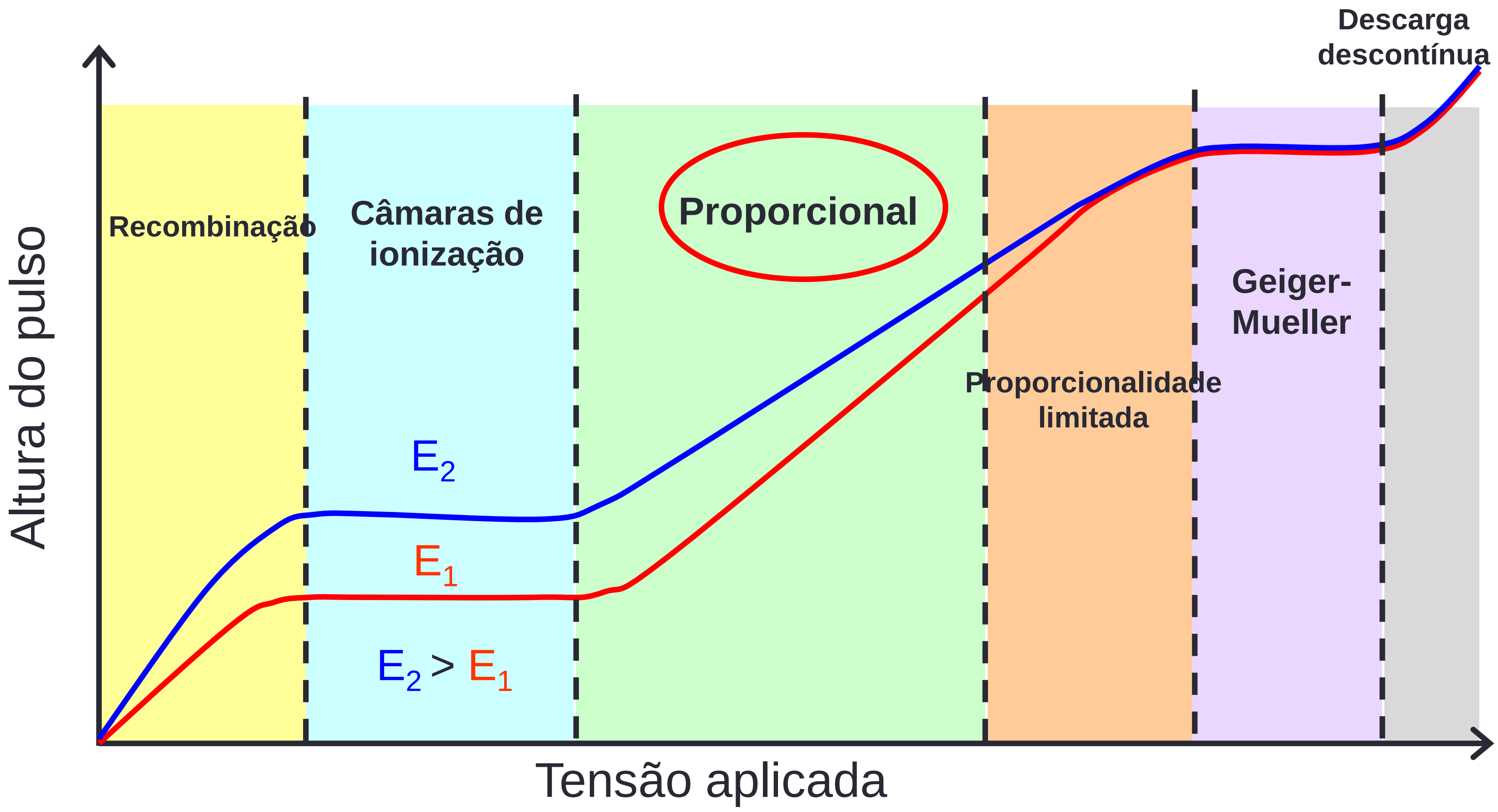
DETECTORES DE RADIAÇÃO

PARTE 2

PAULO R. COSTA

DETECTORES PROPORCIONAIS

Contadores proporcionais

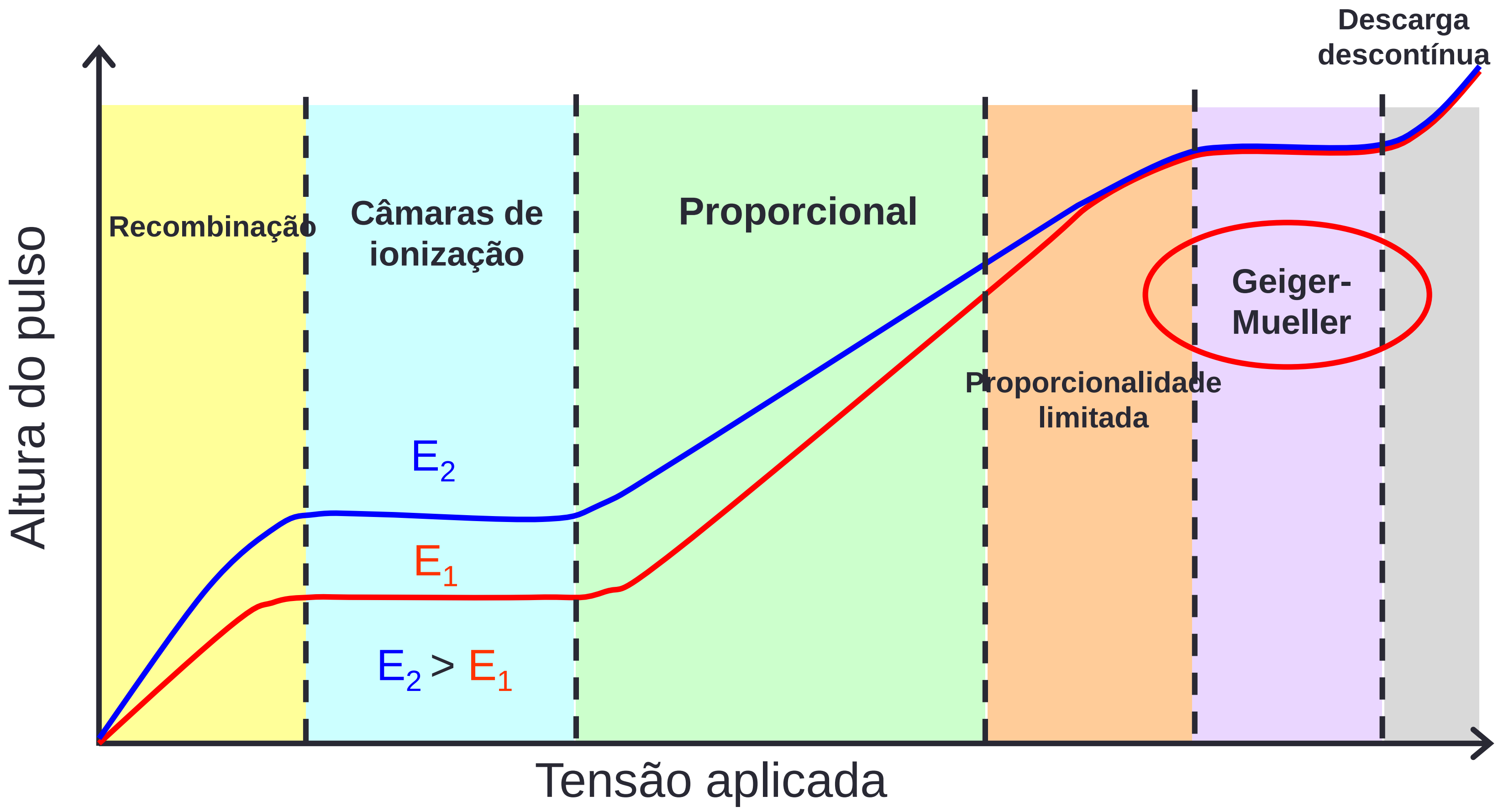


Contadores proporcionais

- Opera na região de multiplicação
  - Diferença de potencial aumenta a energia dos elétrons
    - Multiplicação das cargas
    - Fator constante a cada DDP
  - Sensibilidade maior que das câmaras de ionização
  - Variação do sinal para pequenas variações na tensão de alimentação

CONTADORES GEIGER-MÜLLER

Contadores Geiger-Müller



Contadores Geiger-Müller

- Uma única ionização no gás
  - Avalanche de ionizações
  - Sinal único independente da energia liberada no meio
- Em geral mistura de 2 gases
  - Gás nobre
  - Gás de extinção (*quenching*)
    - Pequena proporção
    - Ajuda na extinção da descarga produzida
    - Moléculas grandes que neutralizam os íons positivos

