DETECTORS

High Resolution Gamma Spectroscopy

UNIVERSITY OF LIVERPOOL

Plan of Lecture

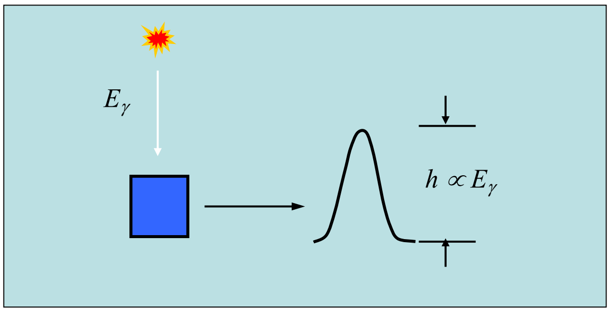
Which material shall we use?

Checking the detector specifications

How do they work?

What types are available?

Requirements for Spectrometry



ESSENTIAL: Output $\propto$ energy absorbed

DESIRABLE: Good detection efficiency

Good energy resolution

Semiconductors

Material	**Temp.as used(K)**	**Atomic number (Z)**	**Energy per e-h (eV)**	**No. of e-h pairs per keV**	**Typical good resolution in keV at**		
					5.9	**122**	**1332**
Si(Li)	77	14	3.76	260	0.17		
Ge	77	32	2.98	350		0.5	1.8
Ge(Li)	77	32	2.98	350		0.5	1.8
CdTe	300	48,52	4.4	230	0.29	0.85	4
HgI_2	300	53,80	4.15	240	0.30	3.5	

Scintillators

Material	Temp.	Z	photoelectrons per keV	Typical good resolution	
				122 keV	1332 keV
Liquid	300	1, 6,	0.7		
NaI(Tl)	300	11, 53	4	30 keV	95 keV
BGO	300	32, 83	0.5		150 keV

Variations

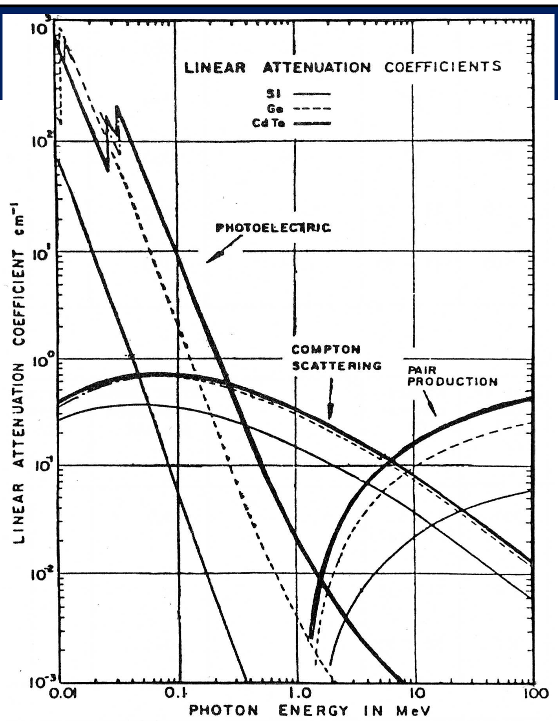
Variation of interaction probability with atomic number

photoelectric effect	Z^4 or Z^5
Compton scattering	Z^0 or Z^1
pair production	Z^2

thus, considering efficiency (η) only [for a given size]

