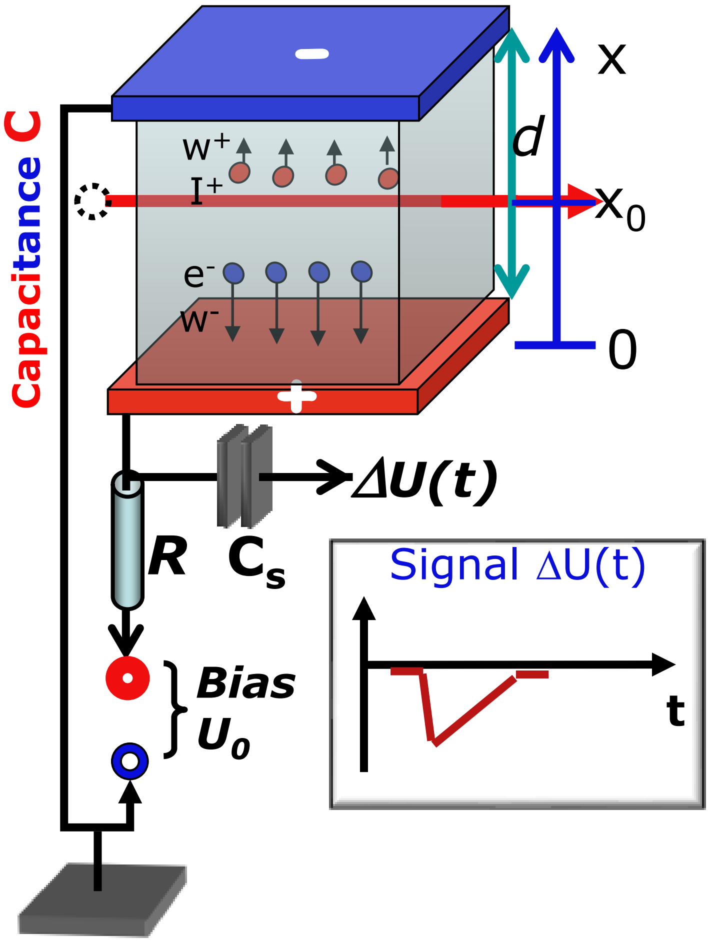
Detection Of Ionizing Radiation

Gas Amplification Counters

Signal Generation in Ionization Counters

Primary ionization: **Gases** I ≈ 20-30 eV/IP, **Si**: I ≈ 3.6 eV/IP **Ge**: I ≈ 3.0 eV/IP
Band gaps (300K) 1.11 eV 0.67 eV



Energy loss Δε: $n = n_I = n_e = \Delta\varepsilon / I$ number of ***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:

