocathode and a series of dynodes

Basic principle:

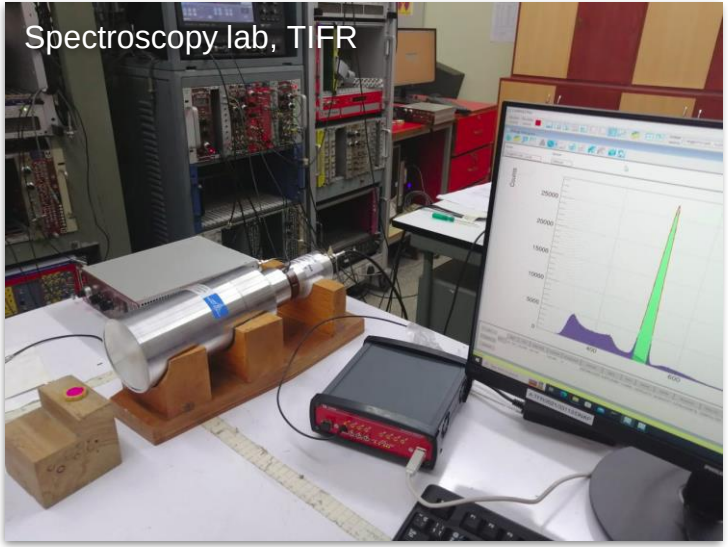
- Photo-emission from the photo-cathode
- Secondary emission from dynodes
- Dynode gain, g ≈ 3-50 (function of incoming electron energy)
- Total gain (for 10 dynodes with g of 4): $4^{10} \approx 10^6$!

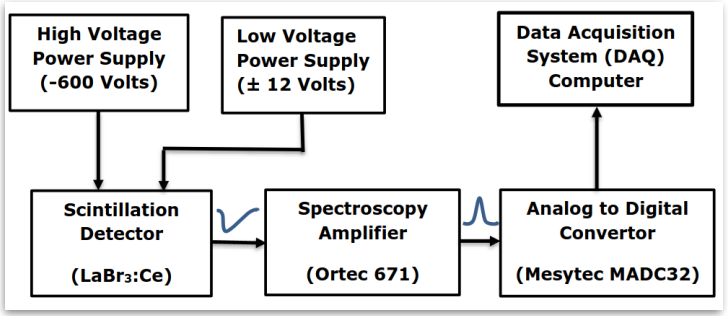


- Limitations : higher operating voltage, sensitive to magnetic field, bulkier, etc.
- Alternative: SiPM

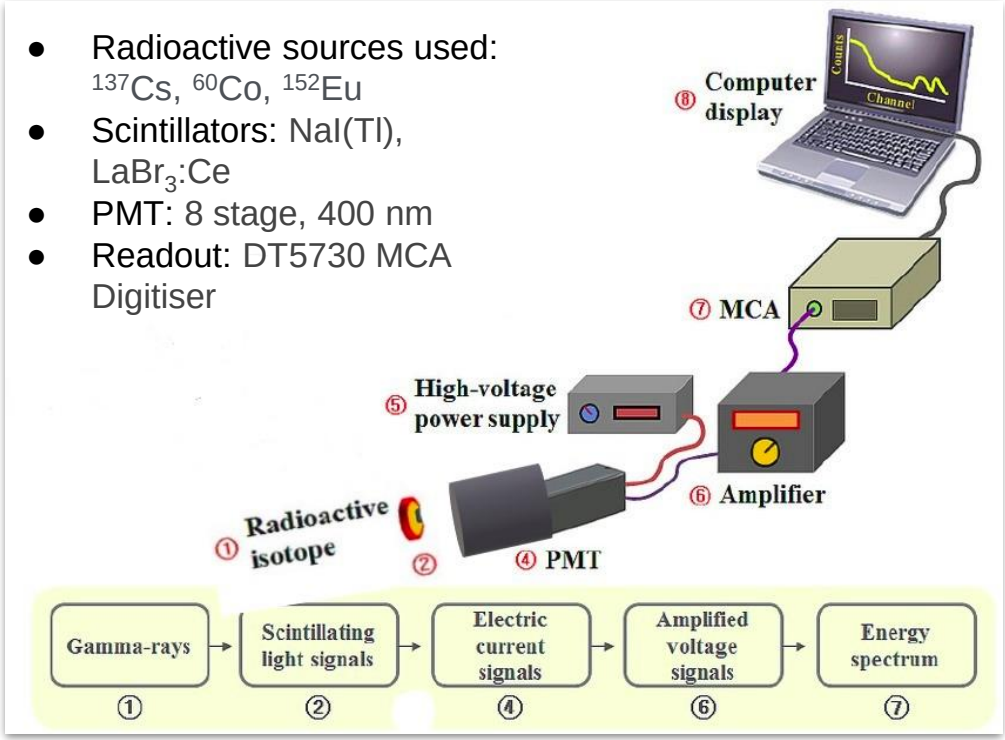


Experimental setup





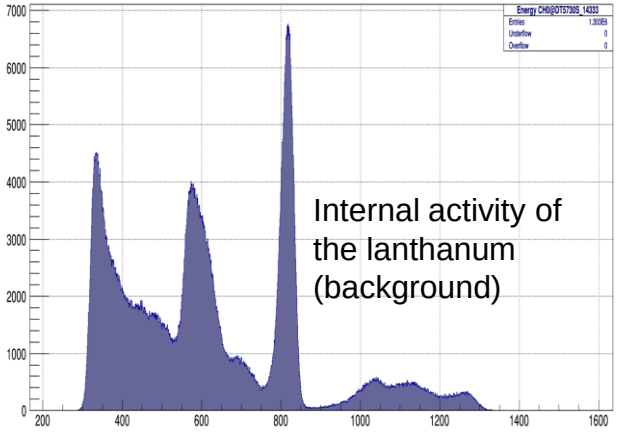
- Radioactive sources used: ^{137}Cs, ^{60}Co, ^{152}Eu
- Scintillators: NaI(Tl), $LaBr_3$:Ce
- PMT: 8 stage, 400 nm
- Readout: DT5730 MCA Digitiser