Contadores Geiger-Müller

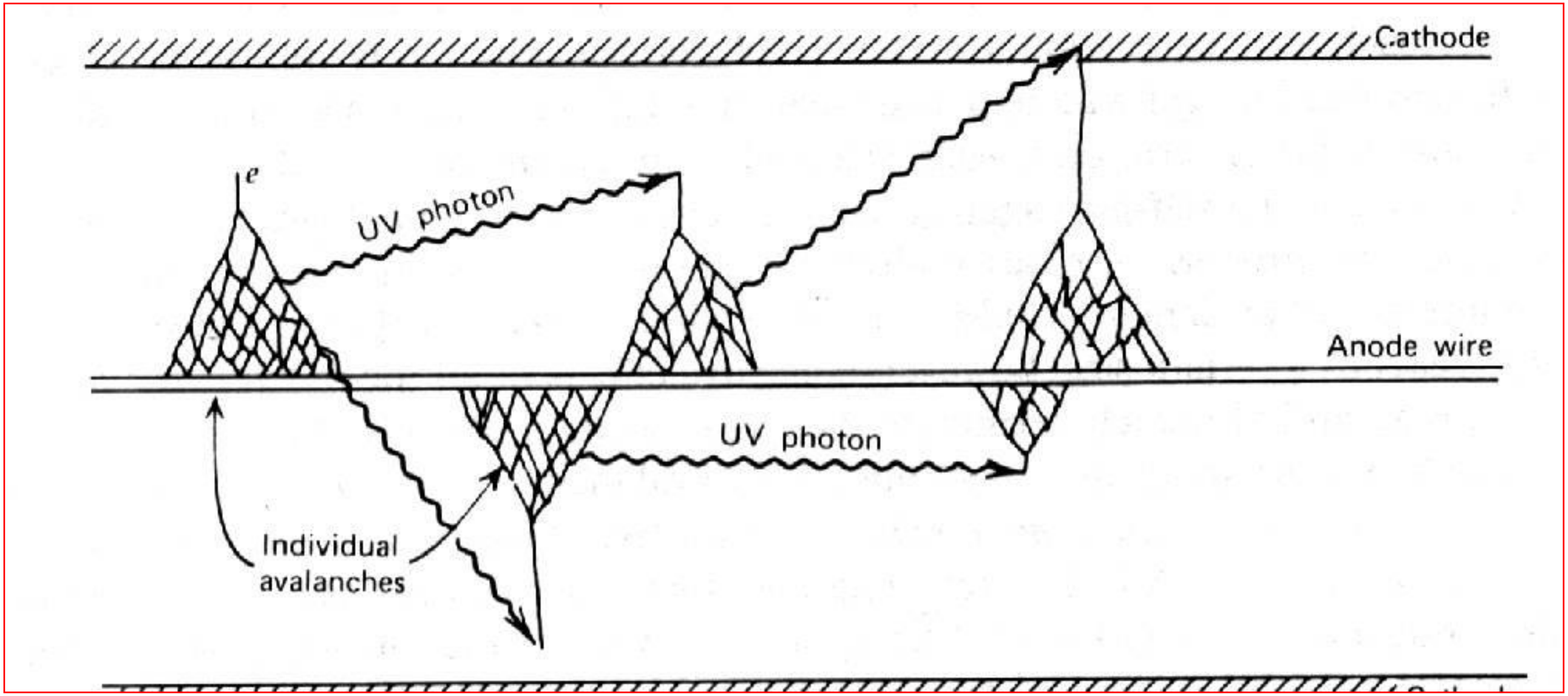
- Detector mais popular
  - Usado em proteção radiológica
  - Robusto e simples de utilizar

- Limitações
  - Tempo de resposta longo
    - Impede o uso em radiologia em geral
  - Não distingue o tipo ou a energia da radiação

Contadores Geiger-Müller

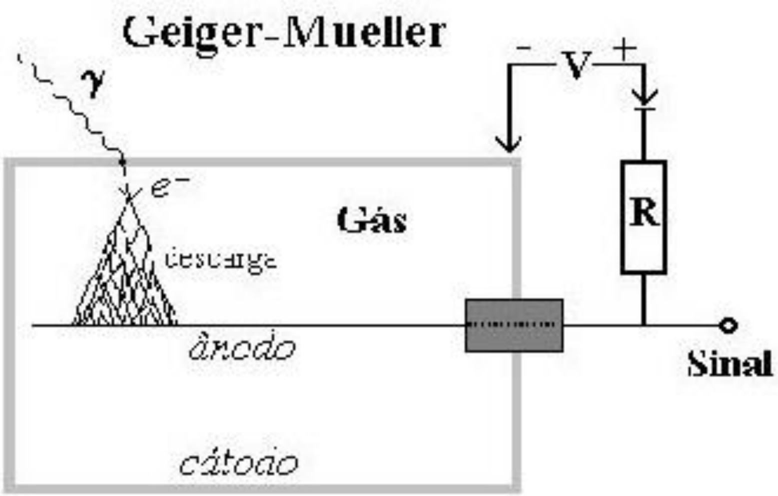
- Princípio de funcionamento
  - Avalanche de Townsend
    - Pode ser gerada por um único evento
    - Formação de moléculas excitadas do gás pela colisão com elétrons e íons secundários
    - Retorno ao estado fundamental com emissão visível ou UV
    - Reabsorção fotoelétrica dos fótons visível/UV
      - No gás
      - No catodo
    - Reinício do processo em avalanche