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

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

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

$w^+(t)(t - t_0)$

1) + 2) ↘

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

$w^\pm$ Drift Velocities

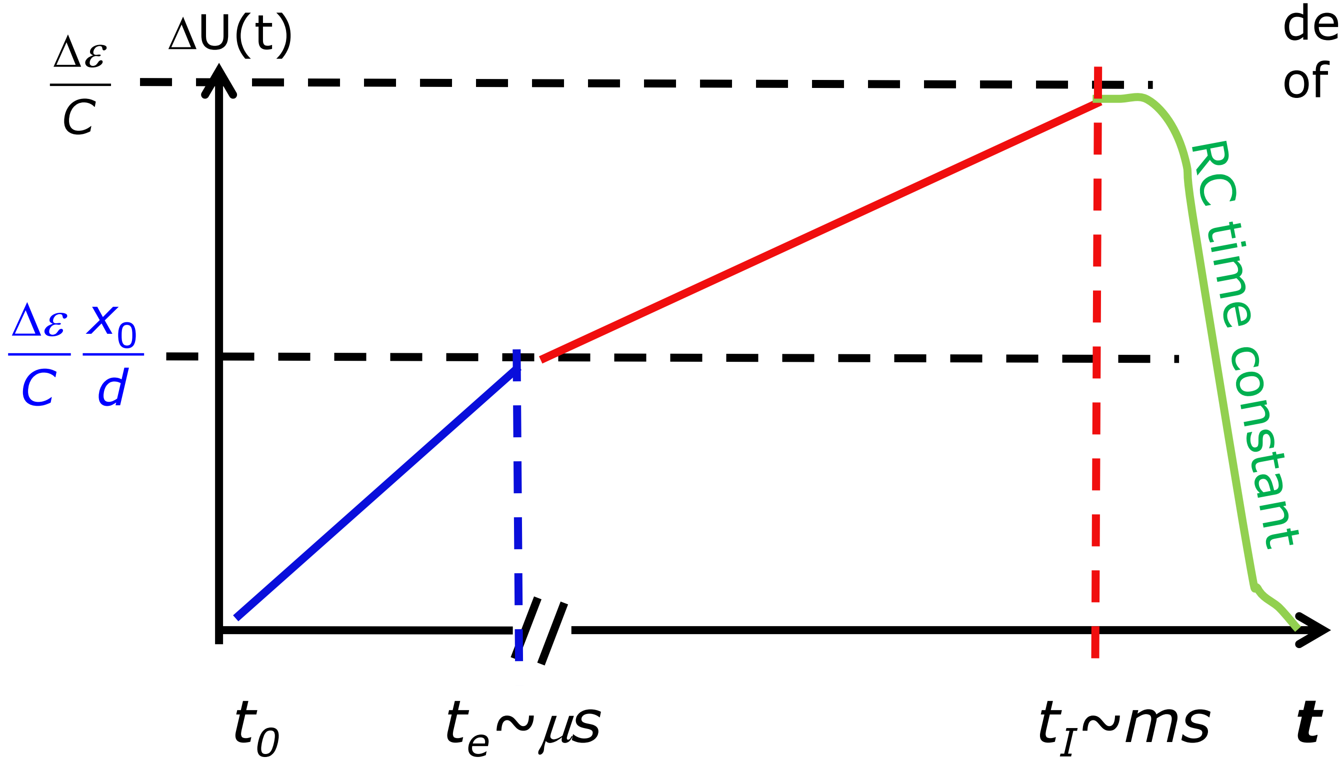
Time-Dependent Signal Shape

Total signal: e & I components

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

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

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



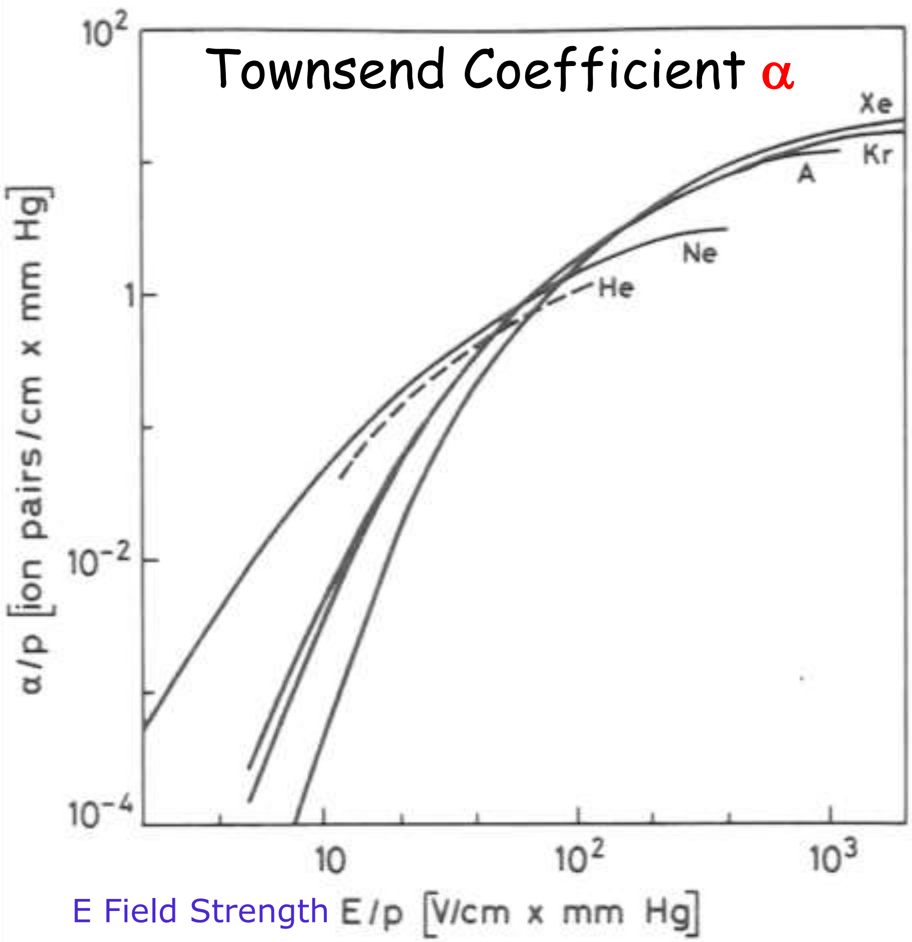
Both components measure $\Delta\varepsilon$ and depend on position of primary ion pairs

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

For fast counting use only electron component.

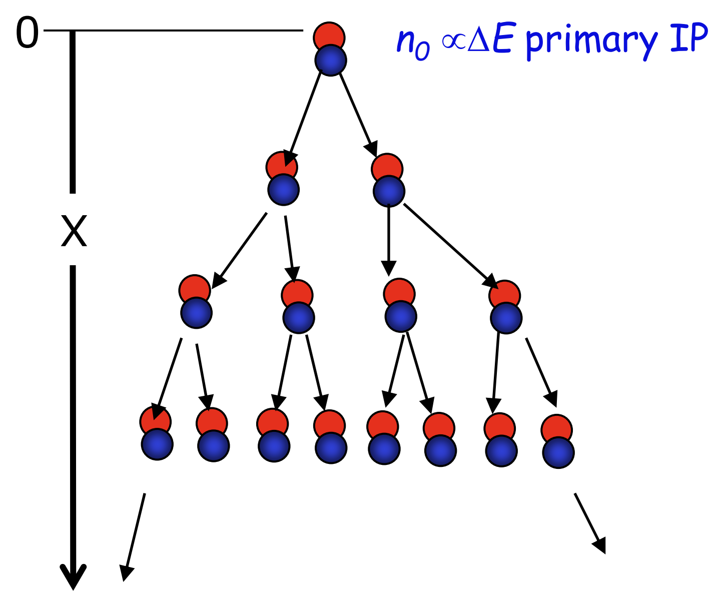
Gas Amplification, Avalanche Formation

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



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

Strong E field: secondary electron-ion pairs through gas ionization → larger signal



