

# Detector Design Principles

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## Ionization (charge separation) Detectors

- Ionization chambers (solid-state and gas)
- **Proportional counters**
- Avalanche counters
- Geiger-Müller counters
- Cloud/bubble chambers
- Track detectors

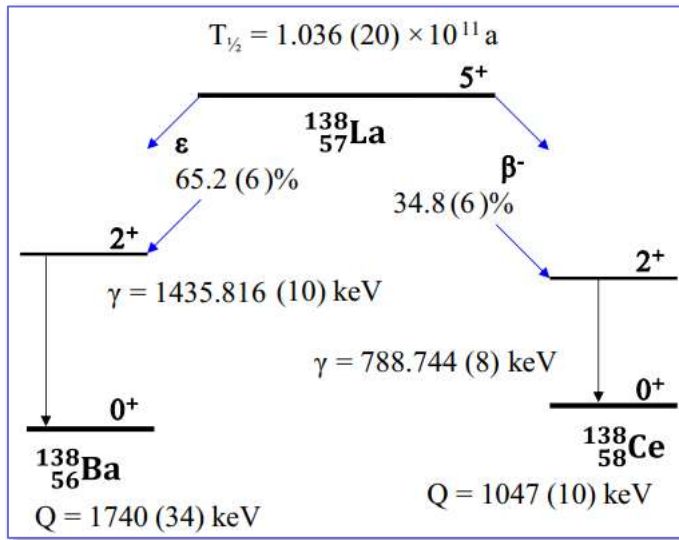
## Scintillation Detectors

- Phosphorescence counters
- Fluorescence counters (inorganic solid crystal scintillators, organic solid and liquid scintillators)
- Čerenkov counters

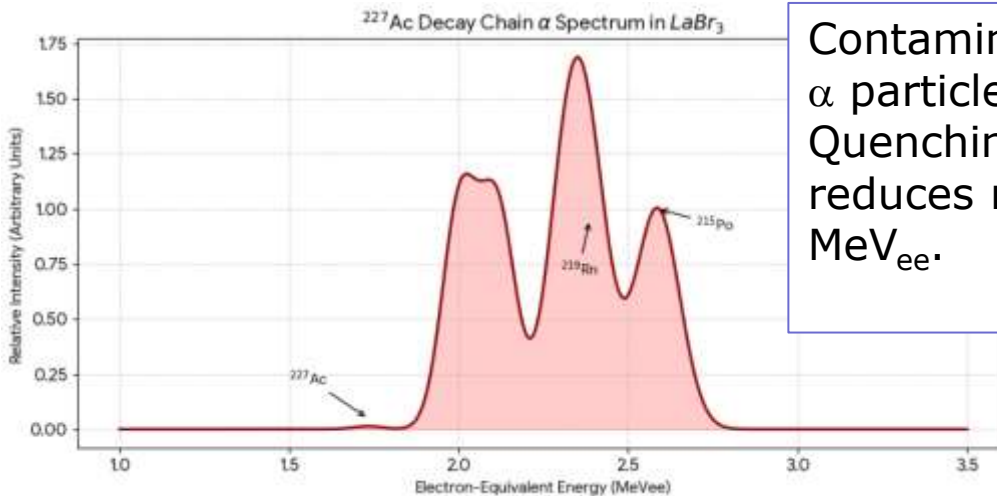
## Associated Techniques

- Photo sensors and multipliers
- Charged-coupled devices
- Electronic pulse shape analysis
- Processing/acquisition electronics

# Lanthanum Halide Scintillation Counters



Lanthanum halide scintillators have an energy resolution of 3-4% at 662 keV, x2 improvement over NaI(Tl). Intrinsic radiation from beta-decay of isotope La-138 and traceAc-227.



Contamination with Ac-227  $\rightarrow$  chain  $\alpha$  particles (5-7.4 MeV). Quenching (ion-pair recombination) reduces recorded energies to 1.7-2.6  $\text{MeV}_{ee}$ .