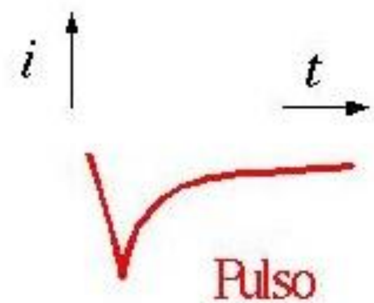
Contador Geiger-Mueller

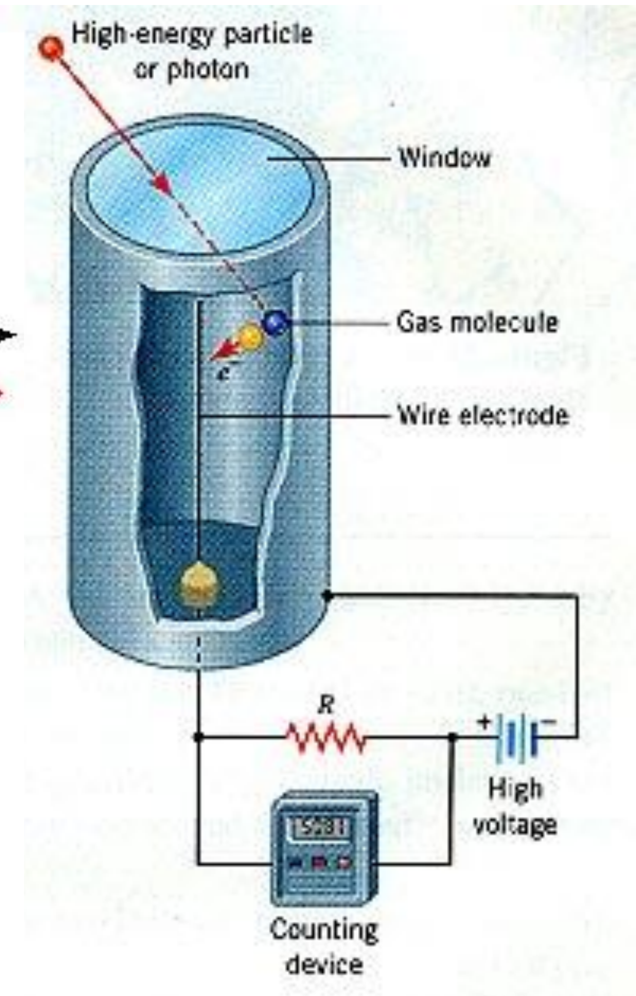


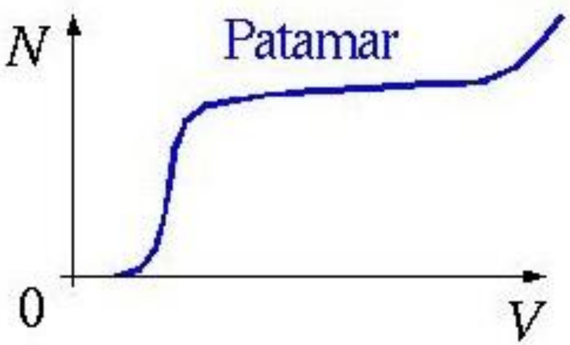
Avalanche de Townsend

Contador Geiger-Müller





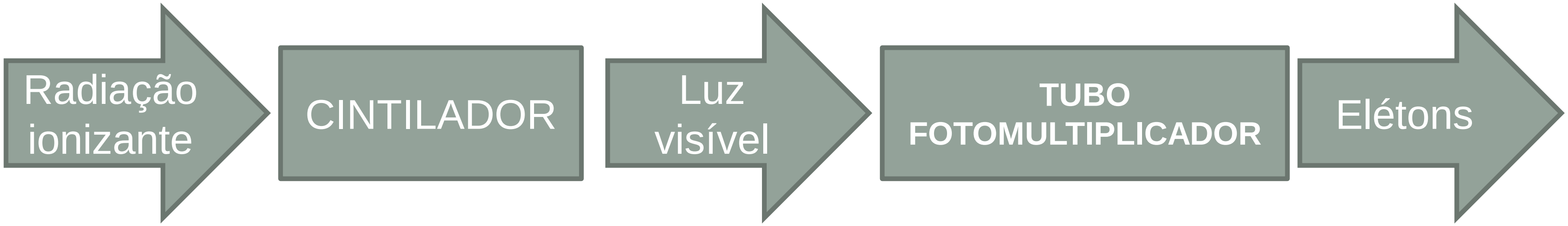




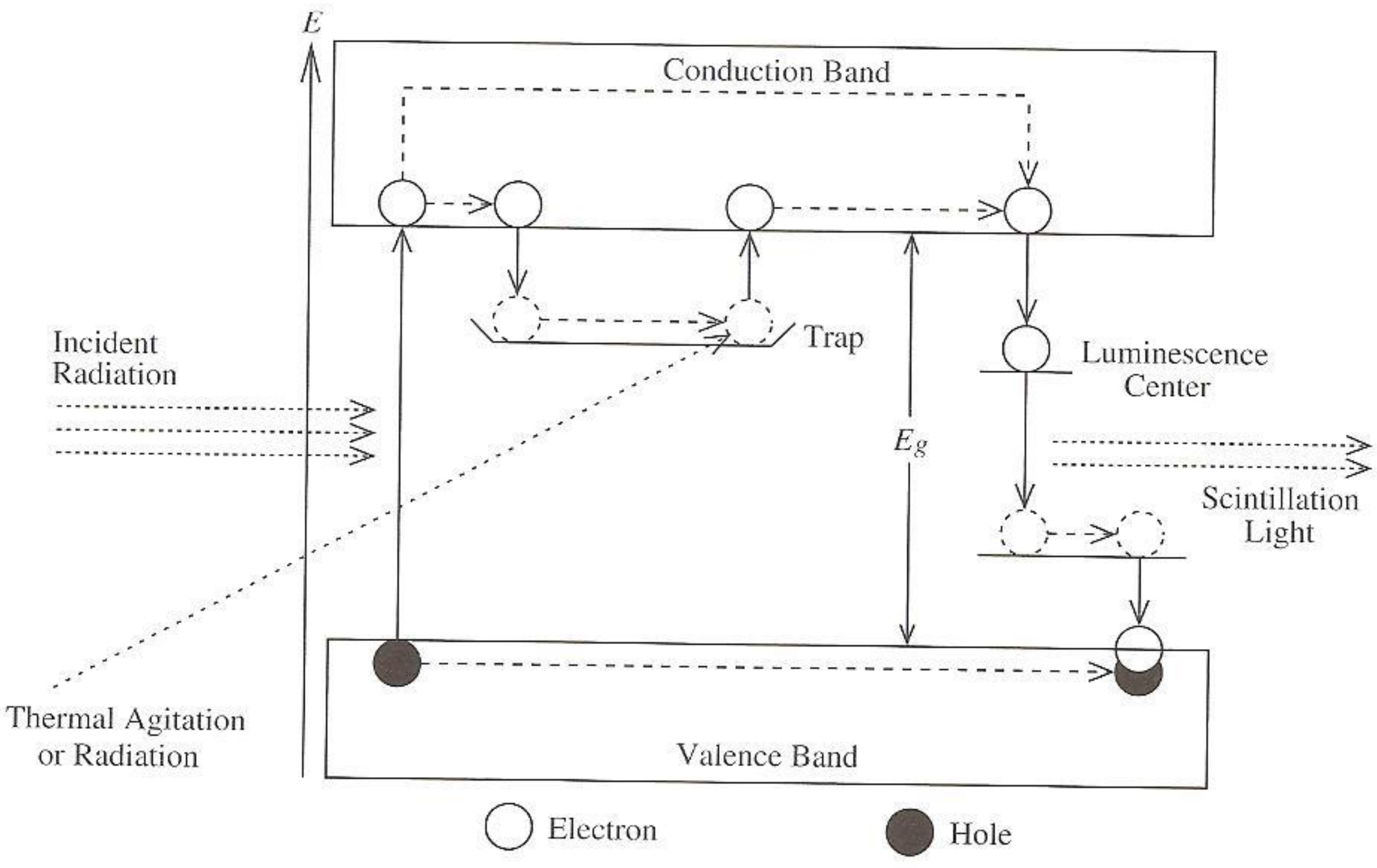
DETECTORES CINTILADORES/SEMICONDUTORES

Detectores Cintiladores

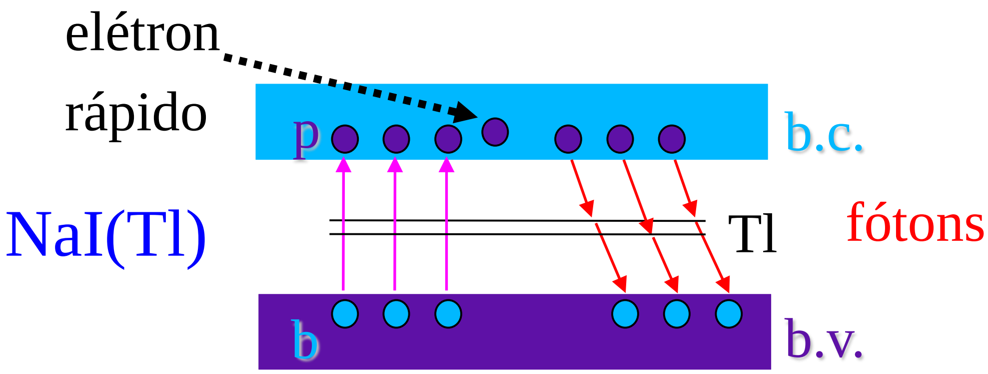
- Discriminação da energia dos fótons
  - Hartmut Kallmann – 1948
  - Emissão de luz por um cristal
    - Intensidade da luz proporcional à energia
- Categorias
  - Orgânicos
  - Inorgânicos



Mecanismo de cintilação



O cintilador de NaI(Tl)



NaI(Tl)

Iodeto de Sódio dopado com Tálio

Gap: ≈7 eV

Energia média por fóton: 3 eV

Produção de luz: 38 fótons de luz por keV

Eficiência na produção de luz

- Parâmetro mais importante
- Em geral, muito baixa
- Quantificada em fótons/MeV de radiação absorvida
- Dependência
  - Material do cintilador
  - Tipo de partícula incidente
  - Energia das partículas
  - Temperatura