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

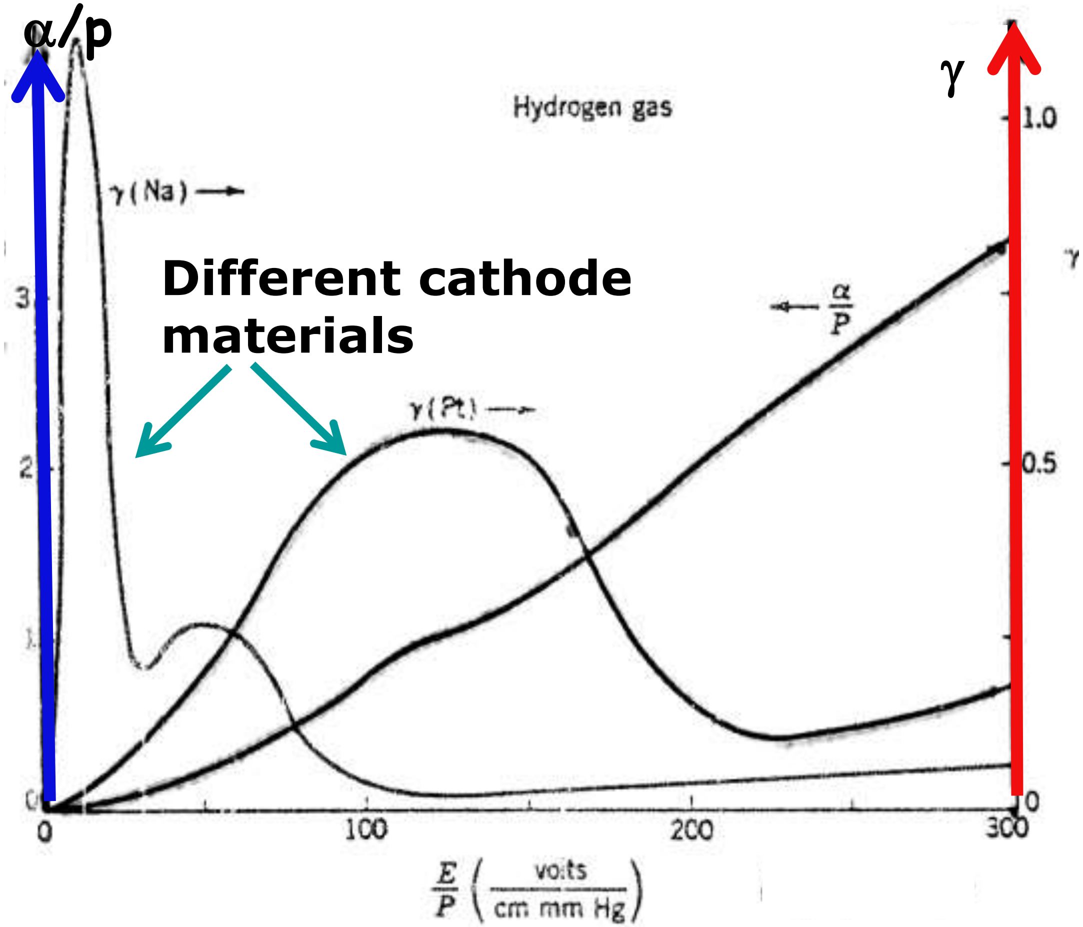
$$For\ \alpha = const$$

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

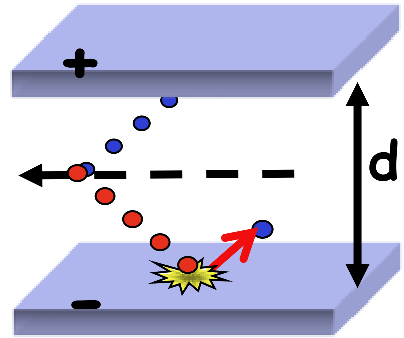
$$n(x) = n_0 \cdot \exp\left\{\int_0^x \alpha(x')dx'\right\}$$

$$\textit{Eventually Spark } n \to \infty \ \to \textit{GM counter}$$

Sparking and Spark Counters



Impact ionization Probability γ



Amplification by impact ionization

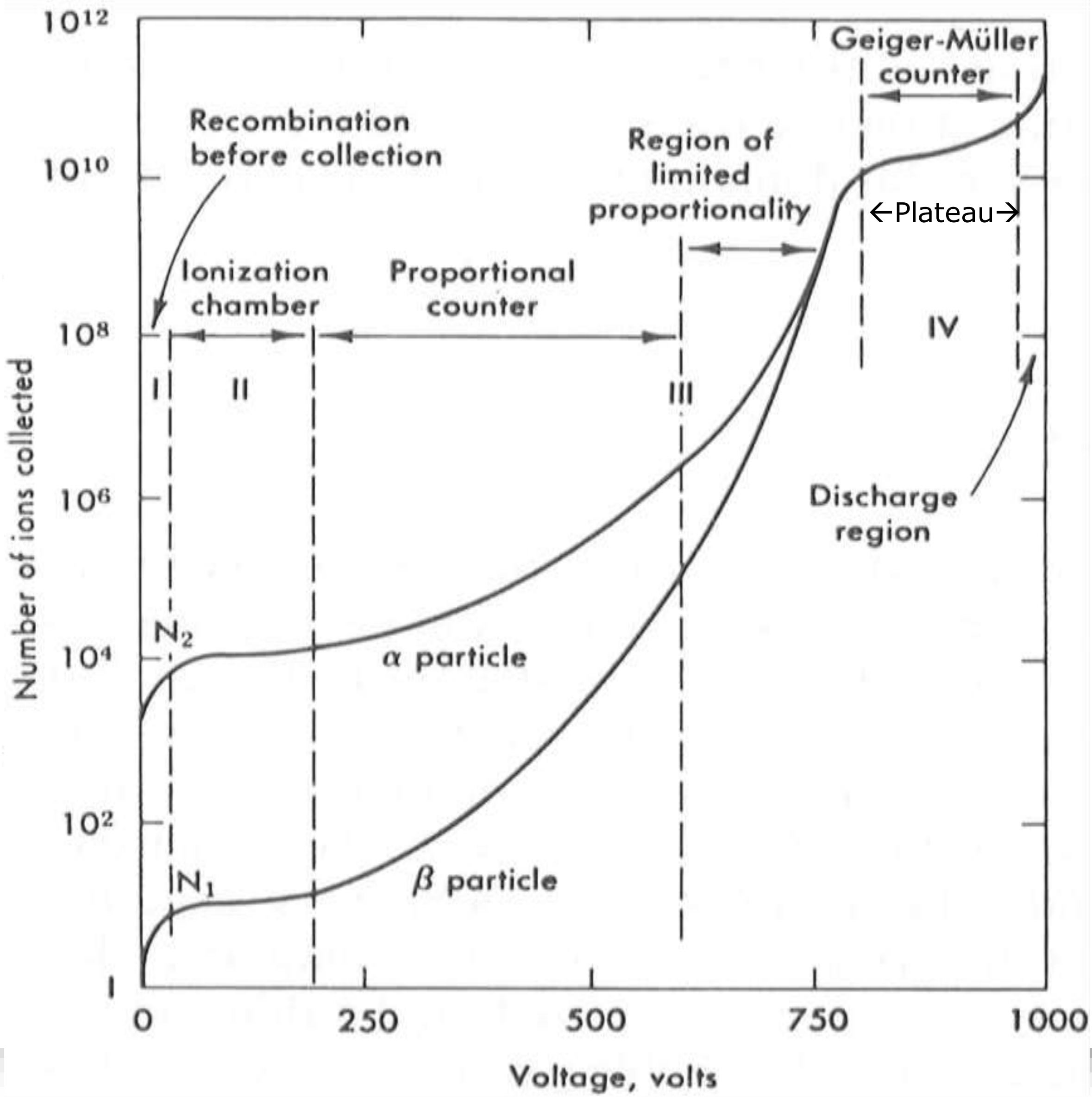
$$M = \frac{n}{n_0} = \frac{e^{\alpha \cdot d}}{1 - \gamma \cdot \left[e^{\alpha \cdot d} - 1 \right]}$$