Detection Of  
Ionizing Radiation  
Gas Amplification  
Proportional Counters



# X Ray Energies

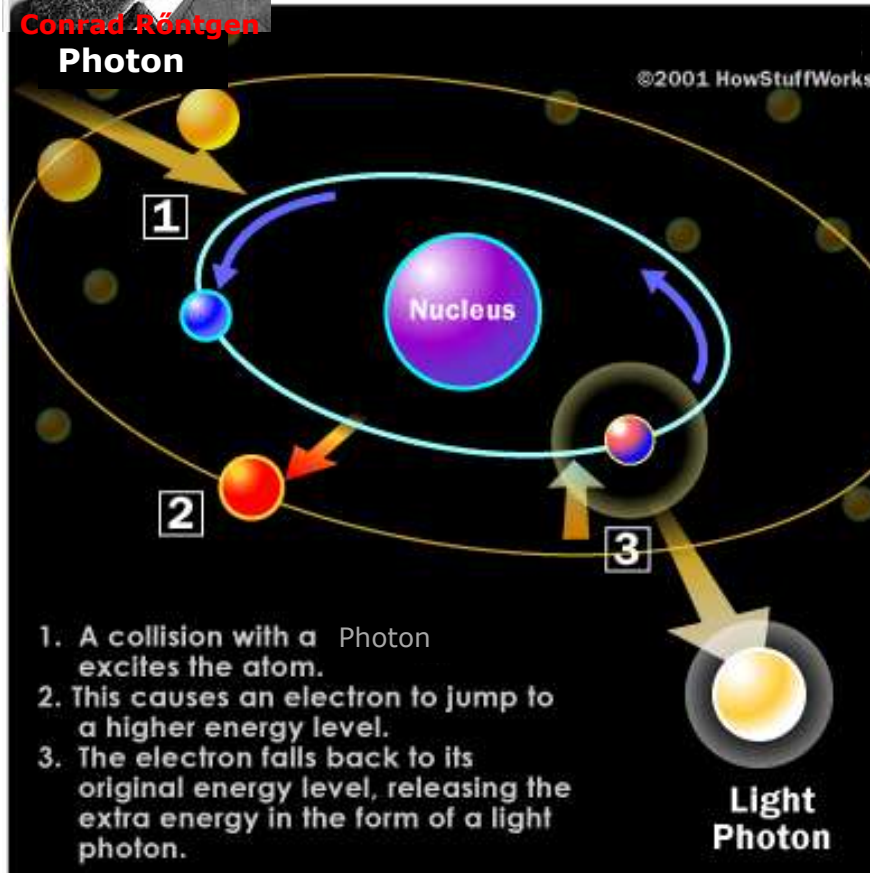


Conrad Röntgen  
Photon

**Conrad Röntgen**

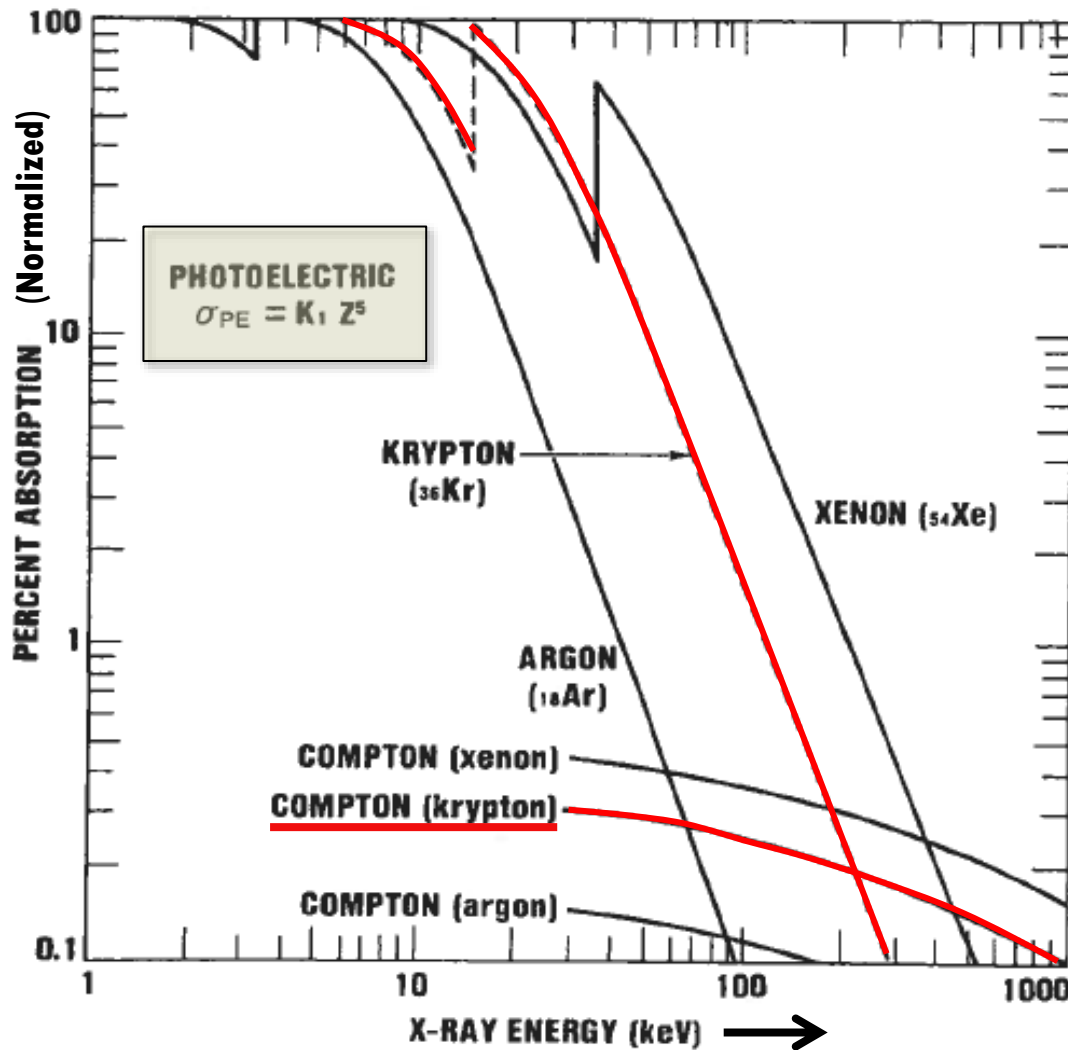
**Discovered X rays:**

**Electron Transitions**



Nuclide	Energy of X-Rays and Low-Energy Gamma (keV)	Energy of High-Energy Gamma (keV)	Intensity Ratio $x/y$
<sup>54</sup> Mn	5.414 ( $K\alpha$ )	834.8	0.2514 ( $\pm 0.5\%$ ) $K\alpha + K\beta$
	5.946 ( $K\beta$ )		
<sup>57</sup> Co	6.40 ( $K\alpha$ )	122.1	0.5727 ( $\pm 2.0\%$ ) 0.7861 ( $\pm 2.9\%$ ) 0.112 ( $\pm 1.8\%$ )
	7.06 ( $K\beta$ )		
	14.43 ( $\gamma$ )		
<sup>65</sup> Zn	8.04 ( $K\alpha$ )	1115.5	0.6596 ( $\pm 0.8\%$ ) 0.0911 ( $\pm 2.0\%$ )
	8.9 ( $K\beta$ )		
<sup>241</sup> Am	11.89 $N_p L_1$	59.5	0.022 0.375 0.512 0.138 0.07
	13.90 $N_p L\alpha$		
	17.8 $N_p L\beta$		
	20.8 $N_p L\gamma$		
	26.35 $\gamma$		
<sup>85</sup> Sr	13.38 ( $K\alpha$ )	514.0	0.5020 ( $\pm 0.65\%$ ) 0.0880 ( $\pm 1.4\%$ )
	15.0 ( $K\beta$ )		
<sup>86</sup> Y	14.12 ( $K\alpha$ )	898.0	0.5491 ( $\pm 1.2\%$ ) 0.0989 ( $\pm 1.9\%$ )
	15.85 ( $K\beta$ )		
<sup>109</sup> Cd	22.10 ( $K\alpha$ )	88.0	22.02 ( $\pm 4.9\%$ ) 4.68 ( $\pm 5.0\%$ )
	25.0 ( $K\beta$ )		
<sup>113</sup> Sn	24.14 ( $K\alpha$ )	391.7	1.219 ( $\pm 3.5\%$ ) 0.267 ( $\pm 3.6\%$ )
	27.4 ( $K\beta$ )		

# Photoelectric Absorption of X Rays in Gases



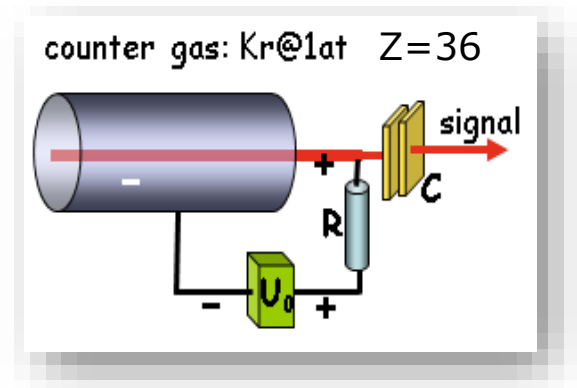
Relative absorption of various proportional counter gases for low energy x-rays (Taken from Reference 1).

$$\sigma_{PE} \propto Z_{\text{absorber}}^5$$

→ High-Z counting gas

Low-energy X and  $\gamma$ -ray photons interact with matter dominantly via photo effect, mostly with K-shell (1s) electrons.