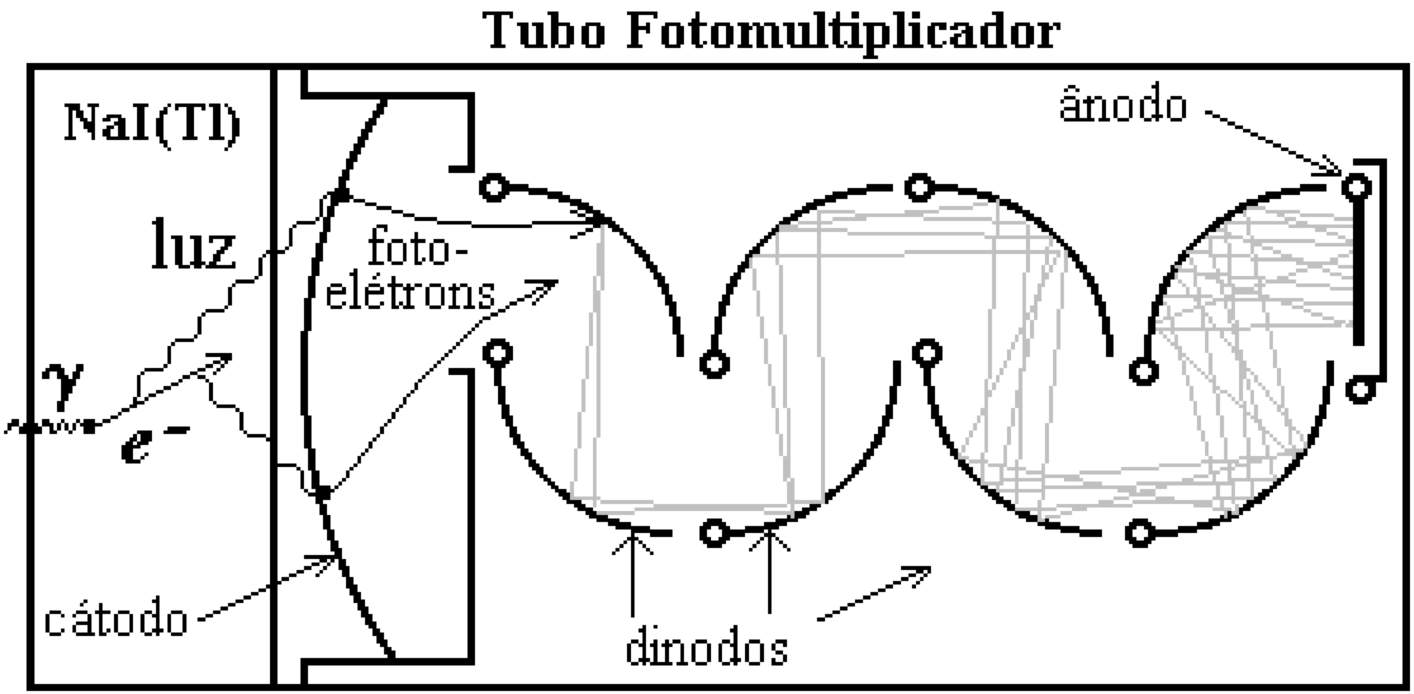
Eficiência de detecção - cintiladores

Eficiência na qual a energia perdida pela partícula incidente é convertida em fótons de cintilação

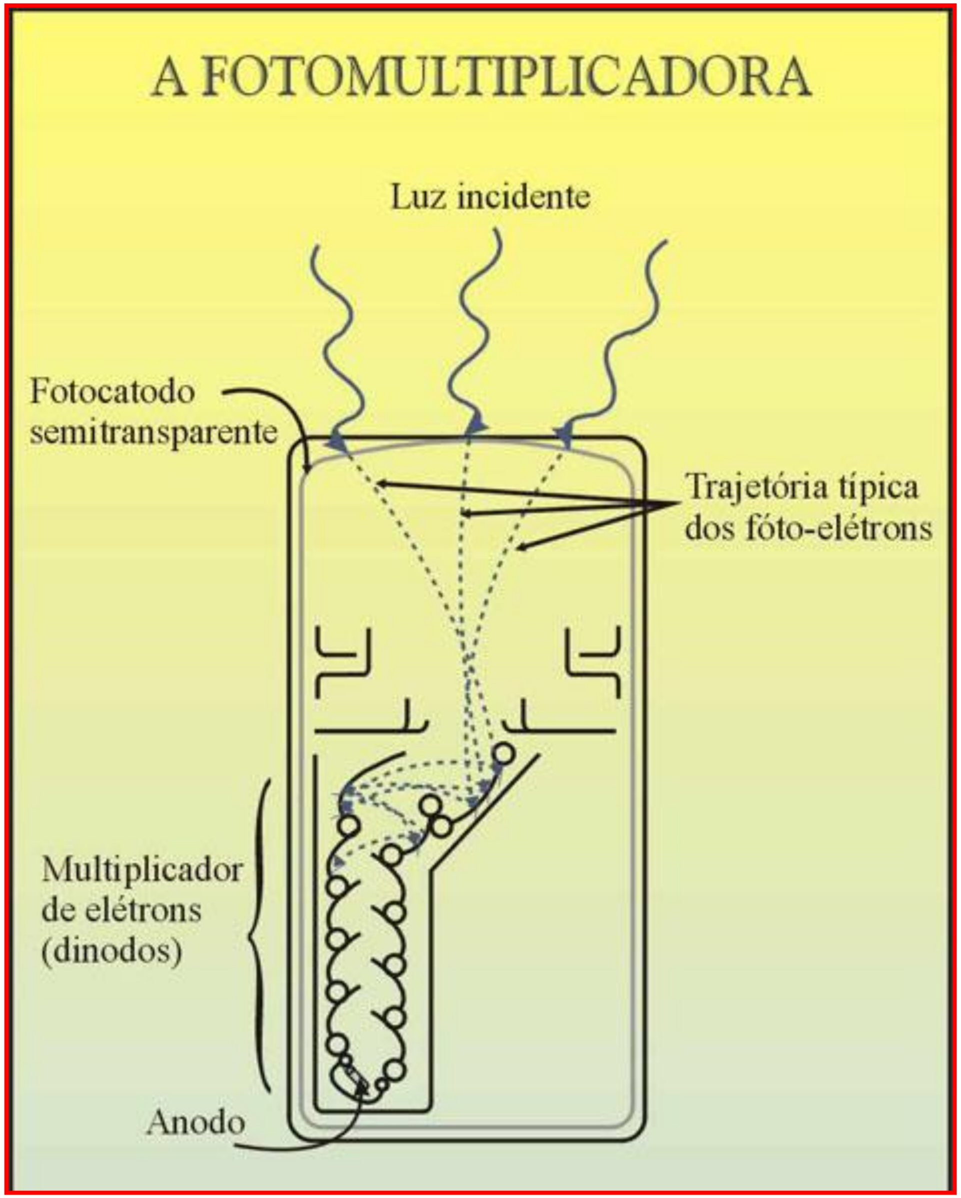
$$\eta = \frac{energia\ total\ dos\ fótons\ de\ cintilação}{energia\ depositada\ pela\ radiação\ incidente} = \frac{E_s}{E_i}$$

Processo complexo e de múltiplos passos !