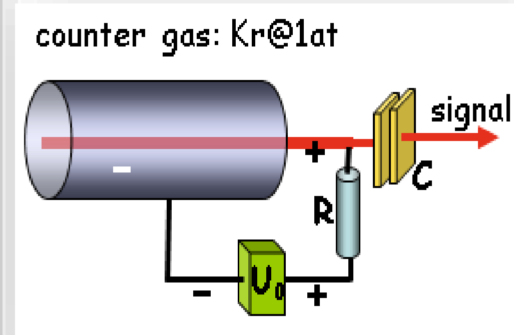
$$Sparking: \gamma \cdot e^{\alpha \cdot d} \approx 1$$

$$p \sim (10^{-1} - 10^{-3})\, Torr$$

Prevent spark by reducing λ for ions: collisions with large organic molecules → **quenching** additives, self-quenching gases

Gas Counters



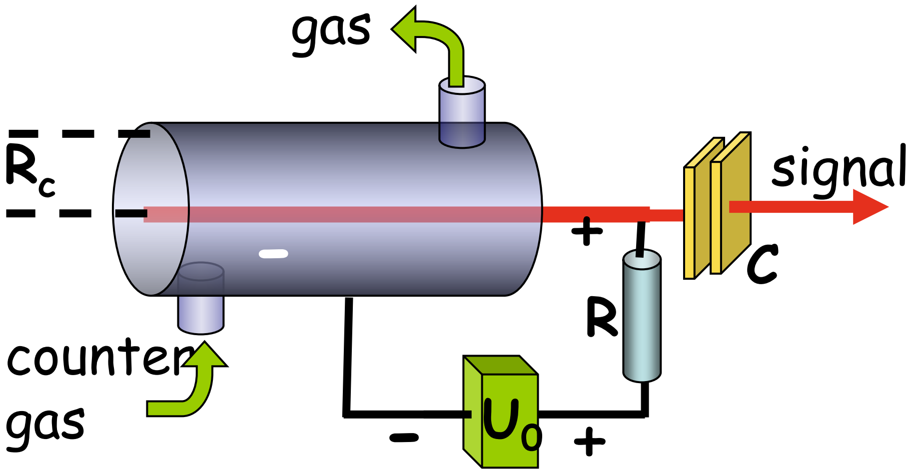


Most commercial counters are permanently sealed.

Exponential increase of signal amplitude with voltage.

Moderate (10%) resolution, but economic counter.

Proportional Counter

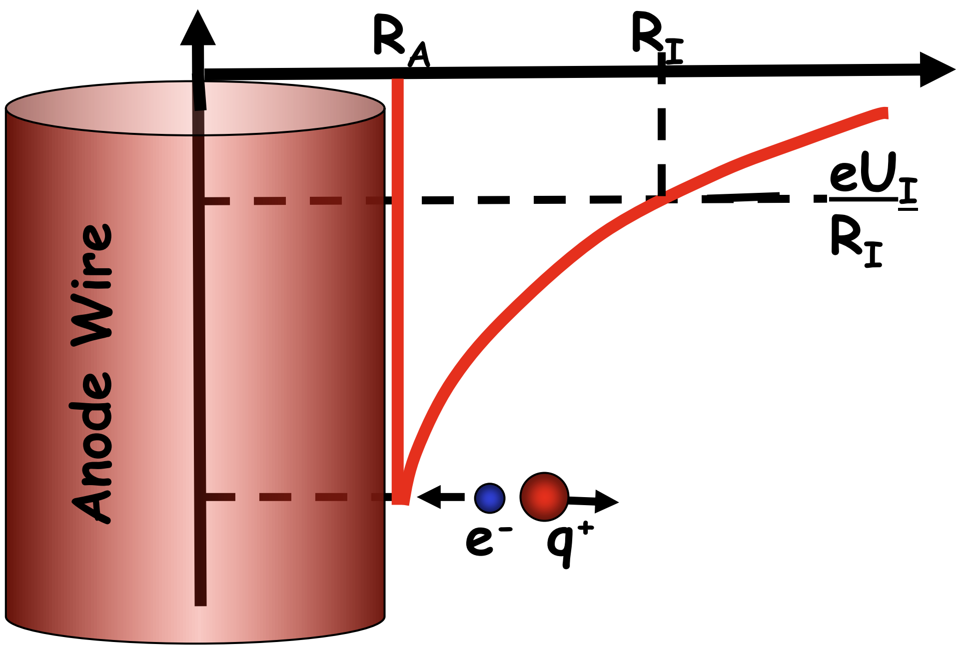


Anode wire: small radius
$R_A \approx 50\ \mu m$ or less

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

Field at r from wire

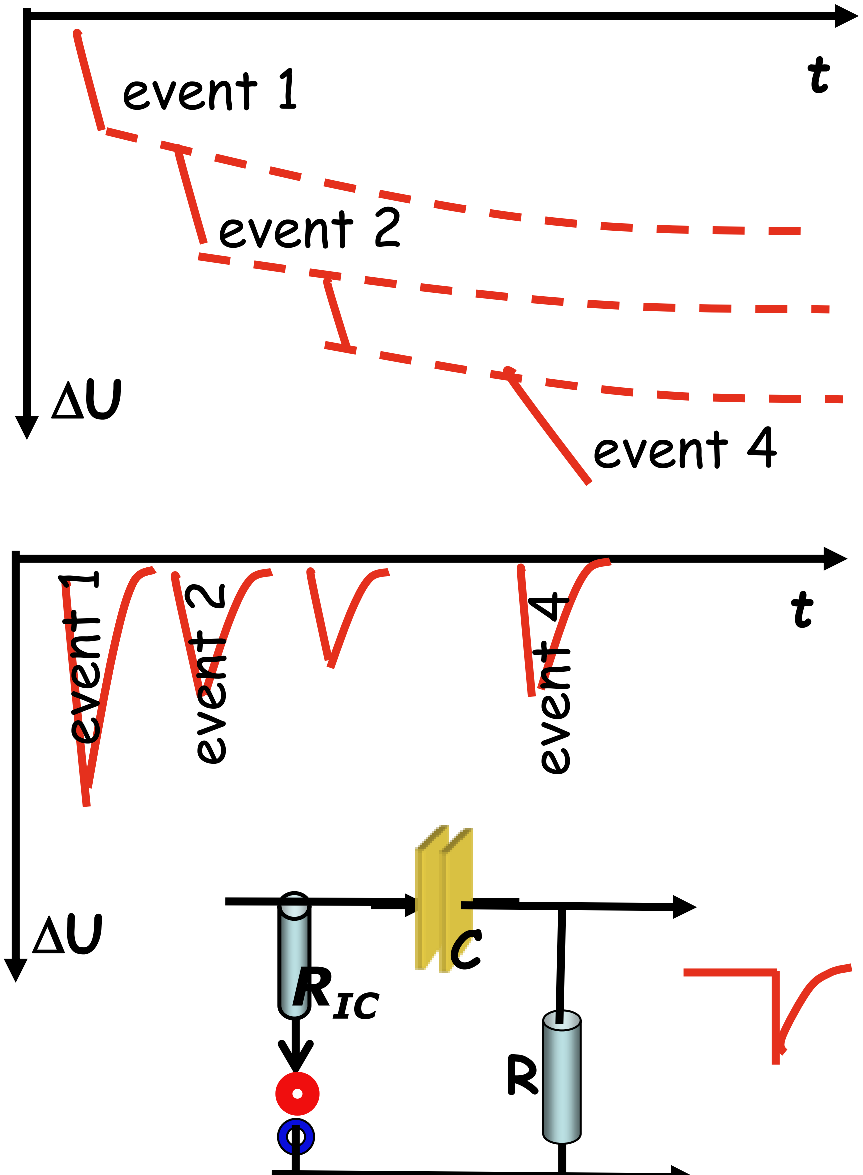
$$E(r) = \frac{U_0}{\ln(R_C/R_A)} \cdot \frac{1}{r}$$