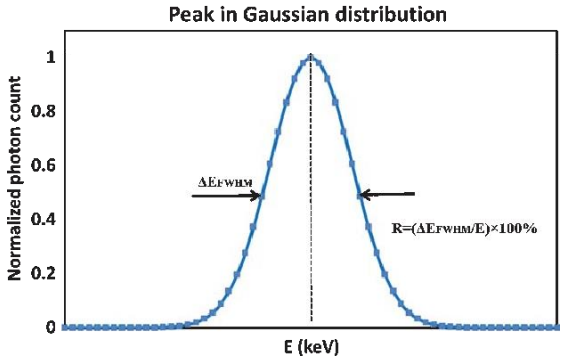
Schematic of the setup

Results

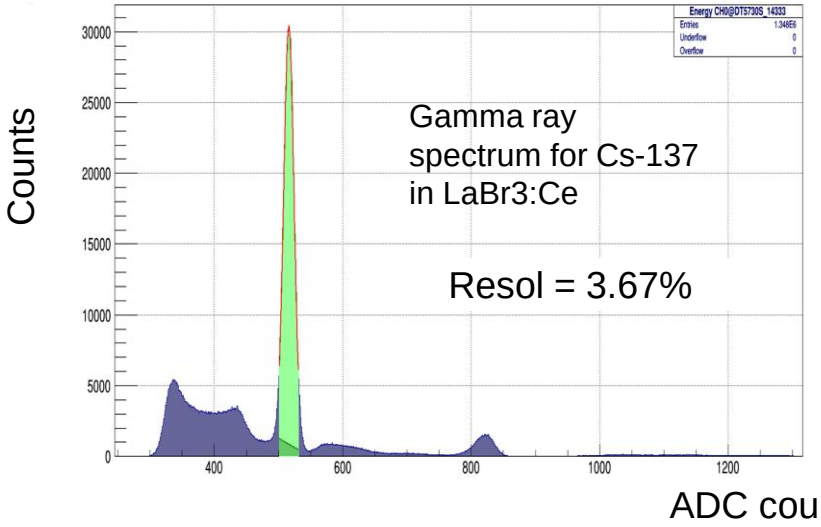
Gamma spectrum using $LaBr_3$:Ce - with and w/o gamma source (Cs-137)



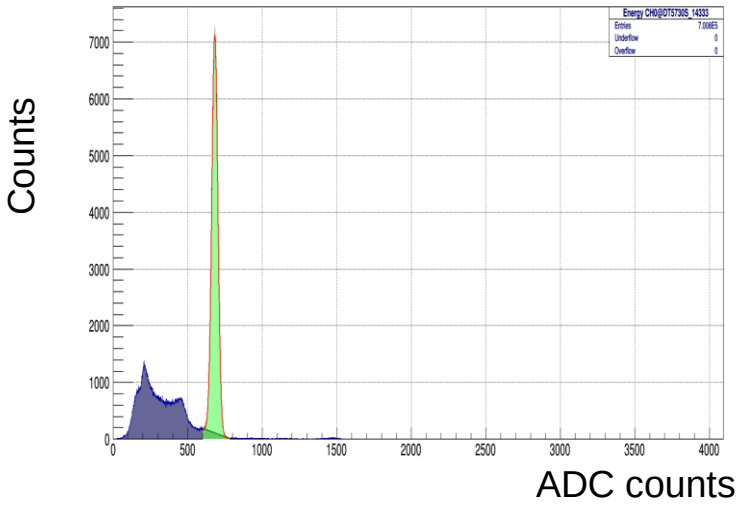
- Internal activity in the **$LaBr_3$:Ce** crystal due the La-57 radioactive decays (alpha, beta, gamma radiation.
  - One of the drawbacks
- The energy resolution is good - ~60k photons/MeV energy deposition inside of the crystal



$$\sigma = \frac{\Delta E}{E} 100\%$$

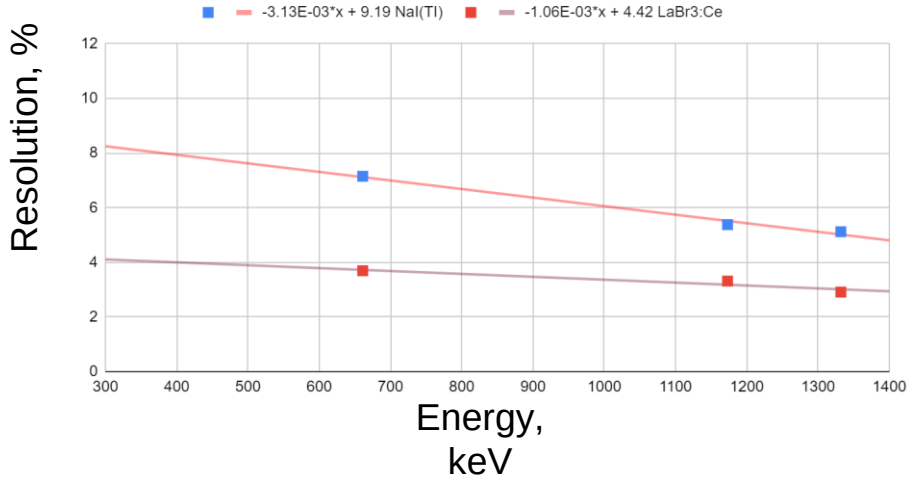


Gamma spectrum using NaI(Tl)- with gamma source (Cs-137)