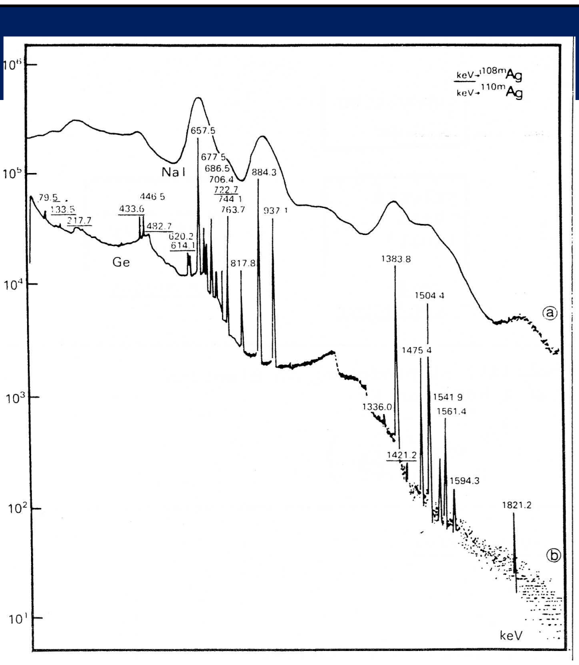
$$\eta(\mathrm{HgI}_2) > \eta(\mathrm{CdZnTe}) > \eta(\mathrm{Ge}) > \eta(\mathrm{Si})$$

and $\eta(\mathrm{BGO}) > \eta(\mathrm{NaI}) > \eta(\mathrm{LSC})$



Two commonly used gamma detectors

NaI(Tl)	Ge
older	
cheaper [by ~ × 10]	
more efficient [by ~ × 10]	
larger volumes	
room temp operation	must be cooled [77K]
large temp sensitivity	relatively insensitive to temperature
large bias voltage sensitivity [V^7]	relatively insensitive to bias volts
poor energy resolution [~ 8%]	good energy resolution [~ 0.15%]



Selection of Material

OPTIONS: **HgI$_2$, CdTe ~ CZT[CdZnTe], Ge, Si, BGO, NaI, LSC**

Parameter	**Choice**	**Reason**
resolution [in theory]	**semiconductors HgI$_2$, CdZnTe, Ge, Si**	**number of information carriers**
resolution [in practice]	**Ge, Si**	**good charge collection**
efficiency	**Ge**	**high Z**

Specification of a Ge Detector

as provided by a supplier

1. Efficiency
2. Resolution
3. Peak to Compton ratio

Ge “Efficiency"

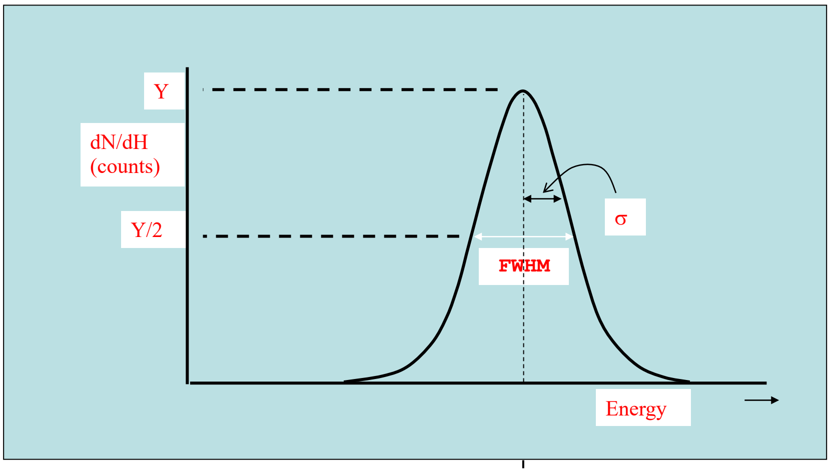
- Defined relative to a 76 × 76 mm [NaI] detector
- for a specific energy: 1332 keV [from ^{60}Co] at a specific distance: 25 cm

Required A calibrated ^{60}Co point source [~10^5 Bq]

Action

- Collect a spectrum from the ^{60}Co at 25 cm from detector face
- Note the area [counts] of the full-energy peak at 1332 keV; note the live time
- Calculate cps; divide by Bq, to give cps/Bq
- Compare this with 1.2×10^{-3}; express as %