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

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

Practical RC-Signal Shape



IC signal shape

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

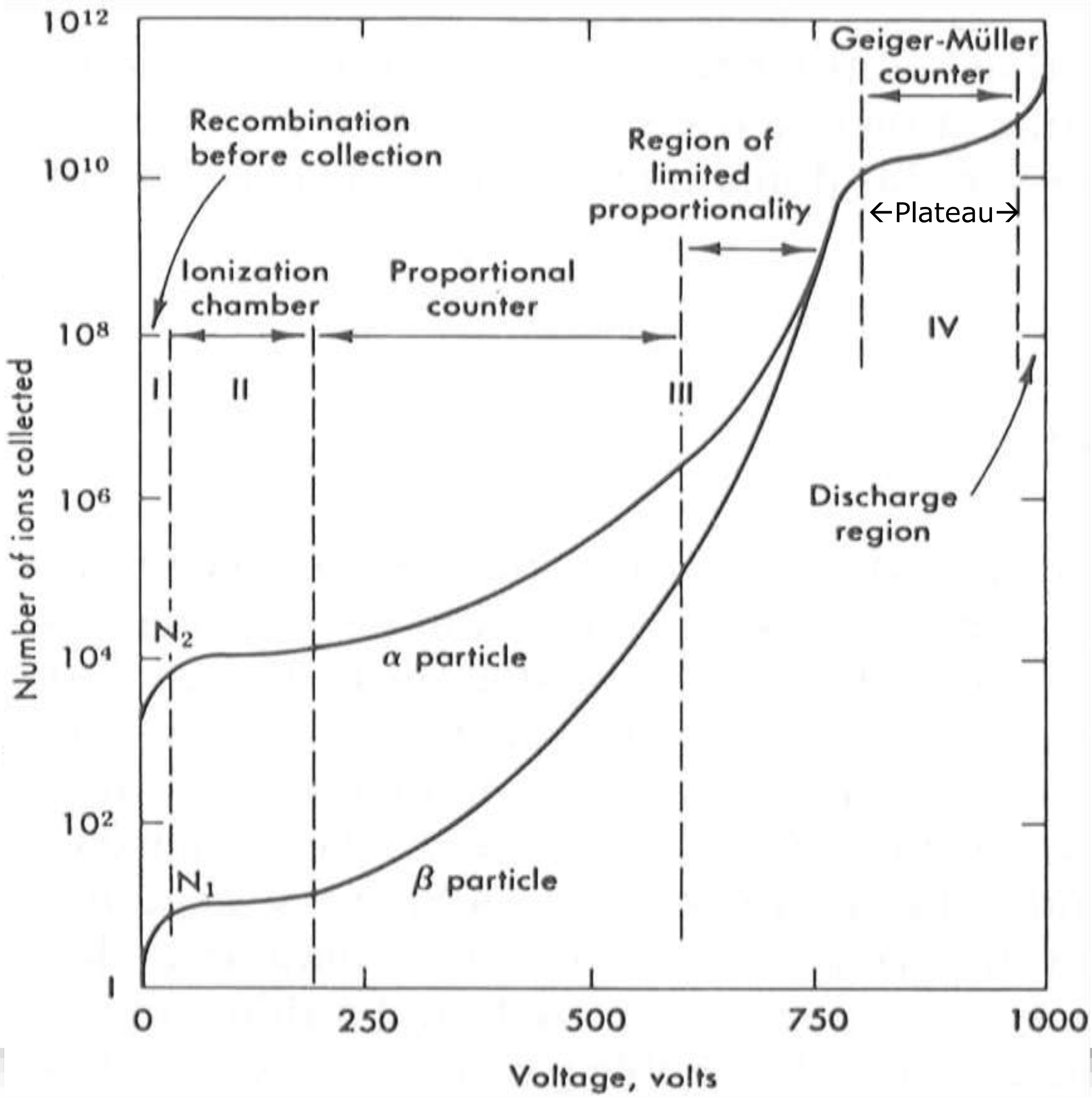
Two sections of signal contain same information Δε →

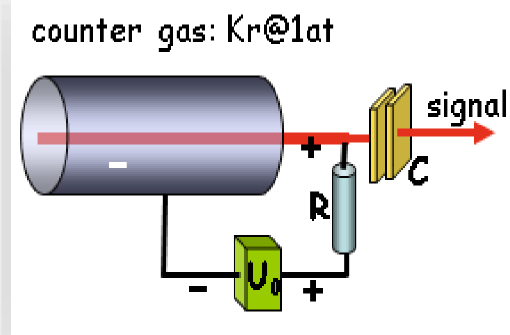
Long decay time of pulse → pulse pile up, summary information