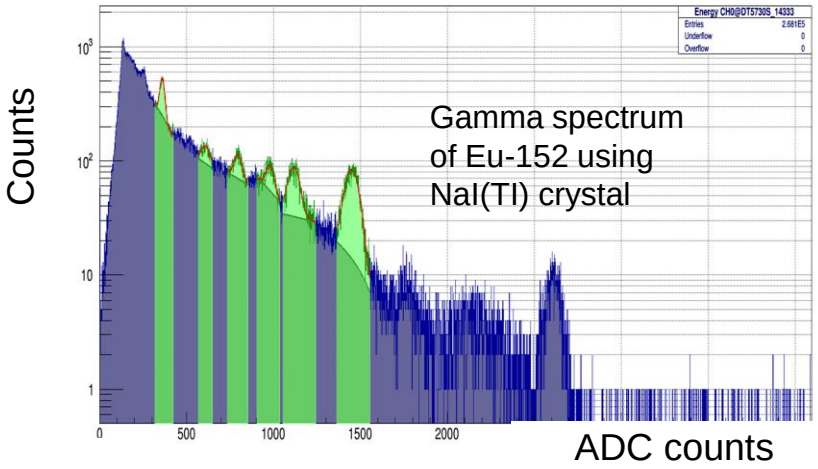


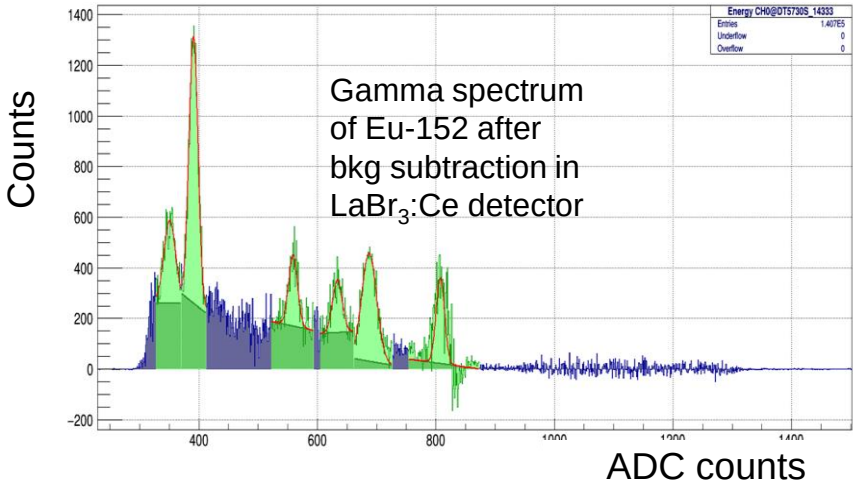
- No internal activity in NaI crystal
- ~30k photons/MeV energy deposition - resulting into worse energy resolution as compared to LaBr3:Ce crystal

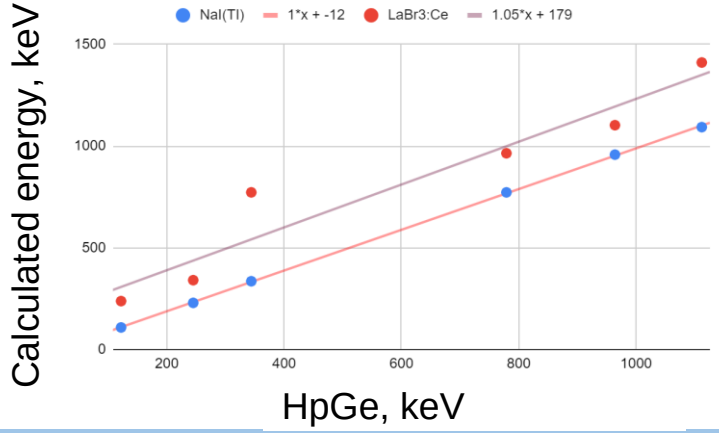
- The following plot shows the energy resolution as a function of energy using NaI & LaBr3 crystal.
- The response of the scintillator is also found to be linear with energy.



Identifying the unknown peaks at NaI(TI) and LaBr3







- The following plot shows the gamma spectrum in NaI(TI) and LaBr3:Ce for Eu-152
- The plot on left is showing the peak energy using NaI(TI), LaBr3:Ce scintillator vs HpGe (HpGe taken here are just for reference).

Conclusion

- Understand different gamma sources and corresponding spectrum.
- Observed and understood the internal activity of $LaBr_3$:Ce scintillator crystal.

- Compared NaI(TI) & $LaBr_3$:Ce and $LaBr_3$:Ce has better energy resolution,
  - It has huge background due to internal activity.
  - $LaBr_3$:Ce is much costly than NaI(TI) and at higher energies, the difference of energy resolution is not that significant
  - Hence NaI(TI) are most commonly used scintillators.

- Identified different peaks: CS, PEE, beta and alpha background in gamma spectrum of Cs-137, Co-60 & Eu-152.

Thank You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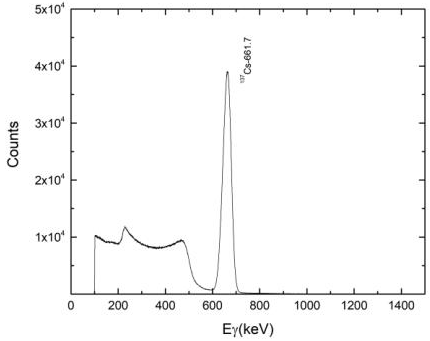
Instrumentation
Life is
All About
Compromises

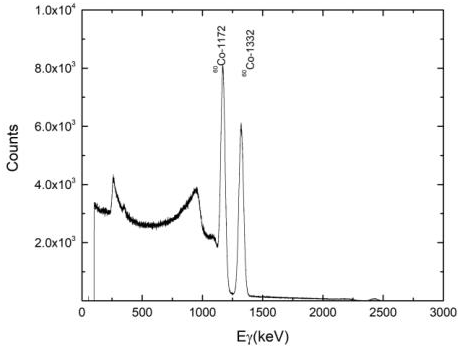
Thanks everyone!