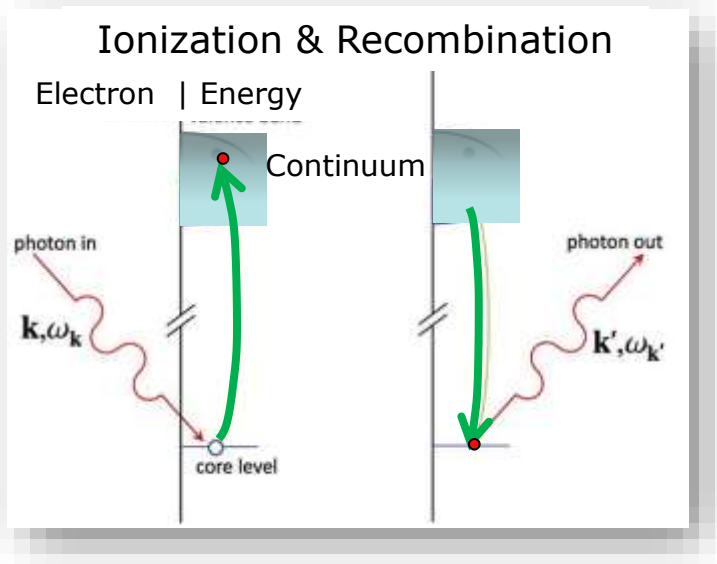
→ ionization & Compton  
(used in Mössbauer expt.)



# Complex PC Response to High Energy Photons

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Gas Amp Detectors



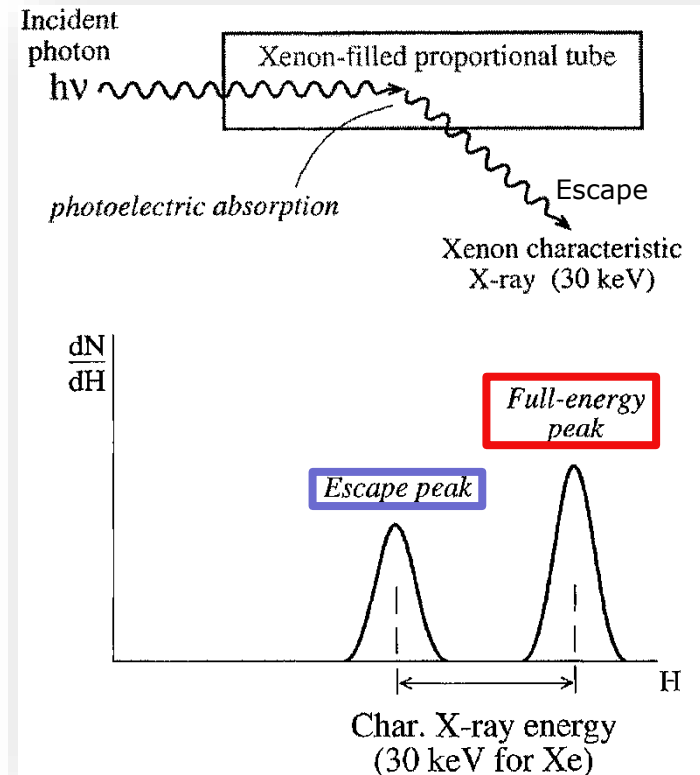
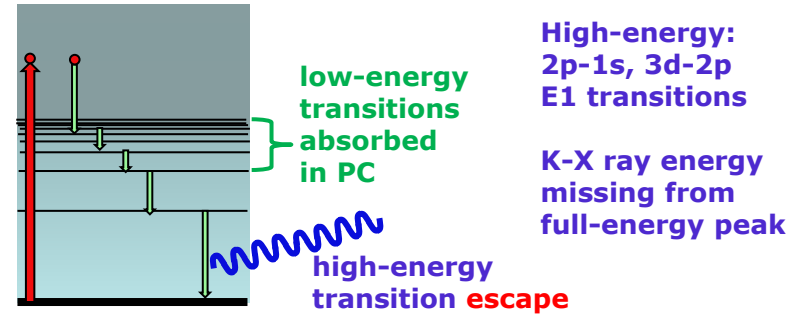
X ray photons from recombination or Auger cascade can escape a "thin" detector → escape lines

(remember escape lines for scintillation/SSD gamma detectors)

Also: Wall effects.

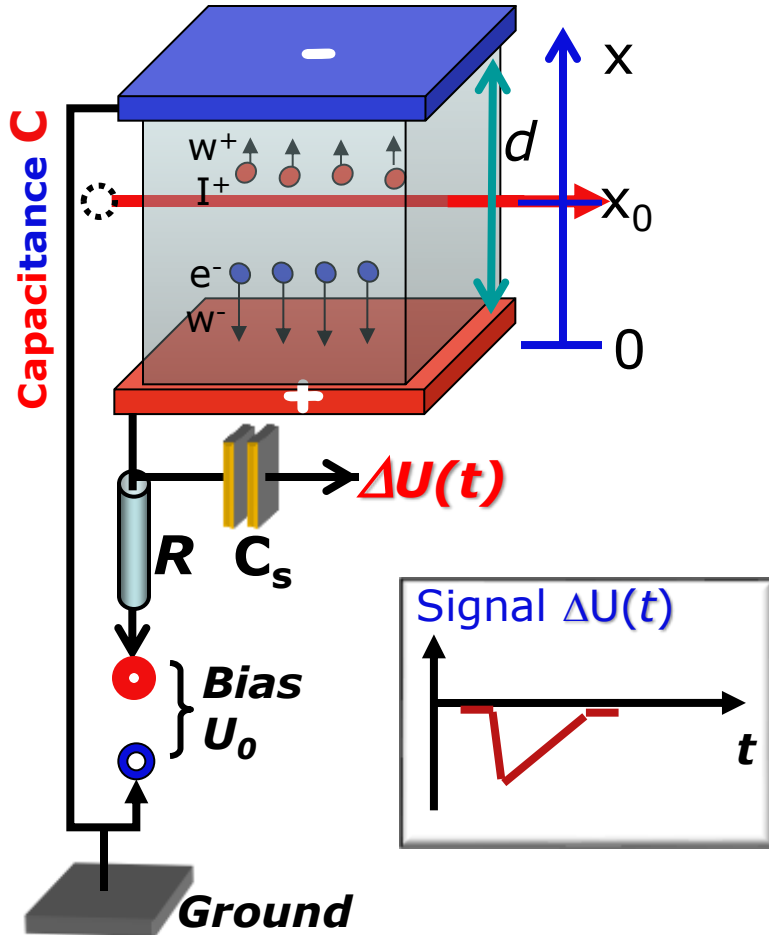
**Kr:** IE(K)=14.263 keV  
 2p-1s 12.6 keV  
 3d-2p 1.64 keV