Reduce info to what is necessary

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

Gas Counters





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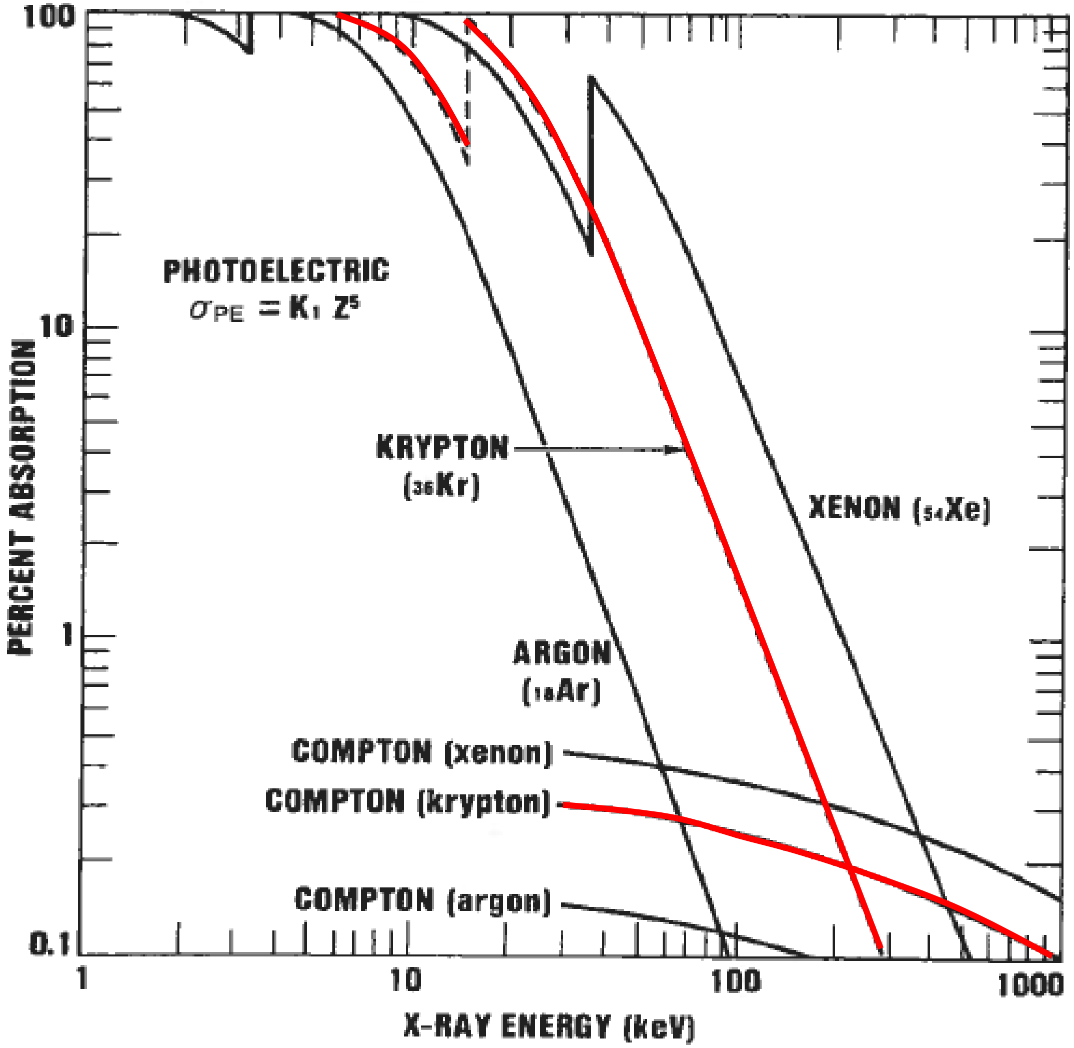
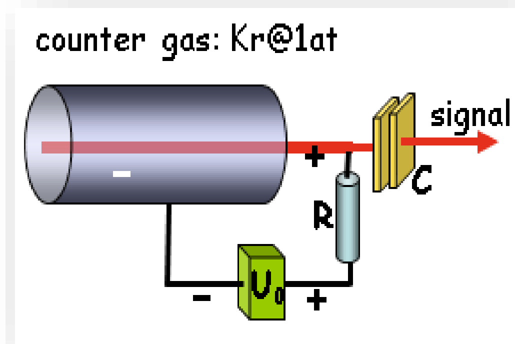
Absorption of X Rays in Gases



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



Low-energy X and γ-ray photons interact with matter dominantly via photo effect (ionization), mostly with K-shell (1s) electrons.
→ Mössbauer expt.