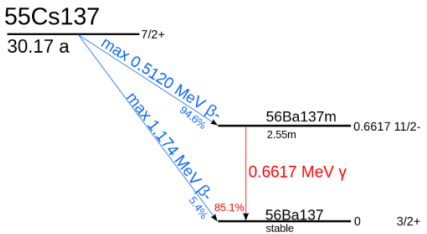
BACKUP

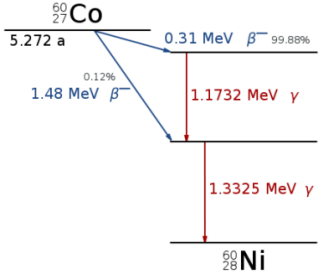
Gamma spectrum of NaI and LaBr3 for Co-60 and Cs-137

- $_{55}Cs^{137}$ decays in 94% due to beta decay into $_{56}Ba^{137}$, then it emits photon with energy 662 keV
- $_{60}Co^{27}$ decays into $_{60}Ni^{28}$ by two variants: beta decay 0.31 MeV with two gamma rays 1.17 and 1.33 MeV or beta decay 1.48 MeV with gamma 1.33 MeV







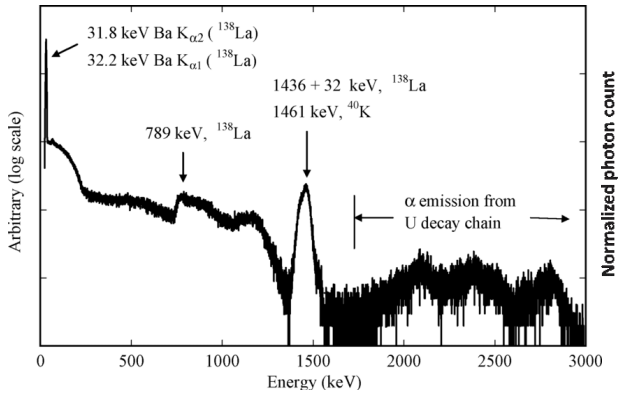


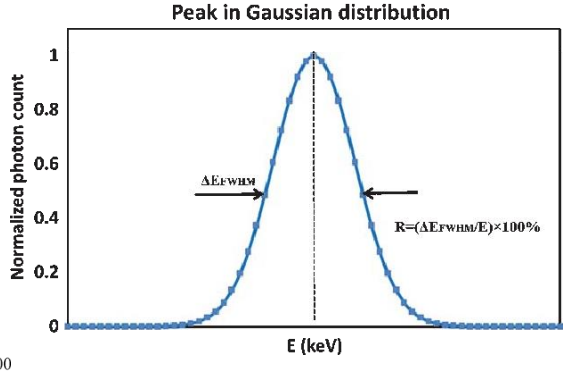
Spectrum of ^{137}Cs

Spectrum of ^{60}Co

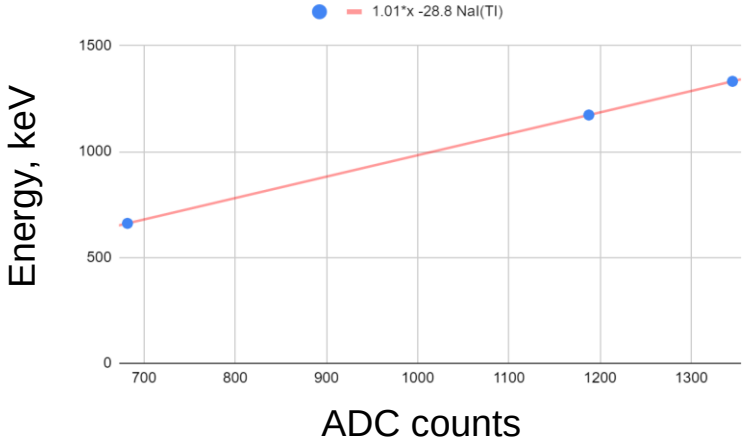
- Cs has one PEE peak, CS plato and backscattering Compton effect
- Co has two PEE peaks, CS plato, backscattering Compton effect and one small peak (2.5 MeV) due to simultaneous registration of two gamma rays

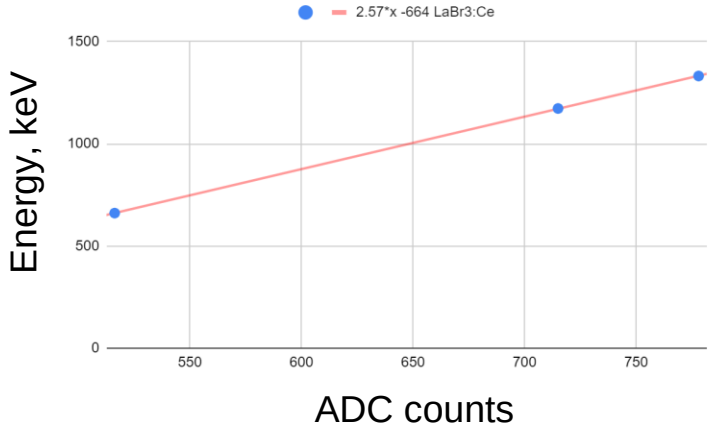
Energy value of gamma peaks for unknown source

