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European Commission

Gamma-ray Spectrometry

Instrumentation Part II

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Obligatory slide

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Semiconductor detectors

Comparison of semi-conductor materials

Material	Z	Density (gr/cm^3)	Bandgap (eV)	Ionization energy (eV per e-h pair)	Mobility (cm^2/V·s)	Resolution (FWHM)
Si (300 K)	14	2.33	1.12	3.61	e: 1350 h: 480	
Si (77 K)	14		1.16	3.76	e: 21000 h:11000	400 eV at 60 keV 550 eV at 122 keV
Ge (77 K)	32	5.33	0.72	2.98	e: 36000 h: 42000	400 eV at 122 keV 900 eV at 662 keV 1300 eV at 1332 keV
CdTe (300 K)	48 / 52	6.06	1.52	4.43	e: 1000 h: 80	1.7 keV at 60 keV 3.5 keV at 122 keV
HgI_2 (300 K)	80 / 53	6.4	2.13	4.3	e: 100 h: 4	3.2 keV at 122 keV 5.96 keV at 662 keV

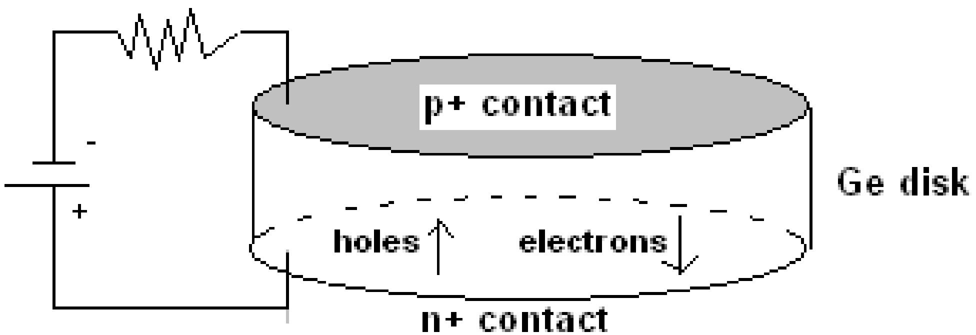
From: G. F. Knoll, “Radiation Detection and Measurement“, John Wiley, 2000

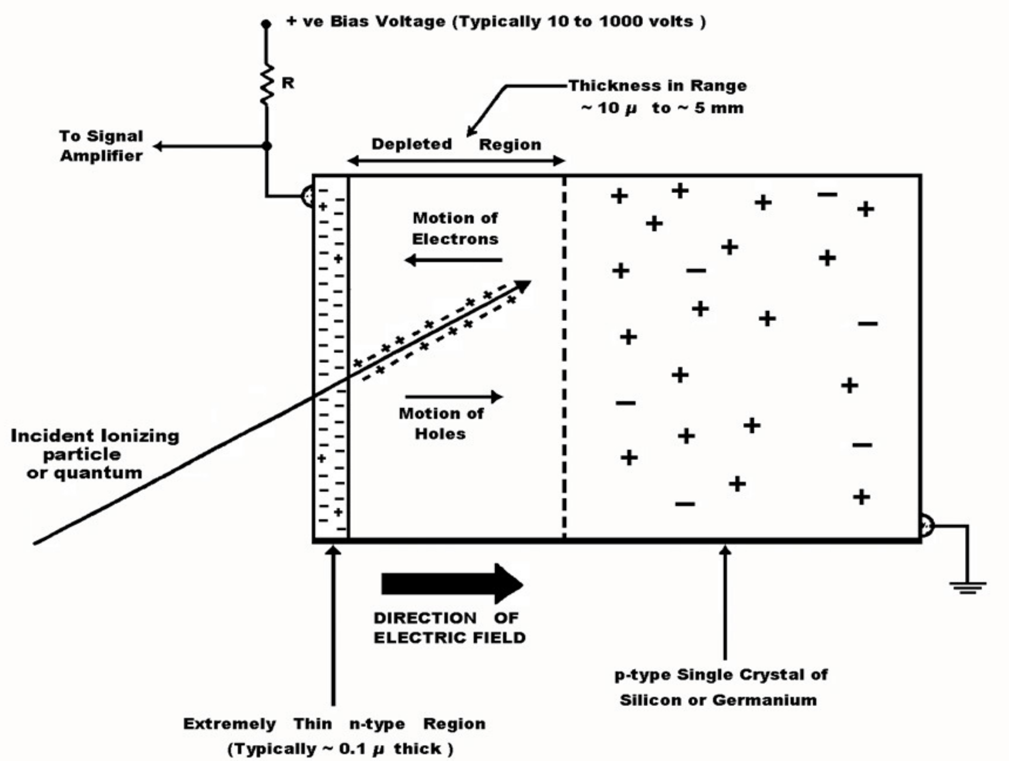
- Si seems the most obvious candidate
  - Available
  - Reasonable cost
  - Operating at room temperature
  - Resolution is within about 25% of being the same as Ge