O Tubo fotomultiplicador



Fator de multiplicação típico → 10^6



Material do fotocatodo deve apresentar baixa função de trabalho (1.5 a 2.0 eV)

(K-Cs, Na-K)

ΔV~100V (por dinodo)

Características principais

- Ganho da fotomultiplicadora ~ $5^N = 10^7$

  N é o número de estágios de multiplicação.
- *Características temporais dos cintiladores.*

  Tempo de decaimento

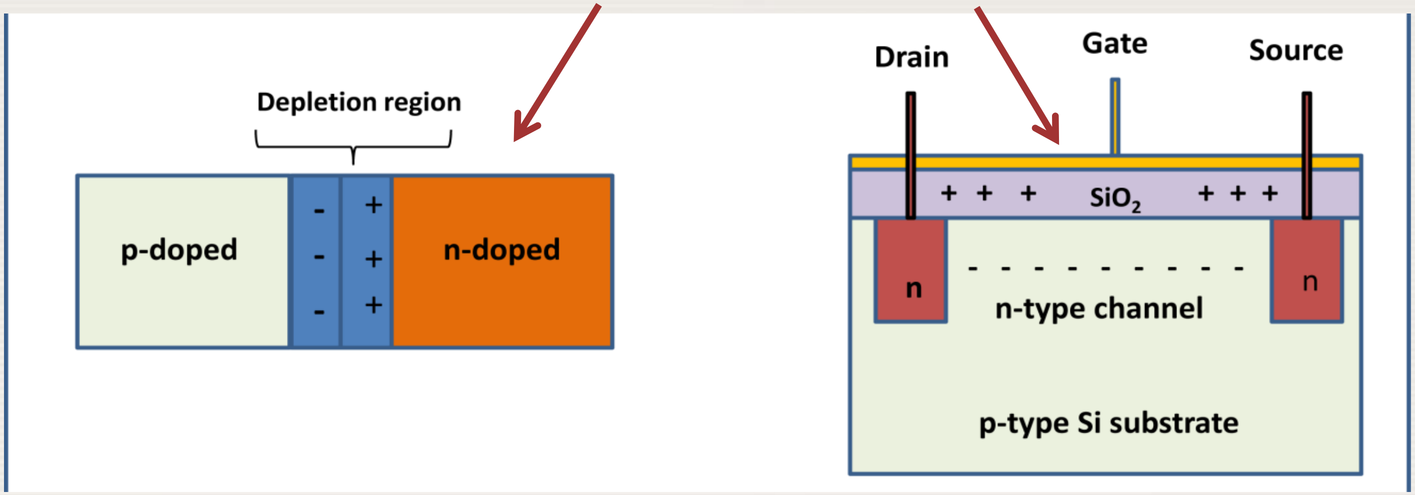
  Orgânicos: alguns ns

  Inorgânicos : centenas de ns
- *A fotomultiplicadora é sensível a campos magnéticos.*

21.4. SEMICONDUCTOR DOSIMETERS

Diagnostic radiology dosimeters based on semiconductor technology have found wide spread use

Two types are used: **silicon diodes** or **MOSFETs**



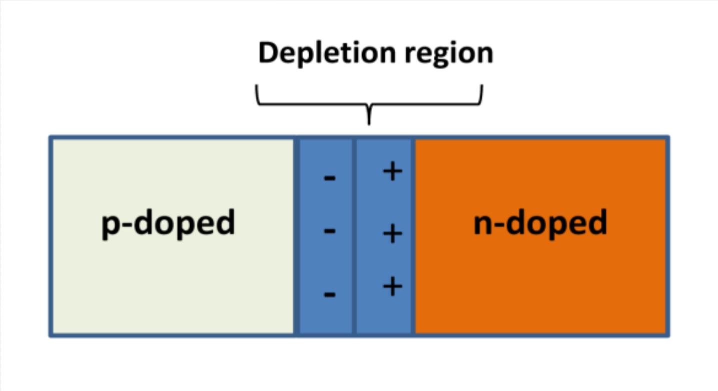
- Due to their small size and rigidness, they are convenient for use in many applications
- MOSFETs often require a connection to a bias voltage during irradiation
- They are mainly used in patient dosimetry

IAEA

21.4. SEMICONDUCTOR DOSIMETERS

21.4.1. Theory of operation

A **silicon diode dosimeter** is a p–n junction diode. In most cases p–type (rather than n-type) diodes are used for diagnostic radiology dosimeters, since they are less affected by radiation damage and have a much smaller dark current (noise)