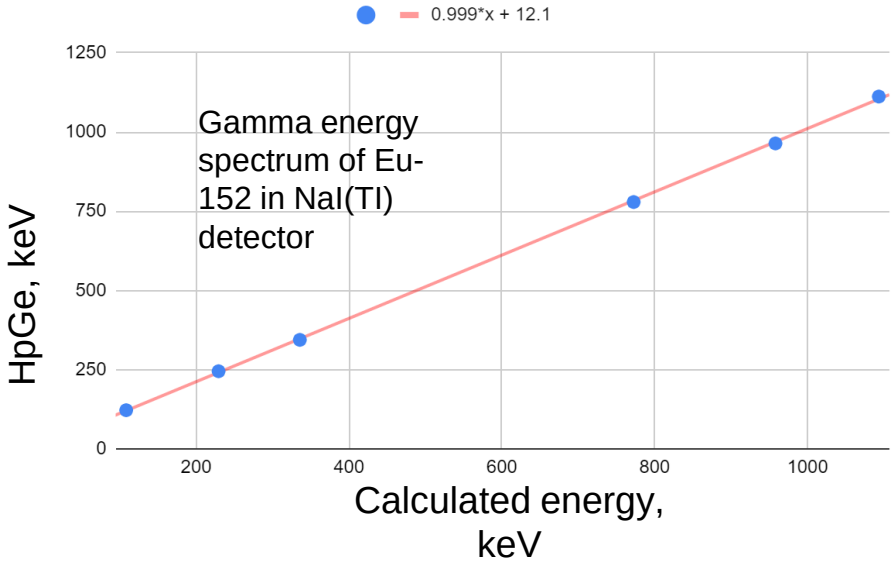


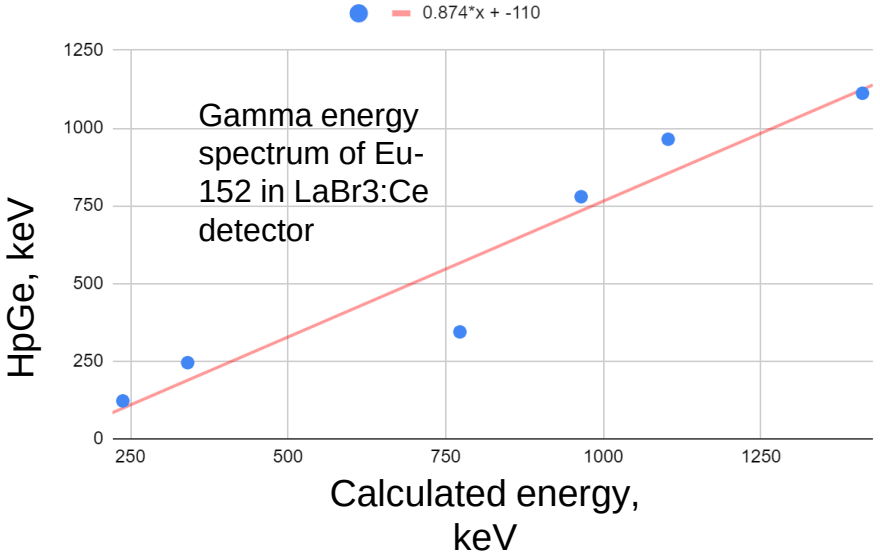


- Energy resolution for NaI(Tl) is around (7.15 and 5.26)% for Cs and Co
- Energy resolution for LaBr3:Ce is around (2-3)%
- Due to the fact that measured signal is proportional to energy, we can calibrate the setup likeY=kx+b and identify all measured peaks by its energy.