But,

  - Low atomic number
    - Measurement of low-energy photons only in practice
    - Routine use in x-ray spectrometry

- Ge is by far the most common
  - Higher atomic number
    - Measurement of higher energy gamma radiation
  - Available (high-purity over recent years)
  - Operating at liquid nitrogen temperature (narrow band gap)
  - High electron & hole mobilities

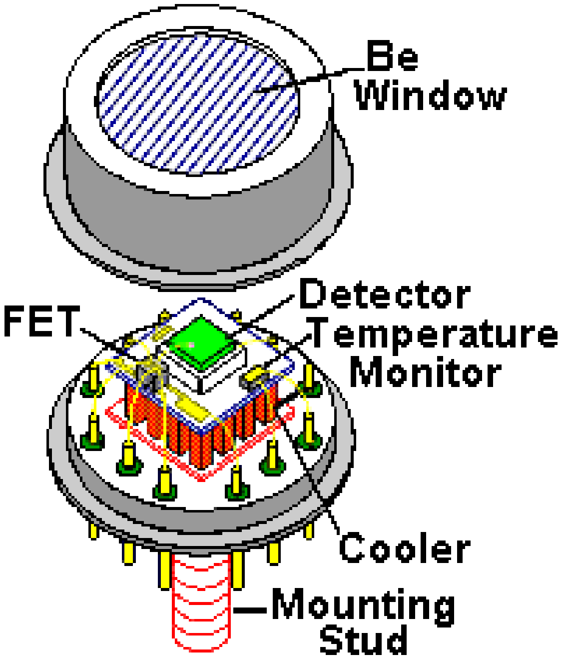


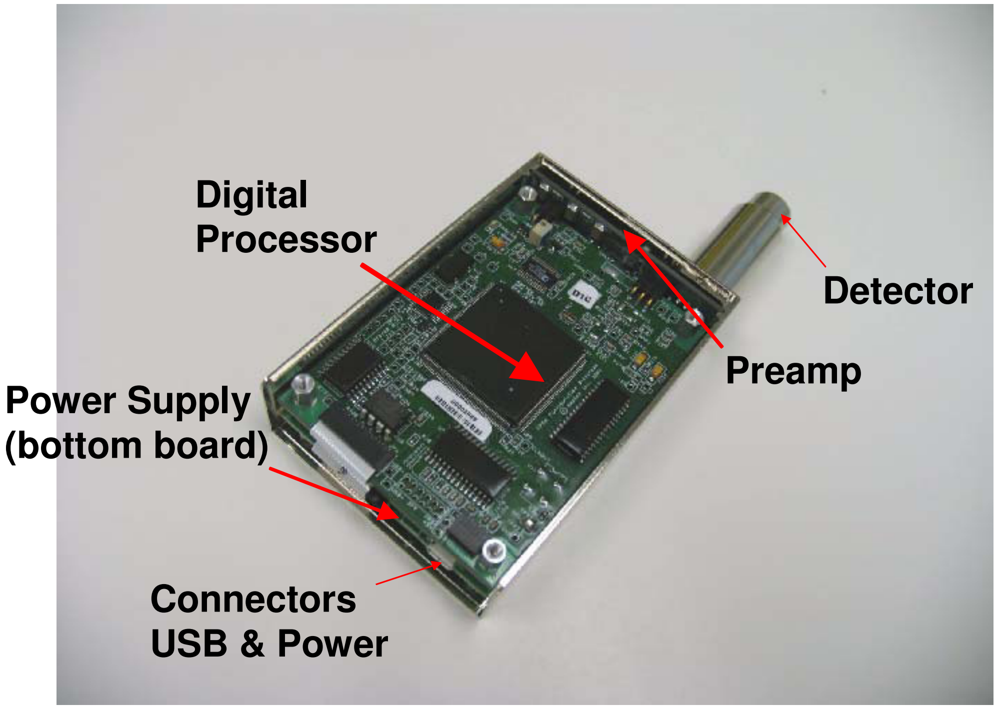


- CdTe and HgI_2 in commercial production but only for limited applications
  - Higher atomic number
  - Large enough band gap energy
  - Operating at room temperature
    - Better to keep CdTe thermoelectrically cooled at -40 ℃ and HgI_2 at 0 ℃
  - Not available with a satisfactory crystalline perfection
  - Lower mobility of the charged particles
    - Charge collection problem on the detector: very difficult to achieve complete charge collection over distances more than 1 mm)
    - Only small detectors (Low-energy gamma-rays)
    - Poor resolution

- CdTe and HgI_2 in commercial production but only for limited applications
  - Capable of detecting energies from a few keV to several hundreds of keV
  - Successful applications in
    - Nuclear medicine (x-ray & gamma-ray detection)
    - PET systems
    - Nuclear material monitoring
    - Uranium & plutonium detection
    - Art & archaeology

- CdTe and HgI_2 in commercial production but only for limited applications
  - Easy integration in electrical modules
  - A promising technique for detecting high-energy gamma-rays