## Auger Cascade



# Signal Generation in Ionization Counters

Primary ionization: **Gases**  $I \approx 20\text{-}30$  eV/IP, **Si**:  $I \approx 3.6$  eV/IP **Ge**:  $I \approx 3.0$  eV/IP  
 Band gaps (300K) 1.11 eV 0.67 eV



Energy loss  $\Delta\varepsilon$ :  $n = n_I = n_e = \Delta\varepsilon/I$   
 $\rightarrow n$  primary ion pairs ( $I^+, e^-$ ) at  $x_0, t_0$

Electrostatic force:  $F_e = -eU_0/d = -F_I$

Energy content of detector capacitance C:

$$1) W(t) = \frac{C}{2} [U_0^2 - U^2(t)] \approx CU_0 \Delta U(t)$$

$$2) W(t) = n_e F_e [x_e(t) - x_0] + n_I F_I [x_I(t) - x_0]$$

$$= + \frac{neU_0}{d} [x_I(t) - x_e(t)]$$

1) + 2)  $\searrow$

$$\Delta U(t) = \frac{W(t)}{CU_0} = \frac{ne}{Cd} [w^+(t) - w^-(t)] \cdot (t - t_0)$$

$w^\pm$  Drift Velocities

# Time-Dependent Signal Shape

Total signal: e & I components

Drift velocities  
( $w^+ > 0$ ,  $w^- < 0$ )

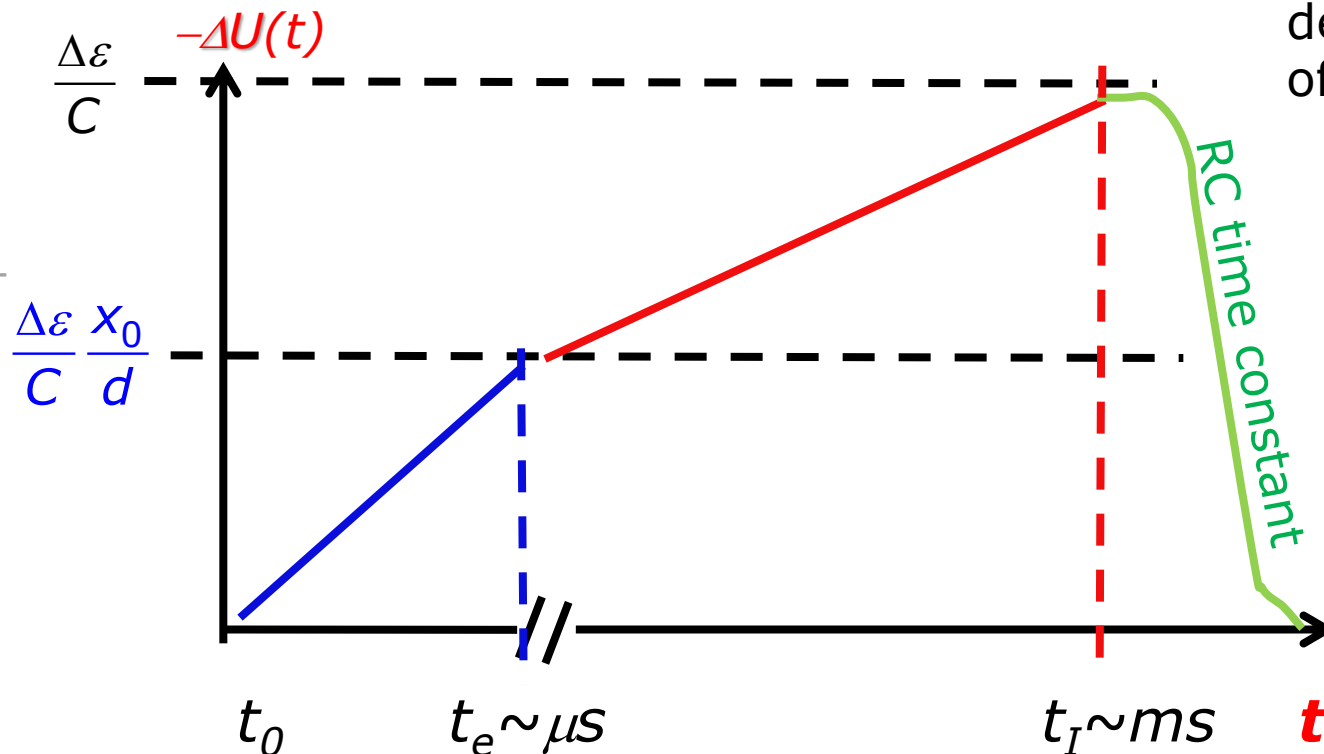
$$\Delta U(t) = \frac{\Delta \varepsilon}{Cd} [w^+(t) - w^-(t)] (t - t_0)$$

$$|w^+(t)| \sim 10^{-3} |w^-(t)|$$

Both components measure  $\Delta \varepsilon$  and depend on position of primary ion pairs