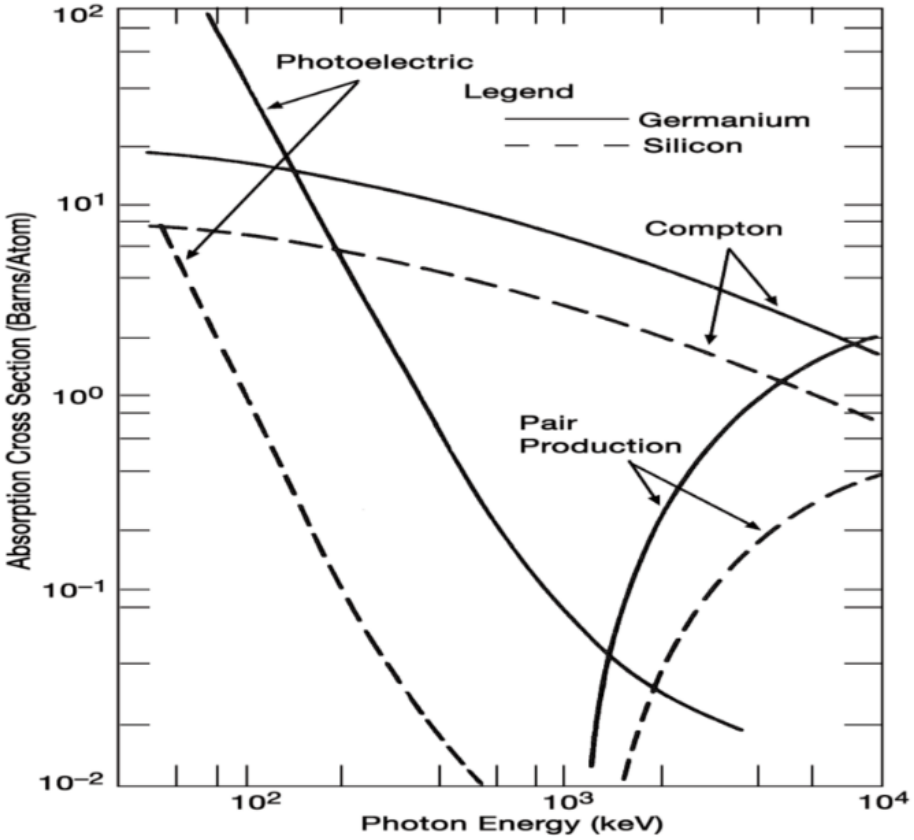




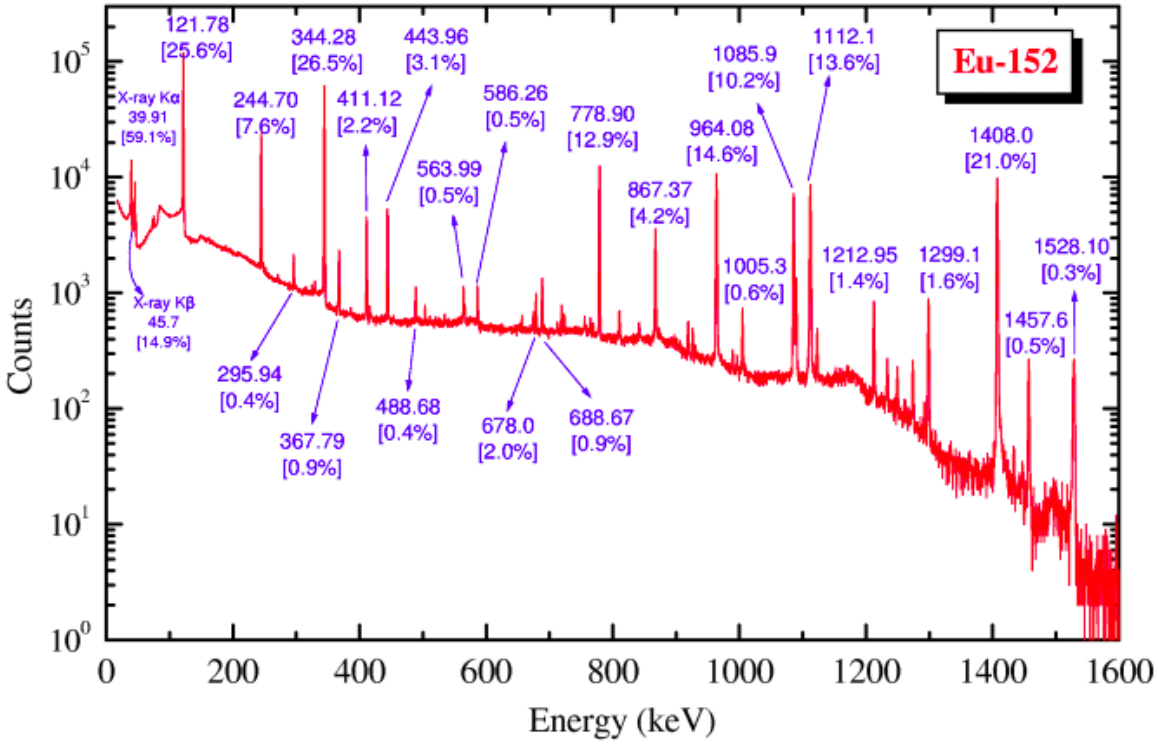

0.999*x + 12.1
Gamma energy spectrum of Eu-152 in NaI(TI) detector
HpGe, keV
Calculated energy, keV
0
250
500
750
1000
1250
200
400
600
800
1000


0.874*x + -110
Gamma energy spectrum of Eu-152 in LaBr3:Ce detector
HpGe, keV
Calculated energy, keV
0
250
500
750
1000
1250
250
500
750
1000
1250

Comparison of photon absorption cross section in Si & Ge



Results using Ge detectors



PMT Technical details

TECHNICAL INFORMATION

TENTATIVE
Jul. 2016

R11833-100-03

For Scintillation Counting, 127 mm (5 inch) Diameter
Bialkali Photocathode, 8-stage, P.C.(Plano-Concave)face plate, Head-on Type

GENERAL

Parameter		Description / Value	Unit
Spectral Response		300 to 650	nm
Wavelength of Cathode Radiant Sensitivity		400	nm
Window Material		Borosilicate glass	-
Photocathode	Material	Bialkali	-
	Minimum Effective Area	111	mm dia.
Dynode Structure / Number of Stages		Box and Line / 8	-
Operating Ambient Temperature		-30 to +50	°C
Storage Temperature		-30 to +50	°C
Base		14-pin base JEDEC No. B14-38	-
Suitable Socket		E678-14W (option)	-

MAXIMUM RATINGS (Absolute Maximum Values)

Parameter		Value	Unit
Supply Voltage	Between Anode and Cathode	1500	V
	Between Anode and Last Dynode	300	V
Average Anode Current		0.1	mA

CHARACTERISTICS (at 25 °C)

Parameter		Min.	Typ.	Max.	Unit
Cathode Sensitivity	Luminous (2856 K)	90	105	-	μA/lm
	Blue Sensitivity Index (Cs 5-58)	12.5	13.5	-	-
	Quantum Efficiency at Peak Wavelength		35	-	%
Anode Sensitivity	Luminous (2856 K)	10	50 (20)	-	A/lm
	Radiant at Peak Wavelength	-	5.5×10^4 (2.2×10^4)	-	A/W
Gain			5.0×10^5 (2.0×10^5)	-	-
Anode Dark Current (After 30 min storage in darkness)		-	20 (8)	100 (40)	nA
Time Response	Anode Pulse Rise Time		3.3	-	ns
	Electron Transit Time	-	41	-	ns
	Transit Time Spread (FWHM)	-	4.6	-	ns
Pulse Linearity (+/-2 % deviation)		-	10 (100)	-	mA
Pulse Linearity (+/-5 % deviation)		-	30 (150)	-	mA

NOTE : Anode characteristics are measured with a voltage distribution ratio (Standard ratio) and supply voltage shown below.
( ) : Measured with the special voltage distribution ratio (Tapered ratio) shown below.