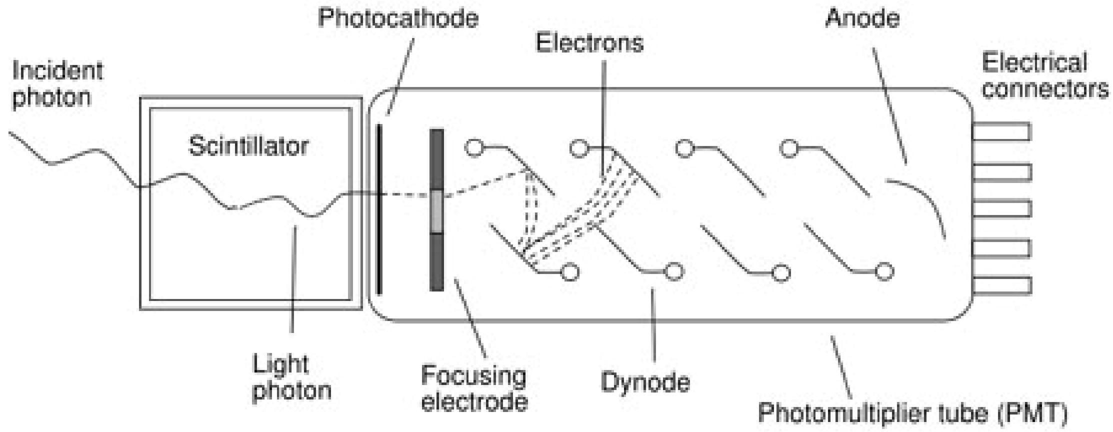


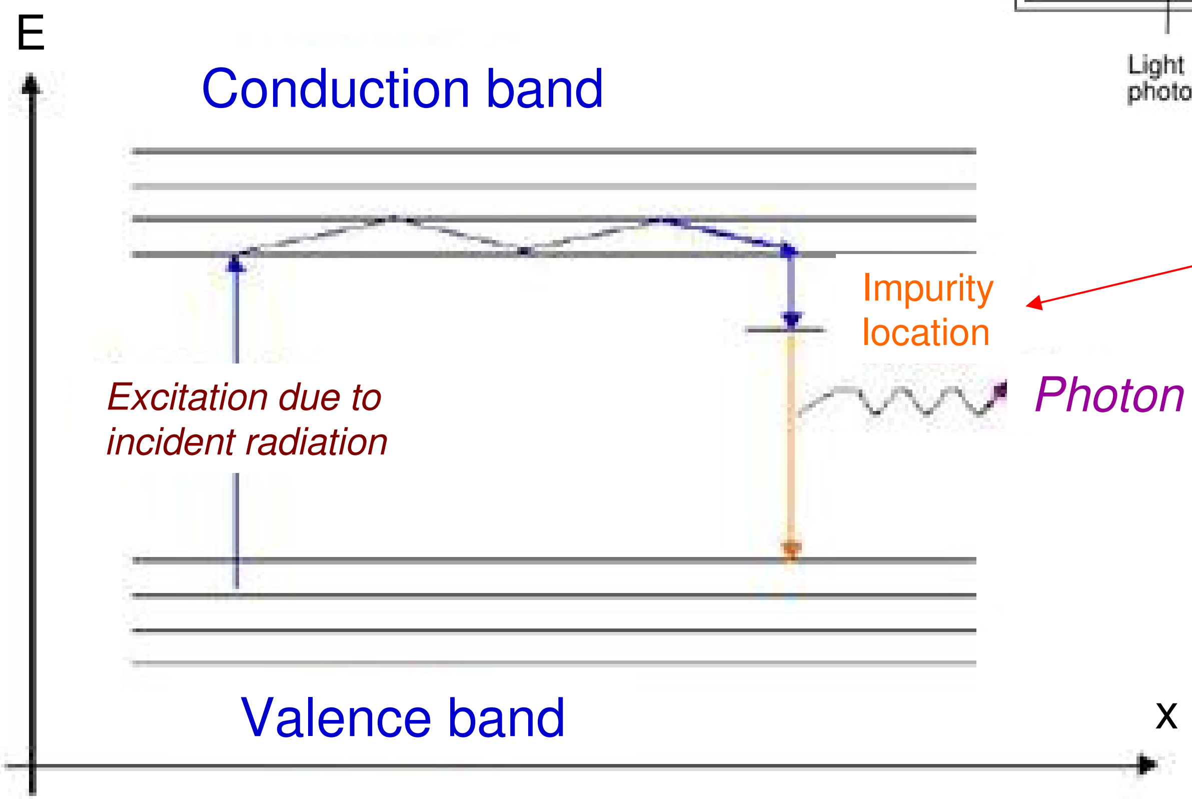
Scintillation detectors

Particular properties of a scintillation material for gamma-ray detection

- High scintillation efficiency
  - Reasonable number of electron-hole pair produced per unit of gamma-ray energy
- The light yield should be proportional to deposited energy (linear conversion)
- High light output with a suitable wavelength
- High stopping power (high density and atomic number)
- Transparent to the emitted light
- Short decay time of the excited state (to allow high count rates)
- Reasonable amount and cost

Scintillation & Scintillation detector





Effect of Tl-activator in NaI

Scintillation materials

Assets of Sodium Iodide - NaI(Tl)

- Readily available
- Cheap
- High gamma-ray absorption coefficient
  - High intrinsic efficiency
- Greatest output of all the inorganic scintillators
  - Best resolution of the scintillation materials (~ xx% at 662 keV)

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Scintillation materials

Drawbacks of Sodium Iodide - NaI(Tl)

- somewhat fragile
- hygroscopic (reacts with moisture)
- can easily be damaged
  - by mechanical or thermal shock

Scintillation materials

Assets of Caesium Iodide – CsI(Tl) & CsI(Na)

- Can also be used without activator
  - Much reduced relative conversion efficiency without activator
- Higher density than NaI
  - Higher absorption coefficient
- Highest gamma-ray absorption per unit size
- Greatest light output
  - Peak at about 565 nm – not well matched to the common photocathode materials

Scintillation materials

Drawbacks of Caesium Iodide – CsI(Tl)