$$x_0 = w^-(t_e - t_0)$$

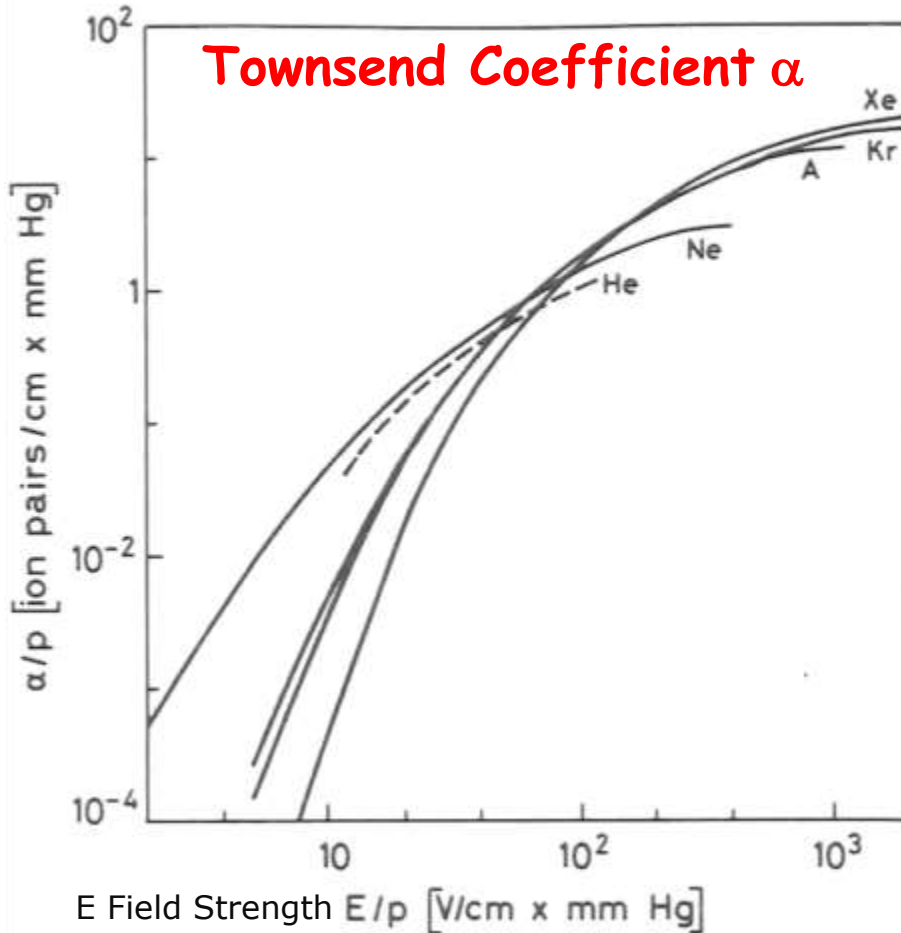
**For fast counting use only electron component.**



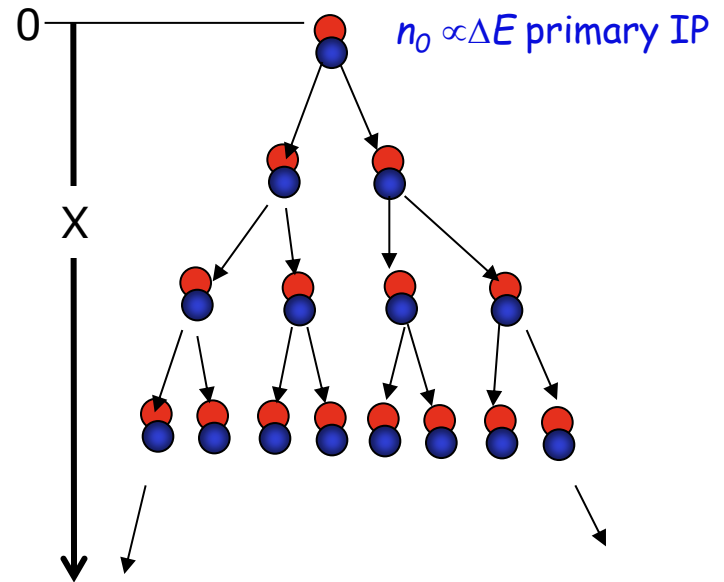
# Gas Amplification, Avalanche Formation

Incident radiation:  $n_0 \propto \Delta E$  primary IP

Strong E field: secondary electron-ion pairs through gas ionization  $\rightarrow$  larger signal



Electrons in outer shells are more readily removed, ionization energies are smaller for heavier elements.