Resolution of a Peak in a Spectrum



FWHM is Full Width at Half Maximum

If shape is Gaussian, then FWHM = 2.355×σ

Resolution of a Peak in a Spectrum

With Ge

Measure at 1332 keV [^{60}Co] OK if value is ≤ 2.0 keV

Also measure at 122 keV [^{57}Co] OK if value is ≤ about 1 keV

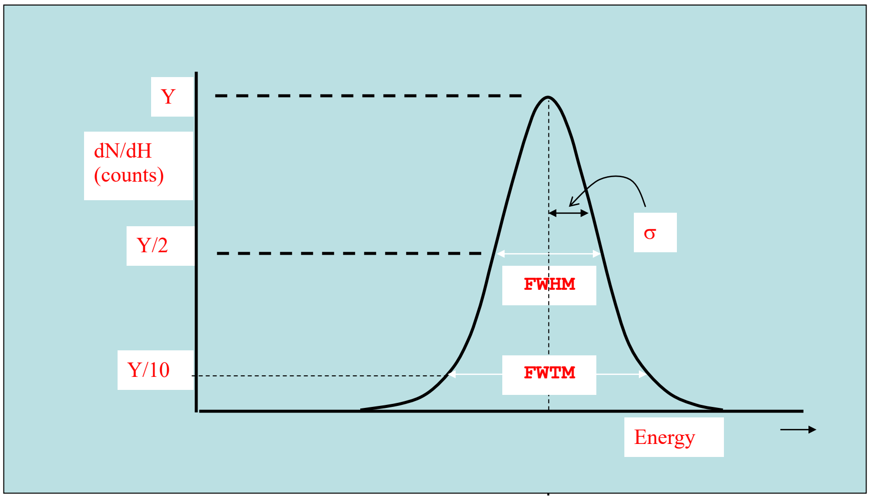
If low-energy detector, also measure at 5.9 keV [^{55}Fe]

With NaI the convention is different.

Measure at 662 keV [^{137}Cs]

FWHM is reported as a % of 662 keV

More Detail on Peak Shape



For a perfect Gaussian shape: $\frac{\text{FWTM}}{\text{FWHM}} = 1.823$

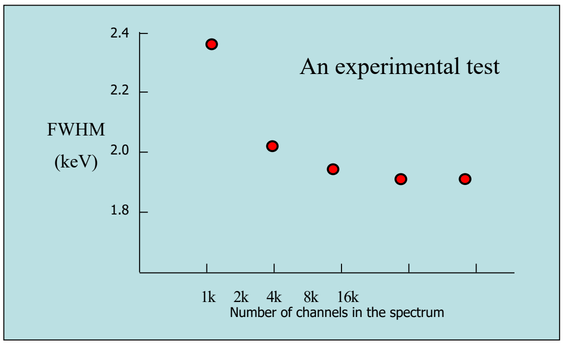
Resolution of a Peak in a Spectrum

HOWEVER: Note that the manufacturer's resolution will have been found with:

- Long time constant, ~ 6 µs
- Low count rate
- Large number of channels in peak, > 20

BUT

These conditions are not usually the best for day-to-day operations



Why are Peaks so Wide?

measure FWHM as ~ 10^3 eV

intrinsic width of gammas ~ 10^{-9} - 10^{-3} eV

Uncertainties come from:

electronic noise (preamp, amp)	FWHM_e
drift during count (temp)	FWHM_d
incomplete charge collection	FWHM_c
charge production (statistics)	FWHM_{stat}

$$\mathbf{FWHM_{overall}^2 = FWHM_{intrinsic}^2 + FWHM_e^2 + FWHM_d^2 + FWHM_c^2 + FWHM_{stat}^2}$$

Charge Production Uncertainty

E_γ produces N_γ charge carriers

- but this is only an average number
- if Poisson statistics apply, then $\sigma_\gamma = \sqrt{N_\gamma}$
- so that $\mathrm{FWHM}_{stat} = 2.355\sigma_\gamma = 2.355\sqrt{N_\gamma}$

This is the limiting, unavoidable, FWHM

Charge Production Uncertainty

- Good resolution occurs when ratio to peak height FWHM/Eγ is small
- The limiting unavoidable resolution is thus proportional to:

$$(\mathrm{FWHM}_{stat})/E\gamma = 2.355 \times \sqrt{N\gamma}/N\gamma = 2.355/\sqrt{N\gamma}$$