- Less brittle than NaI
- Hygroscopic (but less than NaI)
- Can be subjected to more severe conditions of shock and vibration

Scintillation materials

Assets of Bismuth Germanate - BGO

- Needs no activator
- High Z value
  - High photoelectric cross section for gamma-rays
- High density
  - High stopping power
  - Ideal for active shielding systems
- Good mechanical and chemical properties
  - Easy to handle and use
  - More rugged compared to NaI

Scintillation materials

Drawbacks of Bismuth Germanate - BGO

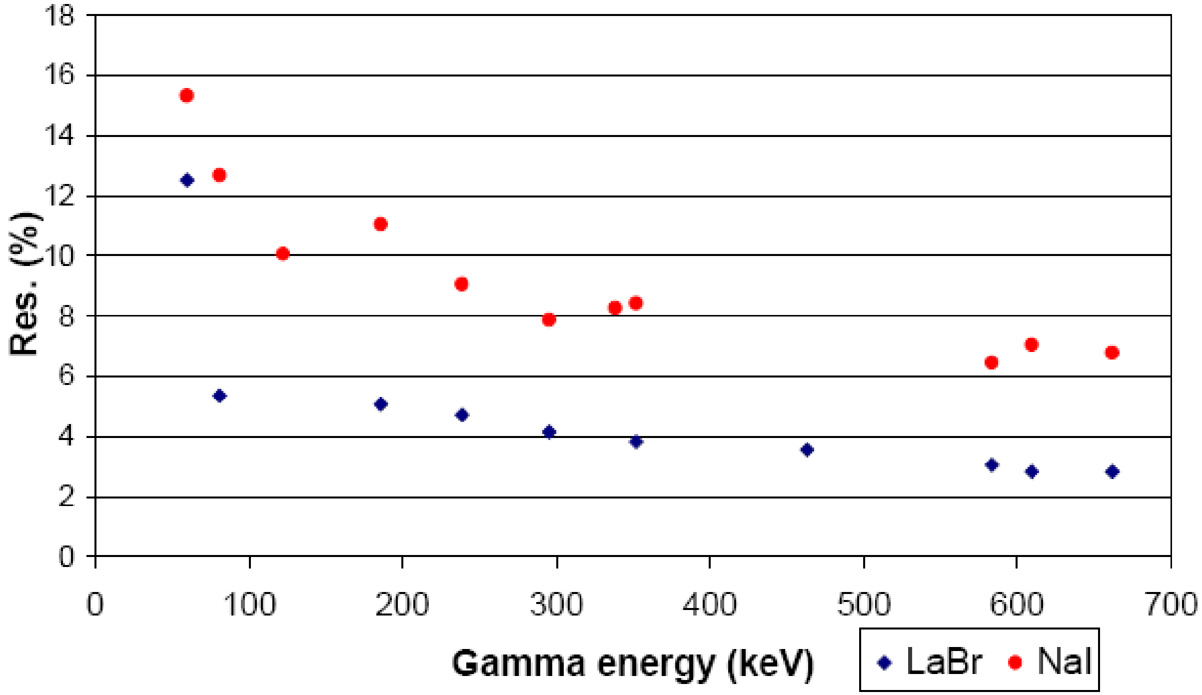
- Expensive
- Smaller light output
  - Worse resolution
  - Not the material of choice for spectrometry as distinct from detection