VOLTAGE DIVIDER AND SUPPLY VOLTAGE

Electrodes	K	G	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8	P
Standerd Ratio	4	0	1.2	1.5	1	1	1	1	1	1	1
Taper Ratio	4	0	1.2	1.5	1	1.2	1.5	1.6	2.4	3	

Supply Voltage: 1250 V, K: Cathode, Dy: Dynode, P: Anode, G: Grid

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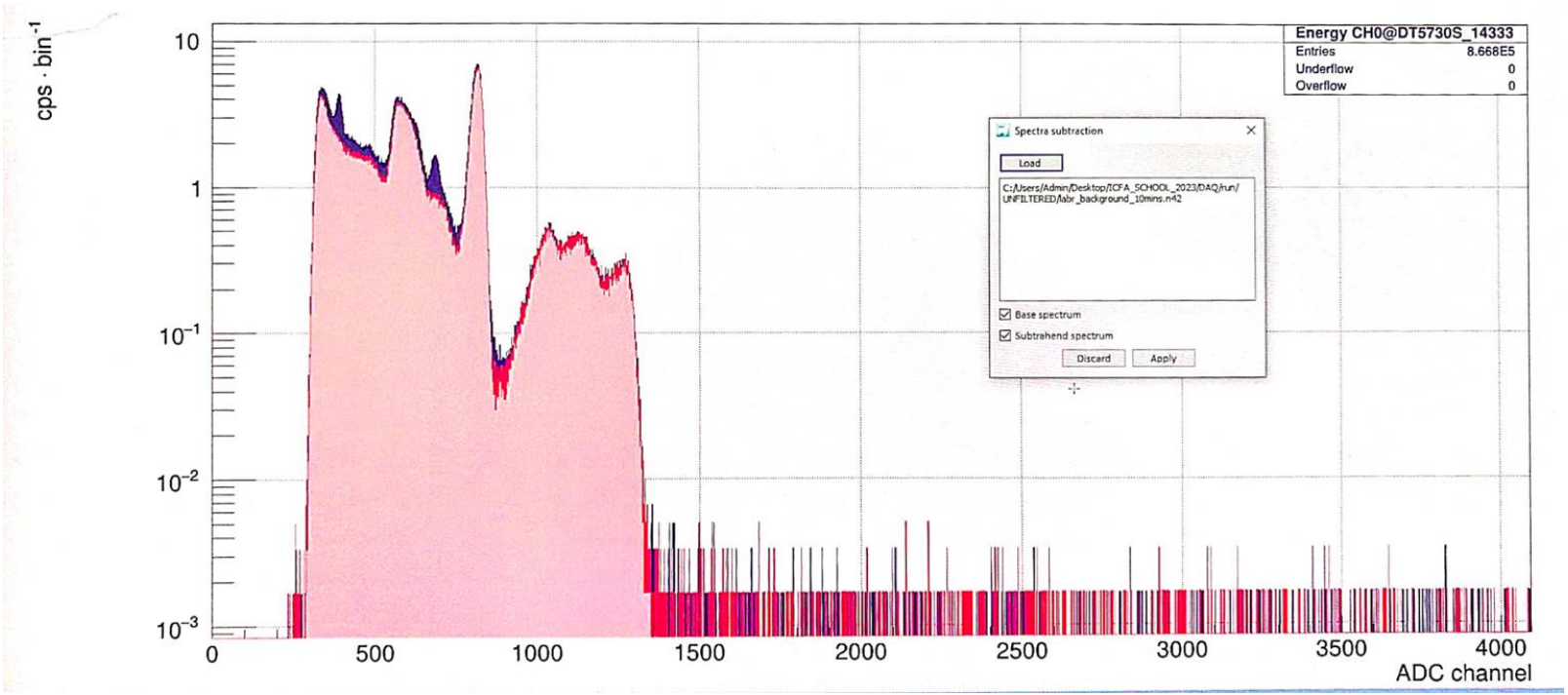
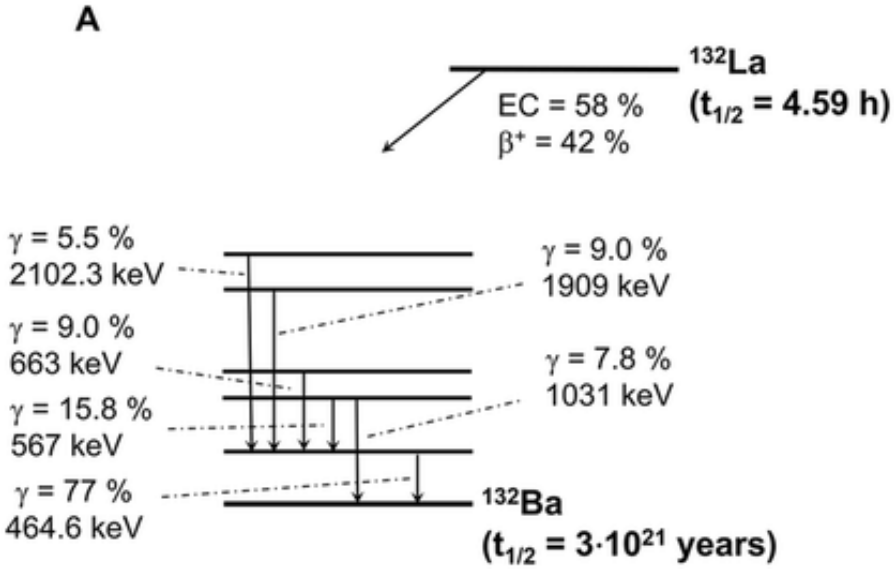
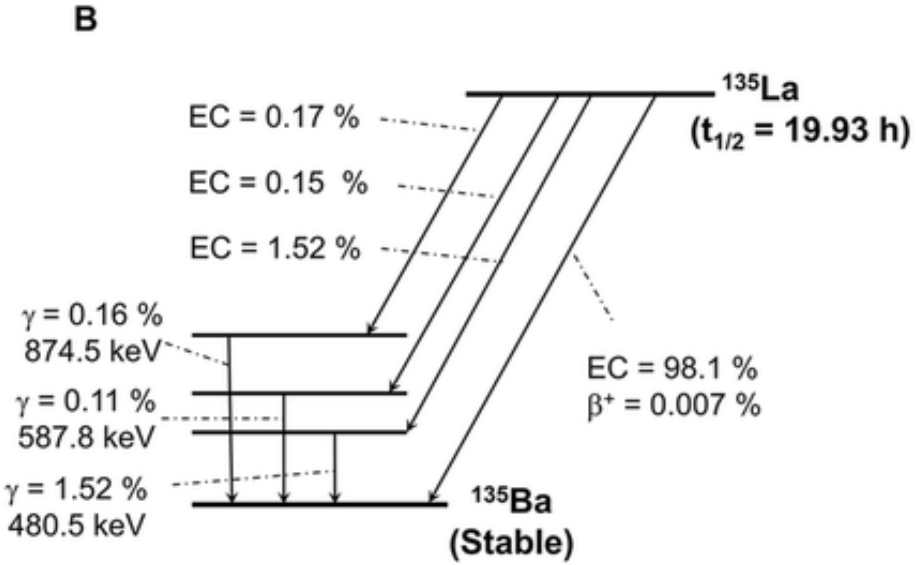
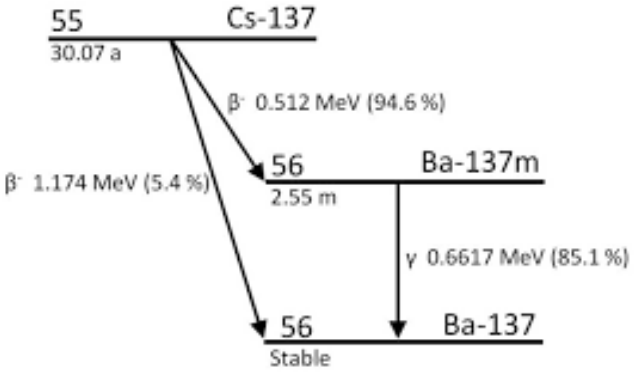
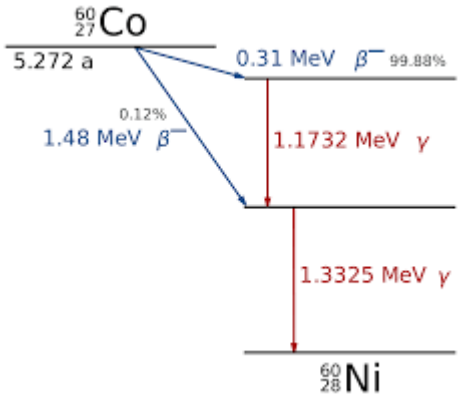
Gamma ray spectrum of Eu-152 using LaBr3:Ce with background