$$\sigma_{PE} \propto Z^5_{absorber}$$

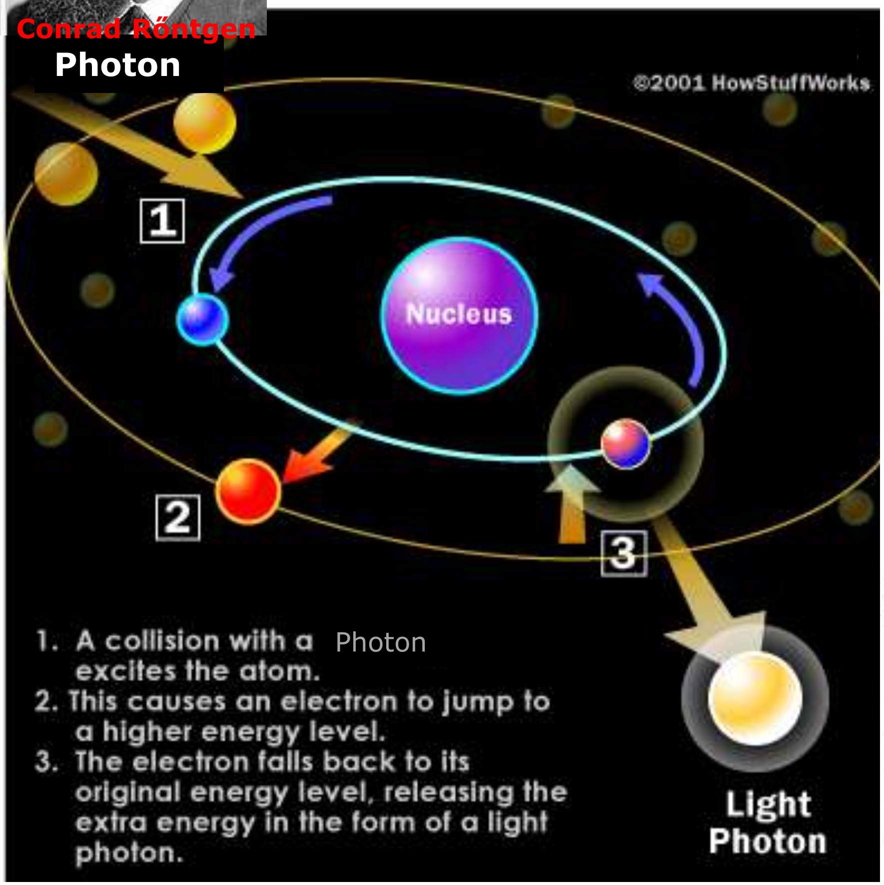
→High-Z counting gas

X Ray Energies

Conrad Rőntgen

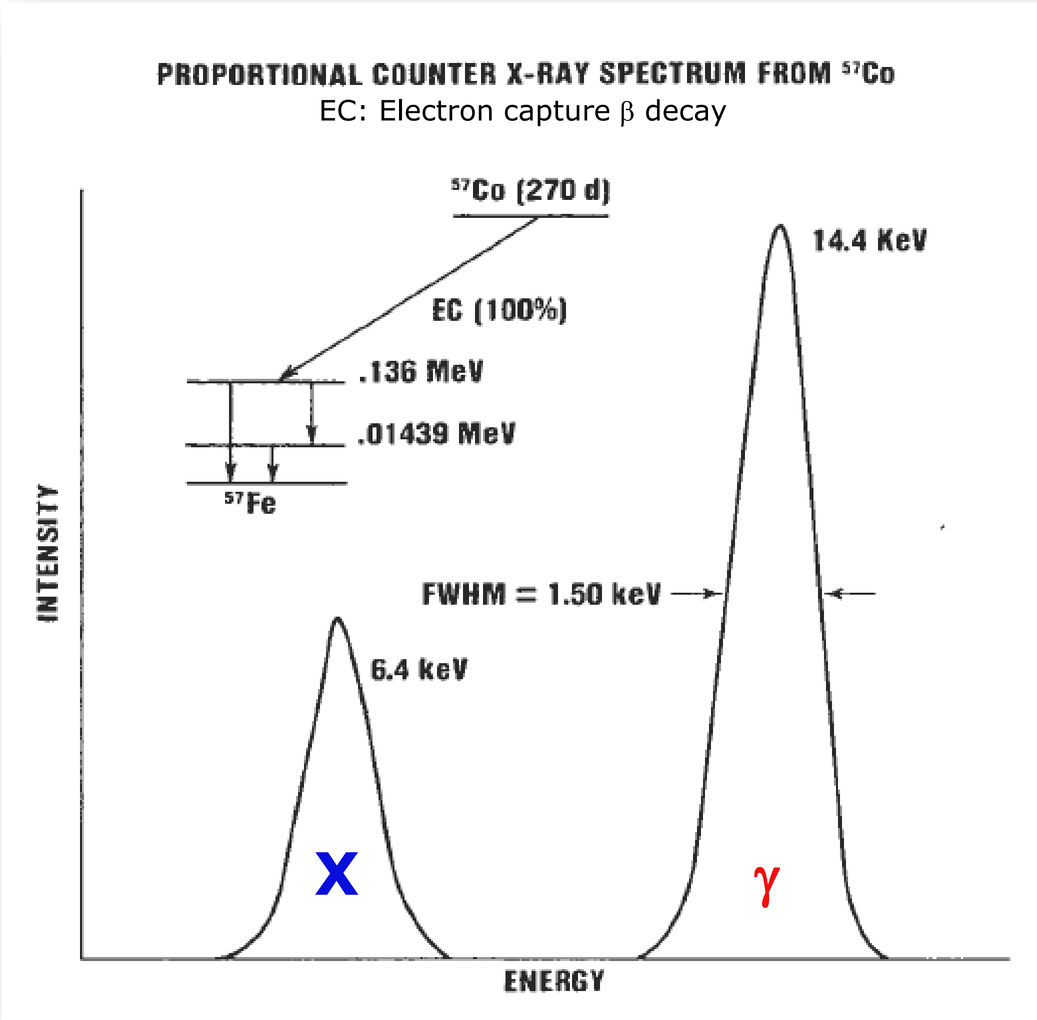
Discovered X rays:

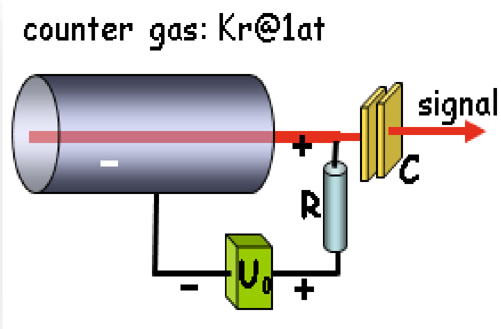
Electron Transitions



Nuclide	Energy of X-Rays and Low-Energy Gamma (keV)	Energy of High-Energy Gamma (keV)	Intensity Ratio x/γ
^{54}Mn	5.414 ($K\alpha$) 5.946 ($K\beta$)	834.8	0.2514 (±0.5%) $K\alpha + K\beta$
^{57}Co	6.40 ($K\alpha$) 7.06 ($K\beta$) 14.43 (γ)	122.1	0.5727 (±2.0%) 0.7861 (±2.9%) 0.112 (±1.8%)
^{65}Zn	8.04 ($K\alpha$) 8.9 ($K\beta$)	1115.5	0.6596 (±0.8%) 0.0911 (±2.0%)
^{241}Am	11.89 N_pL_l 13.90 $N_pL\alpha$ 17.8 $N_pL\beta$ 20.8 $N_pL\gamma$ 26.35 γ	59.5	0.022 0.375 0.512 0.138 0.07
^{85}Sr	13.38 ($K\alpha$) 15.0 ($K\beta$)	514.0	0.5020 (±0.65%) 0.0880 (±1.4%)
^{88}Y	14.12 ($K\alpha$) 15.85 ($K\beta$)	898.0	0.5491 (±1.2%) 0.0989 (±1.9%)
^{109}Cd	22.10 ($K\alpha$) 25.0 ($K\beta$)	88.0	22.02 (±4.9%) 4.68 (±5.0%)
^{113}Sn	24.14 ($K\alpha$) 27.4 ($K\beta$)	391.7	1.219 (±3.5%) 0.267 (±3.6%)