Therefore the best [ie smallest] resolution derives from maximum Nγ [charge carriers per keV]

- This is why semiconductors give better resolution than scintillators

N = 350 per keV Ge   N = 4 per keV NaI

Charge Production Uncertainty

- FWHM in energy units $= 2.355 \times \sqrt{N_\gamma} \times E_\gamma/N\gamma$ keV
- Then for Ge [N = 350] and E = 1332, the *minimum* (theoretical) FWHM = 4.6 keV
- But, in reality, FWHM = 1.8 to 2.0 keV

Probable reason:

Poisson statistics are not applicable as production of electron-hole pairs is constrained

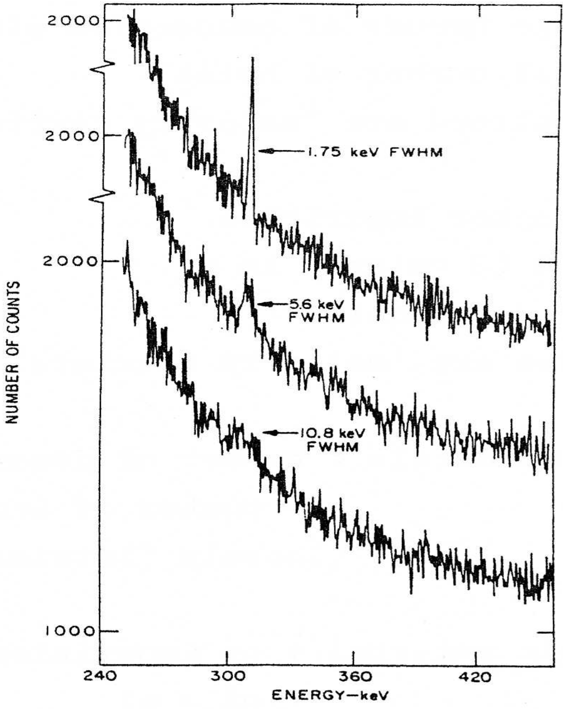
Allowed for, empirically, by **FANO factor** [F]

Good Resolution is required for two reasons:

1. To separate close energies. Readily done if :

   ΔE = about 1 × FWHM

2. To find weak peaks on a poor background



Peak to Compton Ratio

Measured using ^{60}Co

Ratio = $\frac{\text{(count in max channel of 1332 keV peak)}}{\text{(mean count/channel in the Compton region)}}$

The part of the region used is 1040 – 1096 keV

Maximum peak count:

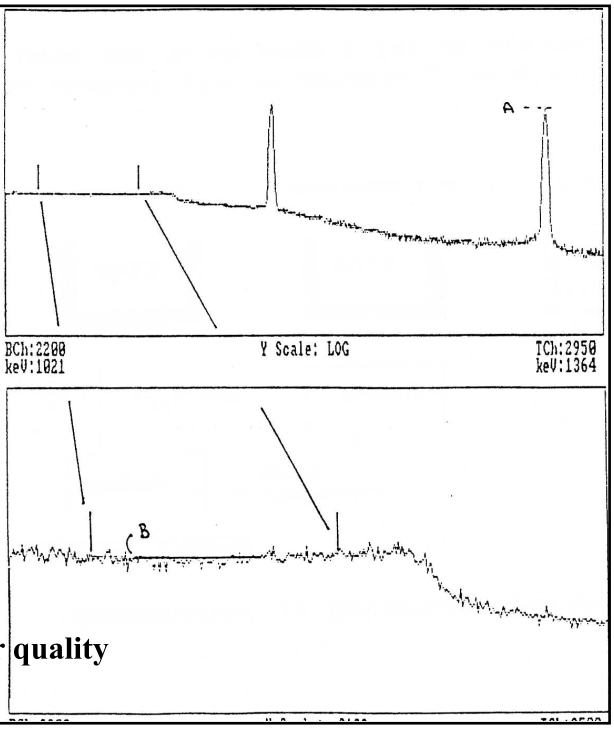
A = 62998

Average count in the Compton region

B = 979.99

Peak-to-Compton ratio:

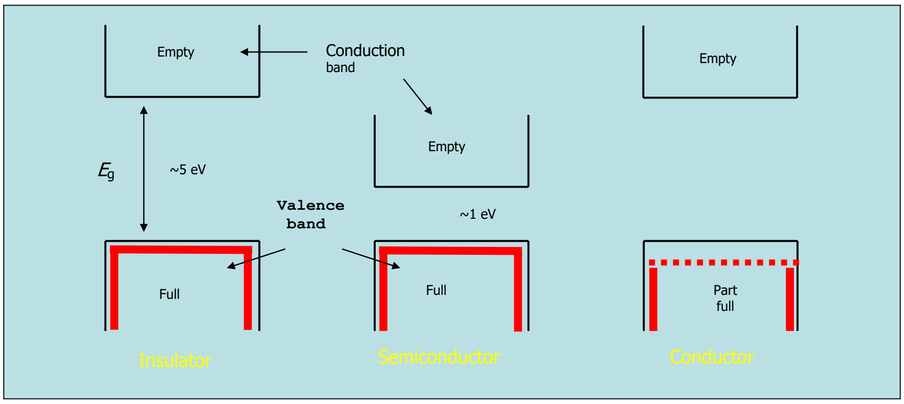
A:B = 64.3:1



Best indicator of detector quality

Semiconductor detectors

-electrons in solids



Mechanisms of Detector Operation

The probability of promoting an electron across a band gap E_g at temp T [K] is approximately

$$T^{3/2} \times \exp\left(-E_g / 2kT\right)$$

as T ↑, probability of thermal excitation ↑↑

as T ↓, thermal excitation ↓↓

Low temperature operation reduces thermal noise

Mechanisms of Detector Operation

n-type

Electrons are donated to the lattice from a ‘donor impurity’

Eg P (valence 5) replacing Ge (valence 4)

These electrons are lightly bound

The result is a large number of conduction electrons and a small number of holes

Electrons are the ‘majority carriers’

n = negative (electron)

p-type

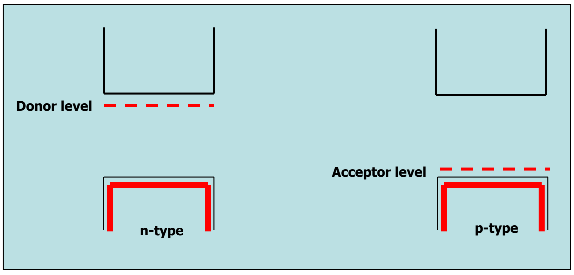
Similar but with acceptor impurities

B (valence 3) replacing Ge

Now gives an excess of **holes**

Holes are ‘majority carriers’

‘p’ = positive (absence of an electron)



Mechanisms of Detector Operation

Compensated material:

Number of donor impurities = Number of acceptor impurities

Intrinsic material: No impurities

Lithium-drifted Ge(Li)	**Intrinsic High purity: HPGe**
Older ~10^{14} impurities cm^{-3} Must be used and stored at 77 K	Post 1975 ~10^{10} impurities cm^{-3} Used at 77 K; may be stored, transported at 300 K

Mechanisms of Detector Operation

Creation of the sensitive volume in a semiconductor detector

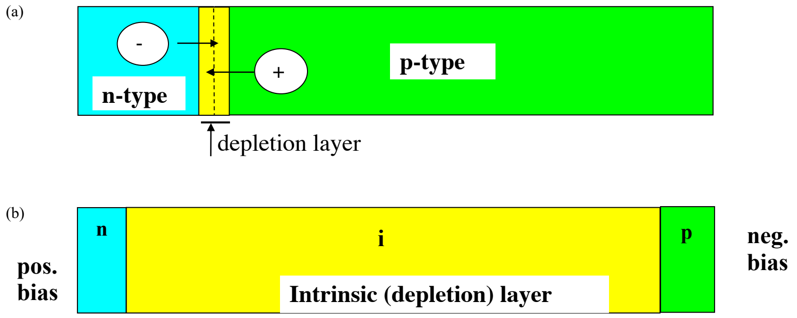
Block of p-type Ge with some n-type at one end