$$dn = \alpha \cdot n \cdot dx \text{ secondary ion pairs}$$

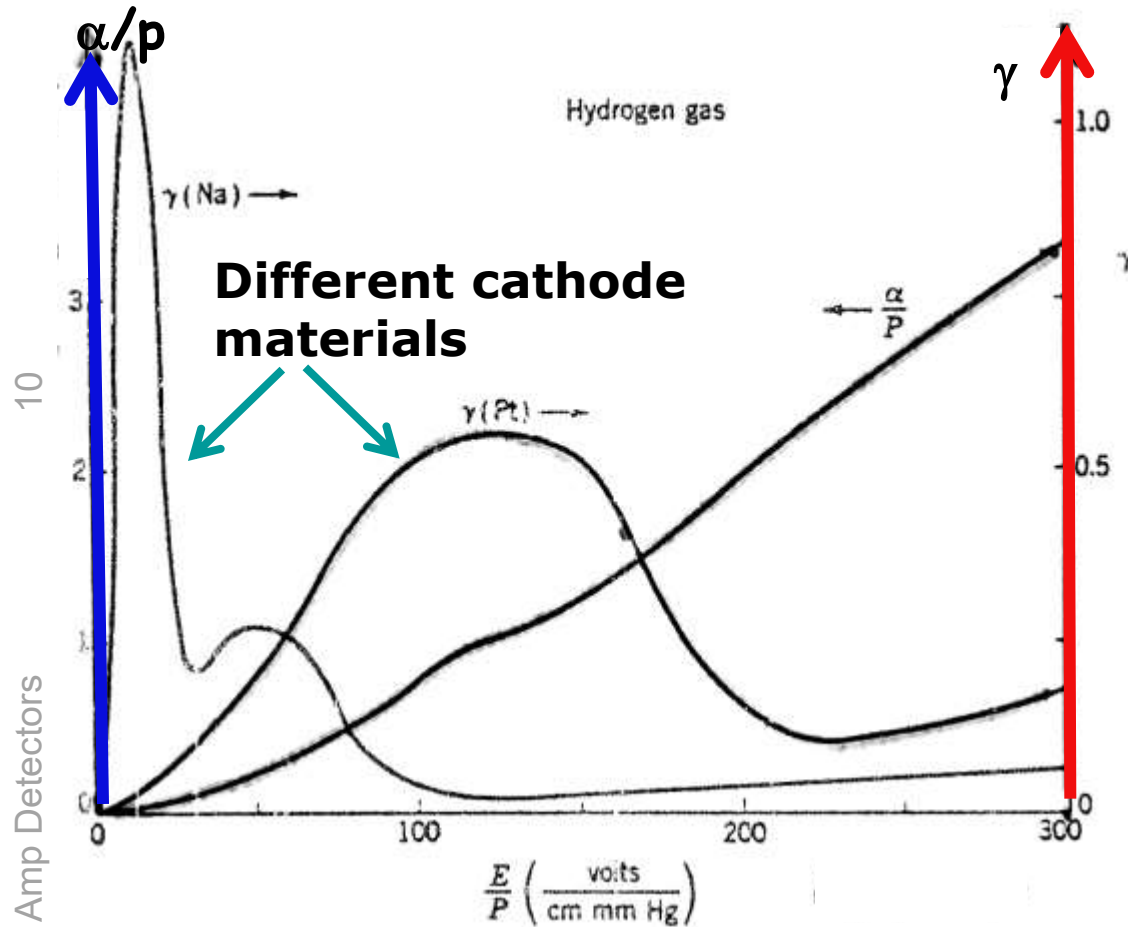
For  $\alpha = \text{const}$

$$n(x) = n_0 \cdot e^{\alpha \cdot x} = n_0 \cdot [1 + \alpha \cdot x + \dots]$$

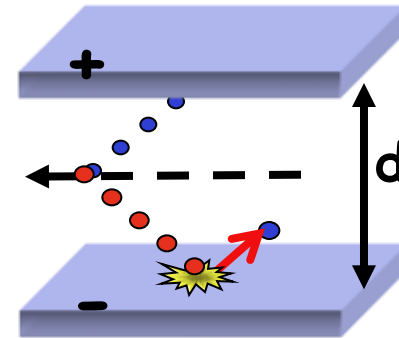
$$n(x) = n_0 \cdot \exp \left\{ \int_0^x \alpha(x') dx' \right\}$$

Eventually Spark  $n \rightarrow \infty \rightarrow$  GM counter

# Sparking and Spark Counters



Impact ionization  
Probability  $\gamma$



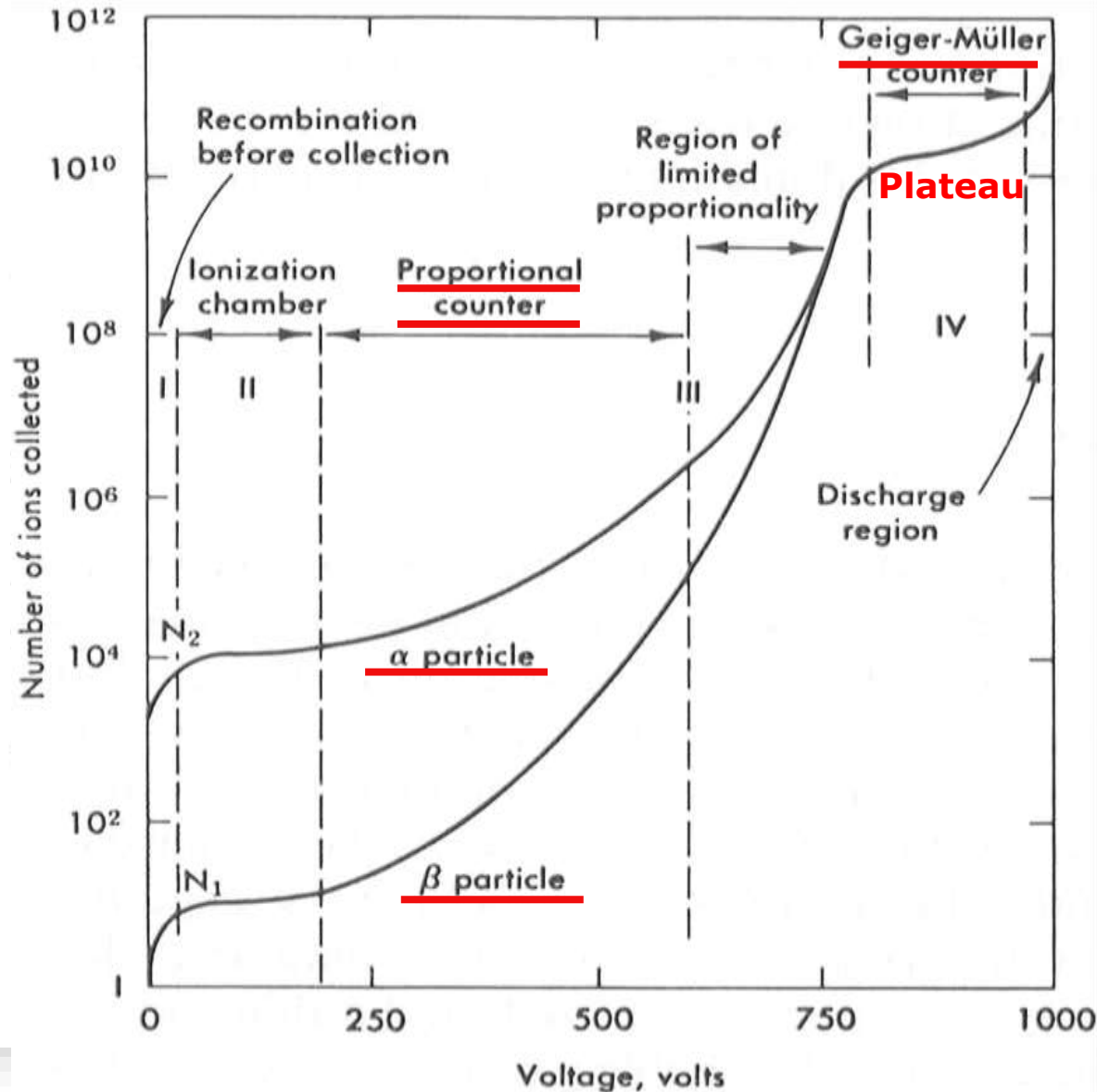
*Amplification by  
impact ionization*

$$M = \frac{n}{n_0} = \frac{e^{\alpha \cdot d}}{1 - \gamma \cdot [e^{\alpha \cdot d} - 1]}$$

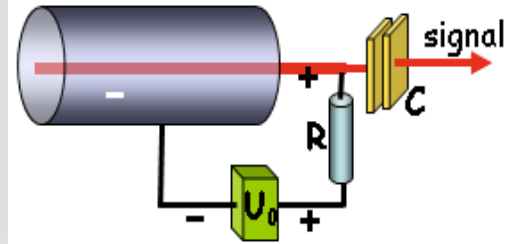
*Sparking* :  $\gamma \cdot e^{\alpha \cdot d} \approx 1$   
 $p \sim (10^{-1} - 10^{-3}) \text{ Torr}$

Prevent spark by reducing  $\lambda$  for ions:  
collisions with large organic molecules  $\rightarrow$   
**quenching** additives, self-quenching gases