Example: ^{57}Co γ-Rays

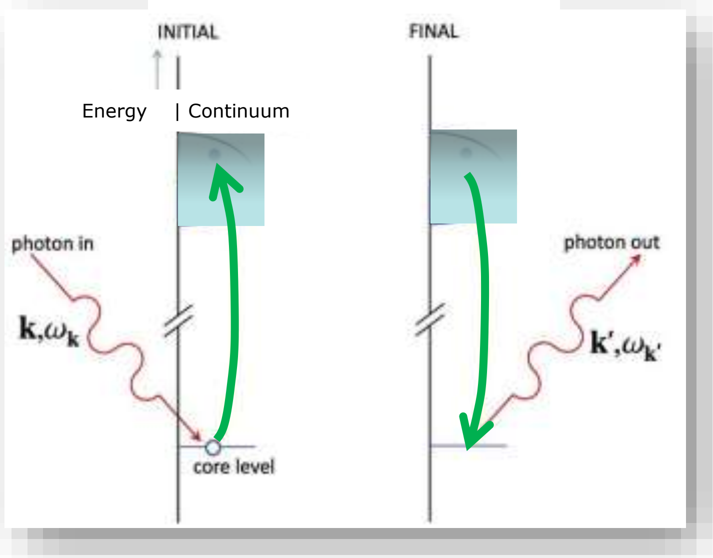




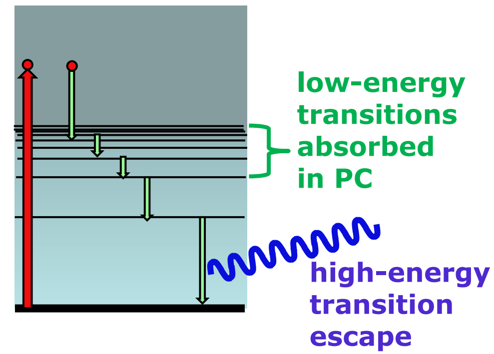
Low-energy X rays: interact with matter dominantly via photo effect, mostly with K shell (1s → ∞).
K-hole migrates to higher atomic levels in cascade of additional electronic X ray transitions

Complex PC Response to he Photons

Recombination



Auger Cascade



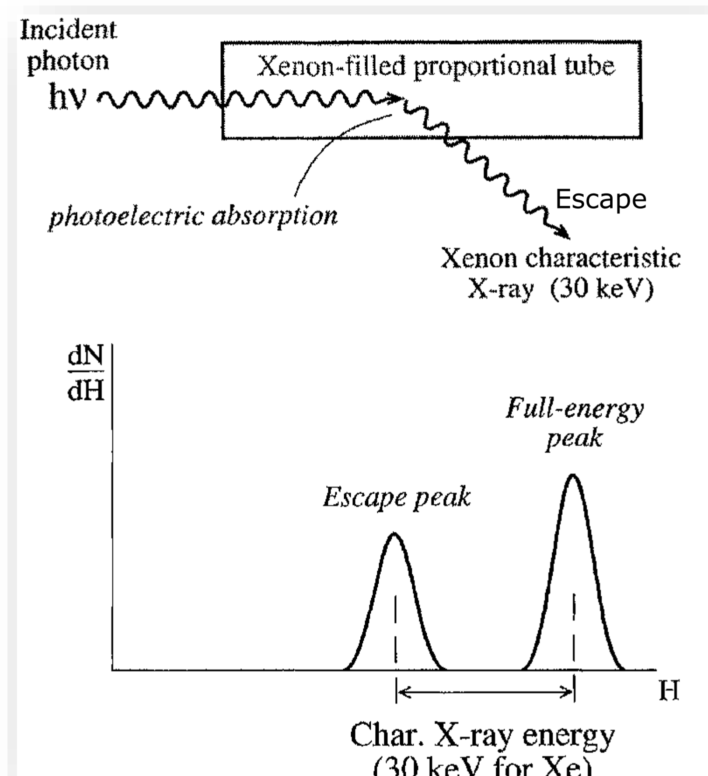
High-energy: 2p-1s, 3d-2p E1 transitions

K-X ray energy missing from full-energy peak

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

(remember escape lines for scintillation/SSD gamma detectors)

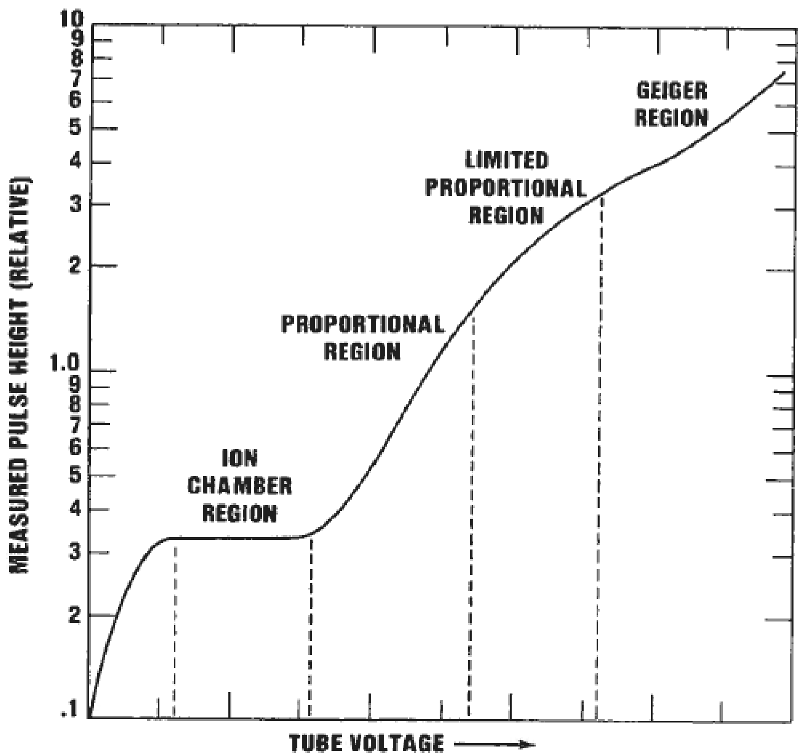
Also: Wall effects.



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

W. Udo Schröder, 2022

Solid-State Gamma Detectors



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