>Tendency for charges to neutralise at the junction

Giving a **'depletion layer'**

This is accentuated by applying 'reverse bias'

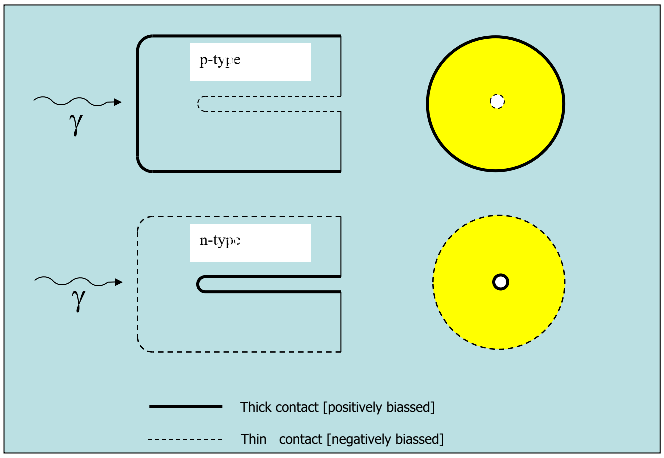
Creates the sensitive **intrinsic volume** with few net charge carriers



Mechanisms of Detector Operation

Arrangement for a coaxial Ge detector

Thin contact, about 0.3 μm thick, is made by ion implantation of boron. $[p^+]$
Thick contact, about 600 μm thick, is made by diffusion of lithium $[n^+]$

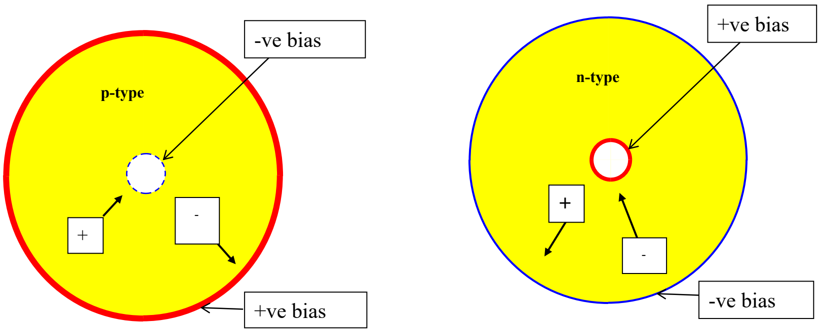


Mechanisms of Detector Operation

A conventional coaxial detector is p-type. Bias is applied to be positive on the outer surface and negative on the inner surface.

Thus, **electrons** travel to **outer** surface and **holes** travel to **inner** surface.

The reverse is the case for an n-type detector

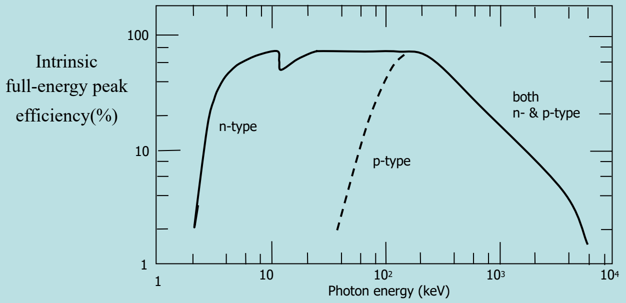


Efficiency vs energy

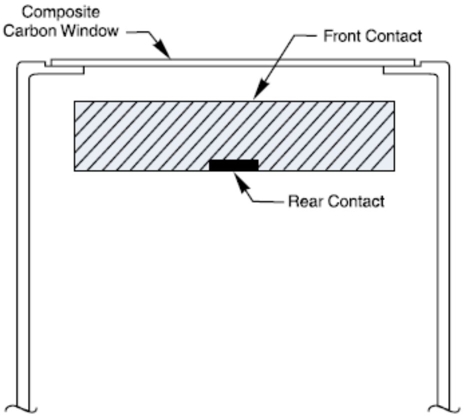
Above 100 keV, n-type and p-type detectors of the same dimensions are equally efficient