# Gas Counter Characteristic



counter gas: Kr@1at

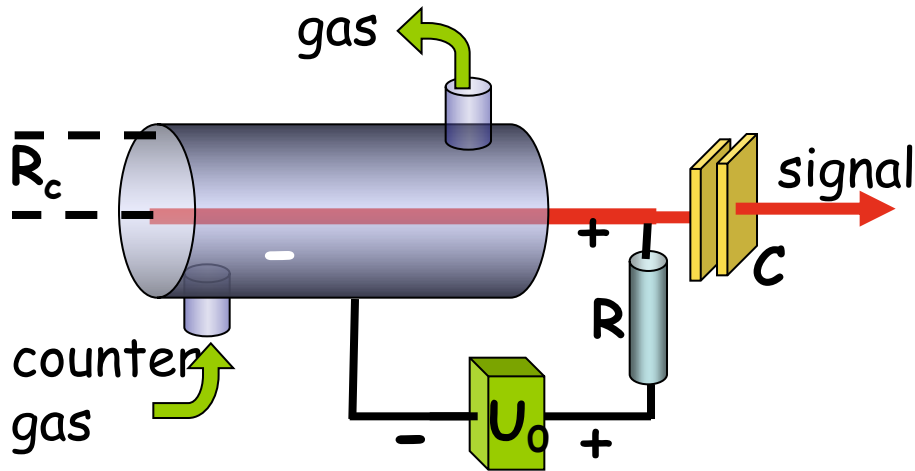


Most commercial counters are permanently sealed.

Exponential increase of signal amplitude with voltage.

Moderate (10%) resolution, but economic counter.

# Proportional Counter

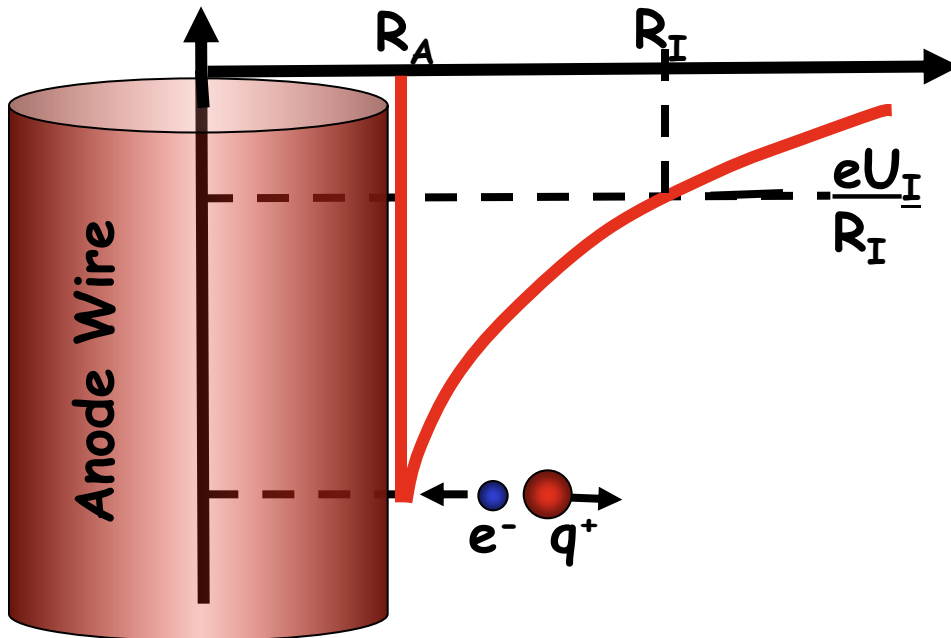


Anode wire: small radius  
 $R_A \approx 50 \mu\text{m}$  or less

Voltage  $U_0 \approx (300-500) \text{ V}$

*Field at  $r$  from wire*

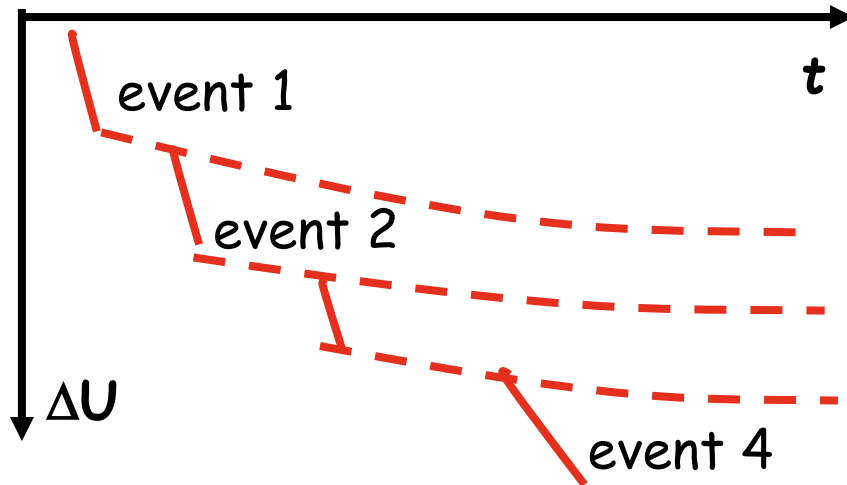
$$E(r) = \frac{U_0}{\ln(R_C/R_A)} \cdot \frac{1}{r}$$



Avalanche  $R_I \rightarrow R_A$ , several mean free paths needed

Pulse height mainly due to positive ions ( $q^+$ )

# Practical RC-Signal Shape



*IC/PC signal shape*

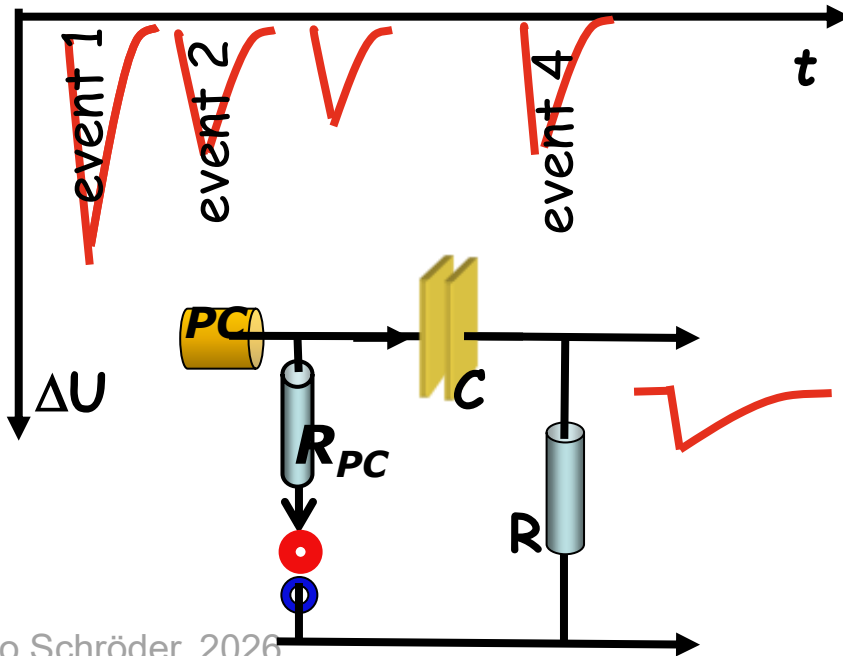
$$\Delta U(t) = \frac{\Delta \varepsilon}{Cd} \left[ w_{\text{slow}}^+(t) - w_{\text{fast}}^-(t) \right] \cdot (t - t_0)$$