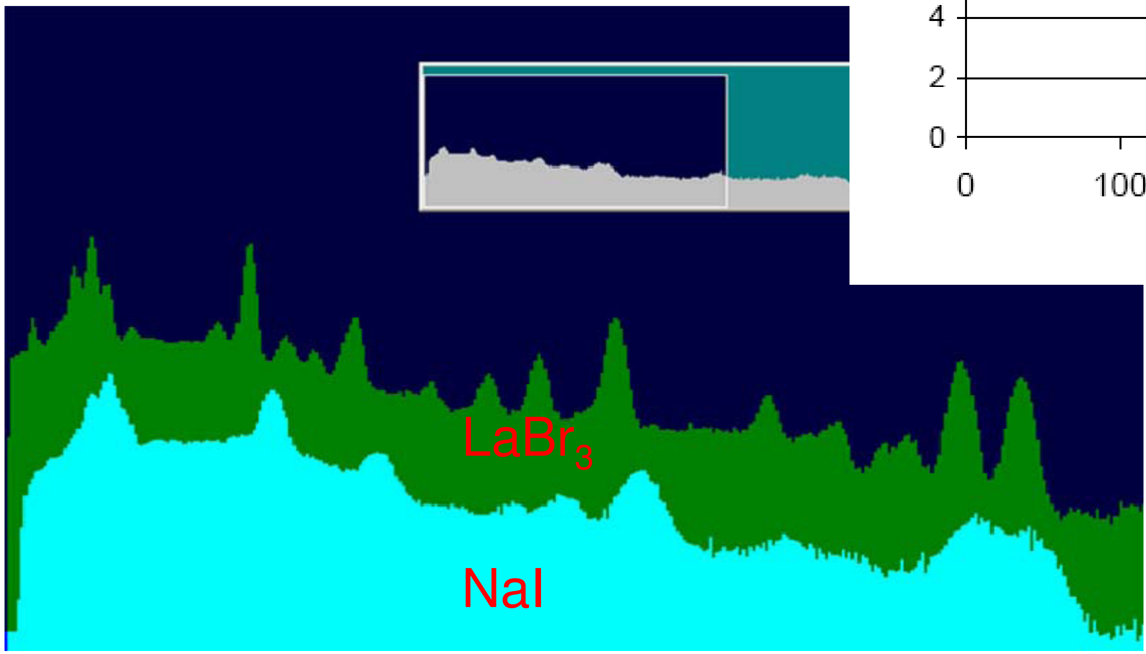
Scintillation materials

<u>Assets of Lanthanum Halides – $LaBr_3$(Ce) & $LaCl_3$ (Ce)</u>

- Can be used as replacement for NaI scintillators
- High density
- Good light yield (at >100 keV)
- Smaller sensing material for the same count rate
  - Improves the resolution of the measurement
- Higher count rate for the same sized crystal
  - Improves the statistics of the measurement
- Good optimization of combination of count rate vs resolution
- Significantly better resolution (<3-4% at 662 keV)