Below 100 keV, the thin window of an n-type makes it much more efficient than the p-type

The discontinuity at 11 keV is due to the Ge absorption edge



Broad Energy Germanium Detectors



Model Number	Area (cm^2)	Thickness (mm)	Typical Rel. Eff. (%) ≥
BE2020	20	20	9
BE2820	28	20	13
BE2825	28	25	18
BE3820	38	20	20
BE3825	38	25	26
BE3830	38	30	34
BE5020	50	20	28
BE5025	50	25	37
BE5030	50	30	48
BE6530	65	30	60

n & p type detectors - merits

Damage sites [Frenkel defects] mainly trap holes

In p-type material, holes *on average* have further to go and are thus much more likely to be trapped than in n-type where *on average* they have a shorter distance to go

n-type material is therefore more resistant to radiation damage.

n-type detectors are called by

Ortec: *Gamma-X* Canberra: *Reverse Electrode Detector*

n-type advantages:

10 to 20 times less sensitive to neutron damage

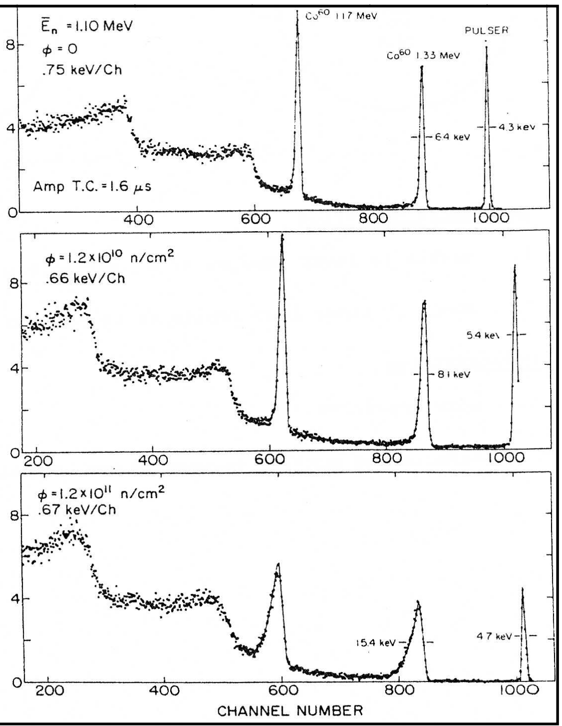
usable to lower energies due to thin entrance

n-type disadvantages:

more coincident summing due to X-rays

more expensive [adds about 25%]

Radiation damage on n-type and p-type detectors



Summary of usage

Application	Activity level	Energy range (keV)	Detector type	Comments
1) Environmental (lots of sample)	low	40–10000	large p-type coaxial	possible low background option possible J geometry
2) As (1) but low energy needed	low	5–10000	large n-type coaxial	as (1). Note: good X-ray efficiency may promote summing
3) Environmental (small sample)	low	30-10000	well	near 4π efficiency, but large summing; not good for complex unknowns
4) Neutron activation	medium-high	40-10000	p-type or n-type	possible Transistor reset preamp (TRP); possible loss-free counting (LFC)
5) Prompt gamma		up to 10000	n-type repairable	possible absorber for X-rays, risk of neutron damage
6) Post accident monitoring	low-high	40-10000	p-type coaxial	TRP for high throughput; LFC for transient high activity
7) Fissile material (Safeguards)	low(-high)	3-1000	n-type (short) or planar	lung monitor needs are similar, large diameter or cluster of smaller detectors
8) Whole body monitor	low	40-10000	large p- or n-type	unusually large 'sample', clusters of detectors, shielded room
9) Portable survey (land/sea/air)	low	40-10000	p-type coaxial	'ruggedised detector, portable cryostat if hand-held, electro-cooled if ship-based
10) Low energy X-rays		1-300. 3-300	Si(Li) Ge ultra-low	Optical reset preamp for best resolution

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