Two sections of signal contain same information  $\Delta \varepsilon \rightarrow$

Long decay time of pulse  $\rightarrow$  pulse pile up, summary information

Reduce info to what is necessary

differentiate electronically, RC-circuitry in shaping amplifier, individual information for each event (= incoming particle/photon)



# Suitable X Ray Calibration Sources

$^{133}\text{Ba}$ atomic X rays		Energy keV	Photons per 100 disint.	
XL	(Cs)	3,8 — 5,7	16,0 (8)	
XK $\alpha_2$	(Cs)	30,625	34,0 (4)	} K $\alpha$
XK $\alpha_1$	(Cs)	30,973	62,8 (7)	
XK $\beta_3$	(Cs)	34,92	} 18,2 (2)	} K' $\beta_1$
XK $\beta_1$	(Cs)	34,987		
XK $\beta_5''$	(Cs)	35,245	}	
XK $\beta_5'$	(Cs)	35,259		

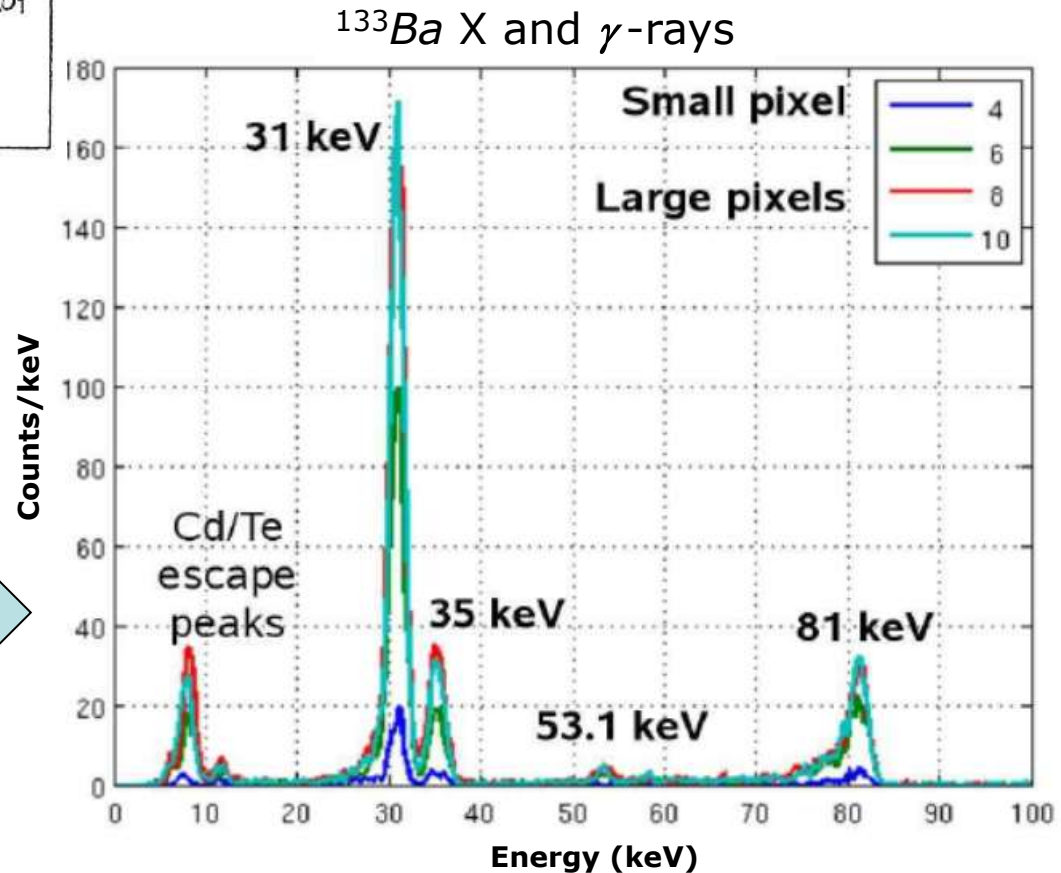
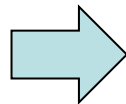
Calibration needed in the *l.e.* range  
 $0 \text{ keV} \leq E_\gamma < 100 \text{ keV} \rightarrow \text{X rays}$

E.g. use  $^{133}\text{Ba}$ ,  $^{109}\text{Cd}$ ,  $^{241}\text{Am}$ , K $\alpha$  and K $\beta$  X ray energies/intensities

Find  $^{60}\text{Co}$   $\gamma$ , X – rays a on data sneets (Internet)

Barium-133 photon spectrum, low-energy region, obtained with a solid-state detector

(patterned CdTe crystal, used on ESA Solar Orbiter). O. Grimm et al. J. Instr. 7. C12015. 10.1088/1748-0221/7/12/C12015.



# PC Calibration Analytical Tasks

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1. Give a plausible explanation of the specific energy dependence of the photon detection efficiency of the ANSEL gas proportional counter (PC). The data have been provided in a data graph, in the ANSEL Manual & Task Sheets.
2. Explain the main process(es) that produce the response of the ANSEL PC to mono-energetic X-rays and  $\gamma$ -rays. What would look the response structure for a 50-keV  $\gamma$ -ray look like on the PC pulse height (energy) scale?
3. Given the ANSEL gas proportional counter (PC) detector technical characteristics provided, what are the main X-rays and  $\gamma$ -rays from the radioactive  $^{57}\text{Co}$  source one would expect to detect within a reasonable run time?
4. What differences from the Ba-133 spectrum measured with a *CdTe* crystal shown previously can be expected?
5. Analyze and fit the lines in the Ba-133 photon spectrum, where the source was placed directly in front of the Be window of the ANSEL PC.
6. Provide an educated guess about what process within the counter gas each line may represent.
7. In the further PC calibration procedure for low-energy X-rays and  $\gamma$ -rays analyze spectra obtained with aluminum absorbers placed between calibration source and PC.  
Access web data on aluminum photon absorption coefficients (e.g. <https://physics.nist.gov/PhysRefData/XrayMassCoef/ElemTab/z13.html>)

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# End of Class