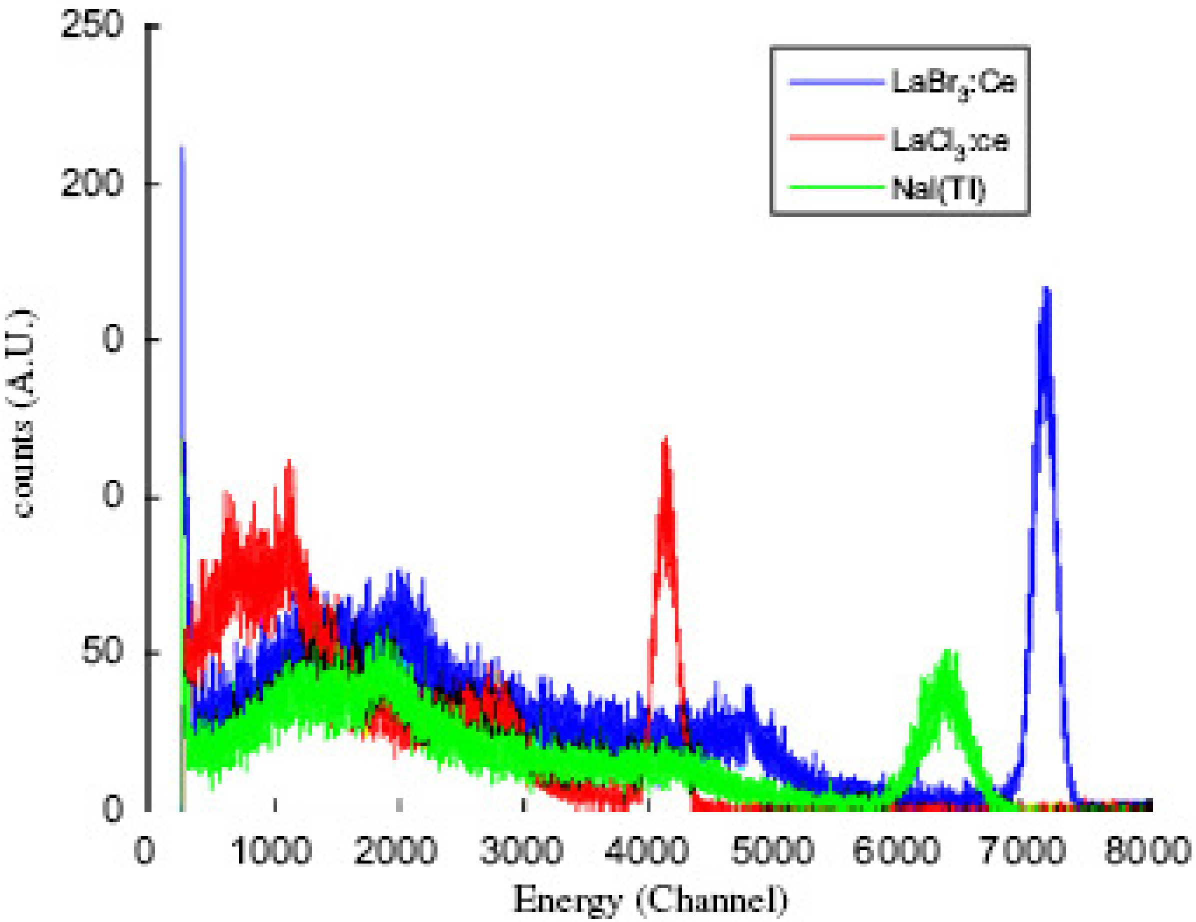
Assets of Lanthanum Halides – $LaBr_3$(Ce) & $LaCl_3$ (Ce)





Th-232 spectra from $LaBr_3$(Ce) and NaI (Tl)

Assets of Lanthanum Halides – $LaBr_3$(Ce) & $LaCl_3$ (Ce)



Comparative Cs-137 spectra for $LaBr_3$(Ce), $LaCl_3$(Ce) and NaI (TI)

Scintillation materials

Drawbacks of Lanthanum Halides – $LaBr_3$(Ce) & $LaCl_3$ (Ce)

- Expensive
- Low-energy response below about 100 keV
  - Not good resolution below 100 keV
- Internal radioactivity due to naturally occurring La-138 and Ac-227 radioisotopes
  - Naturally occurring sum peak is indistinguishable from K-40 peak → (1436 keV γ-ray of La-138) **+** (~32 keV x-ray of Ba-138) **=** 1468 KeV
  - Ac-227 decay chain to Pb-207 includes alpha decay which affects the background spectra

Comparison of scintillator materials

Material	Size of detector	Resolution (keV)		Wavelength (nm)	Light output (%)
		@ 662 keV	@ 1370 keV		
NaI(Tl)	25 mm x 25 mm	40		415	100
	76.2 mm x 76.2 mm		71		
CsI(Tl)	5mm x 7.5 mm	40		550	45
BGO	76.2 mm x 76.2 mm		138	480	20
$LaBr_3$(Ce)	25 mm x 25 mm	16		380	130
$LaCl_3$(Ce)	25 mm x 25 mm	28		350	70-90

$CeBr_3$	Rather similar to $LaBr_3$ but with lower background

Assets of Plastic Scintillators

- Sensitive to x-rays, gamma-rays, fast neutrons and charged particles
- Consists of a solid solution of organic scintillating molecules in a polymerized solvent
- Easily shaped and fabricated
  - Extremely useful
- Relatively inexpensive

More assets of Plastic Scintillators

- Relatively large light output
- Typically, scintillation emission has a maximum at around 400 nm
- Short decay time (on the order of nanosec)
  - Well suited for fast timing measurements
- Ideal for active shielding systems to reduce muon-induced background

Drawbacks of Plastic Scintillators

- Low-Z, extremely low photo-effect.
- Poor resolution