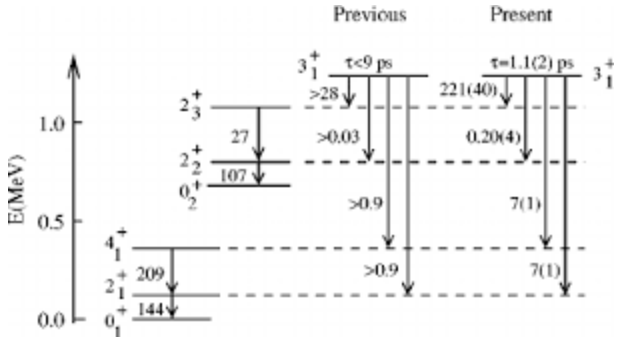



A
^{132}La
EC = 58 %
β⁺ = 42 %
($t_{1/2}$ = 4.59 h)
γ = 5.5 %
2102.3 keV
γ = 9.0 %
663 keV
γ = 15.8 %
567 keV
γ = 77 %
464.6 keV
γ = 9.0 %
1909 keV
γ = 7.8 %
1031 keV
^{132}Ba
($t_{1/2}$ = 3·10^{21} years)


B
^{135}La
($t_{1/2}$ = 19.93 h)
EC = 0.17 %
EC = 0.15 %
EC = 1.52 %
γ = 0.16 %
874.5 keV
γ = 0.11 %
587.8 keV
γ = 1.52 %
480.5 keV
EC = 98.1 %
β⁺ = 0.007 %
^{135}Ba
(Stable)


55
Cs-137
30.07 a
β⁻ 0.512 MeV (94.6 %)
β⁻ 1.174 MeV (5.4 %)
56
Ba-137m
2.55 m
γ 0.6617 MeV (85.1 %)
56
Ba-137
Stable


60 27 Co
5.272 a
0.31 MeV β⁻ 99.88%
0.12%
1.48 MeV β⁻
1.1732 MeV γ
1.3325 MeV γ
60 28 Ni


Previous
Present
E(MeV)
1.0
0.5
0.0
τ<9 ps
τ=1.1(2) ps
>28
221(40)
>0.03
0.20(4)
27
107
>0.9
7(1)
209
144

Answers at the questions

1. Kalium, carbon, water
2. -
3. PEE, CS, backCS, second PEE for Co, one small peak for Co due to measure two gamma rays simultaneously
4. To our amplitude signal will be inside our gate, if we don’t do that, we risk to lose part of the useful signal from the scintillator
5. Time uncertainties can be because of photon multiple scattering inside of scintillator, fluctuations of trigger reactions due to the signal shape fluctuation, fluctuations of emitting the photons inside of scintillators, fluctuations of PMT multiplying, fluctuations due to size of scintillator (gamma ray can come to the scintillator at the different places
6. Compton scattering, photoelectricity

Notes

- The identification and quantification of gamma-emitting radioisotopes using in situ gamma-ray spectroscopy is critical in the decommissioning of nuclear facilities and the disposal of radioactive waste
- Requirements: The decay time of induced luminescence should be short so that fast signal pulses can be generated.
- $LaBr_3$(Ce) (or lanthanum bromide doped with cerium): a better (novel) alternative to NaI(Tl); denser, more efficient, much faster (having a decay time about ~20ns), offers superior energy resolution due to its very high light output. Moreover, the light output is very stable and quite high over a very wide range of temperatures, making it particularly attractive for high temperature applications. Depending on the application, the intrinsic activity of ^{138}La can be a disadvantage. $LaBr_3$(Ce) is very hygroscopic.

- Overall workflow of the data ->
  - All technical details
    - PMT operating voltage
    - Threshold
    - Response time
    - Pulse amplitude - typical value
    - The final observation
    - The radioactive source used