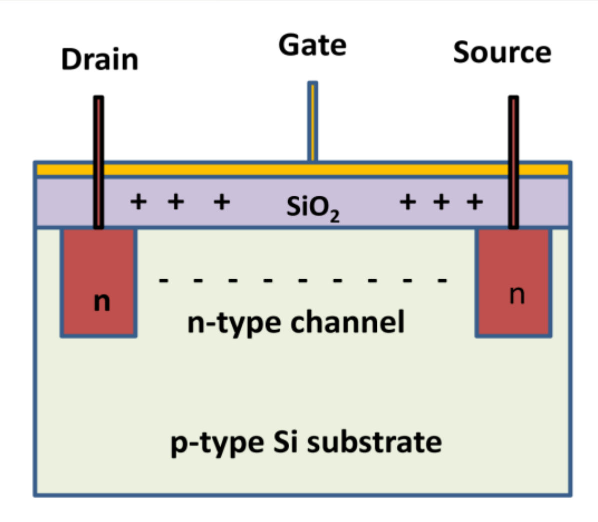
- When radiation falls on the diode, it produces electron–hole pairs in the body of the diode and a current, is generated in the reverse direction in the diode
- The number of such pairs is proportional to the incident radiation dose

- Due to the diode structure and the intrinsically formed potential difference, there is no need to apply a bias voltage across the p and n type diode regions to collect the charge liberated by the radiation

21.4. SEMICONDUCTOR DOSIMETERS

21.4.1. Theory of operation

A metal-oxide semiconductor field effect transistor **(MOSFET),** is a miniature silicon transistor. Its structure is equivalent to a planar capacitor with one of the electrodes replaced by a semiconductor



- When MOSFET dosimeters are exposed to radiation, electron-hole pairs are produced in the SiO_2. The positive charge carriers move in the direction of Si - SiO_2 interface, where they are trapped, building up a positive charge, which causes changes to the current in the n-type channel and leads to change of the gate bias voltage
- The gate bias voltage change is a linear function of absorbed dose. The integrated dose may be measured in real time or after irradiation

21.4. SEMICONDUCTOR DOSIMETERS

21.4.2. Application hints for semiconductors

The following practical points should be considered:

- The response of diodes and MOSFETs generally has a more pronounced energy dependence than that of ionization chambers

  The user should investigate the dosimeter's energy dependence characteristics. In this respect, measurements of the HVL with semiconductor detectors should be avoided

- The angular dependence of semiconductor detectors is comparable to that of plane parallel ionization chambers

  However, semiconductor detectors are sensitive to their positioning in the X ray field, especially to the direction of the heel effect

Detectores semicondutores para espectrometria

- Princípio de operação
  - http://www-physics.lbl.gov/~spieler/SLAC_Lectures/PDF/Sem-Det-I.pdf
  - http://www-physics.lbl.gov/~spieler/SLAC_Lectures/PDF/Sem-Det-II.pdf

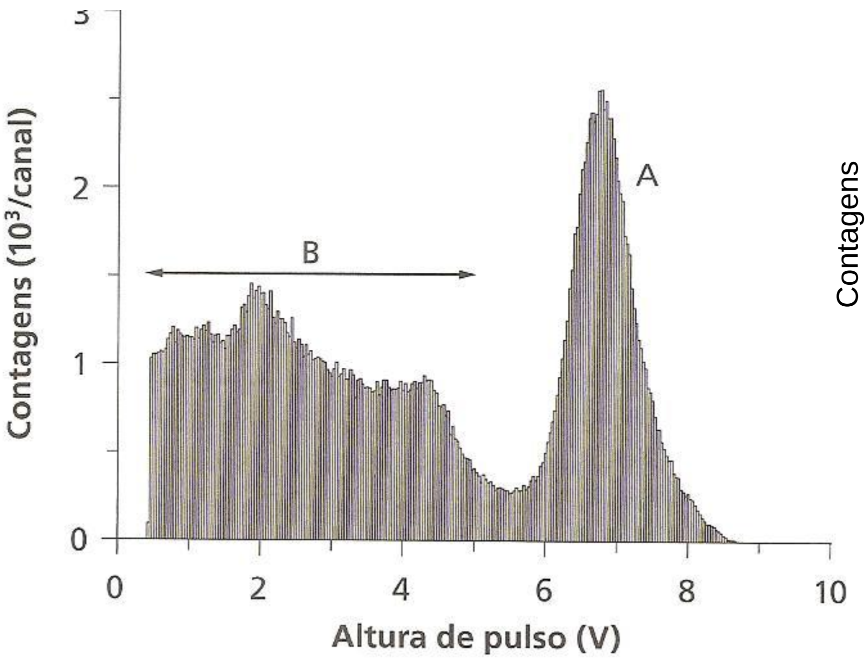
Material	Z	Bandgap [eV]	Mobility [cm^2/Vs]		Density g/cm^3
			electrons	holes	
Si	14	1.1	1350	480	2.3
Ge	32	0.7	3800	1800	5.3
Diamond	6	5.5	1800	1200	3.5
GaAs	31-33	1.5	8600	400	5.4
AlSb	13-51	1.6	200	700	4.3
GaSe	31-34	2.0	60	250	4.6
CdSe	48-34	1.7	50	50	
CdS	48-16	2.4	300	15	4.8
InP	49-15	1.4	4800	150	
ZnTe	30-52	2.3	350	110	
WSe_2	74-34	1.4	100	80	
BiI_3	83-53	1.7	680	20	
Bi_2S_3	83-16	1.3	1100	200	6.7
Cs_3Sb	55-51	1.6	500	10	
PbI_2	82-53	2.6	8	2	6.2
HgI_2	89-53	2.1	100	4	6.3
CdTe	48-52	1.5	1100	100	6.1
CdZnTe	48-30-52	1.5-2.4			

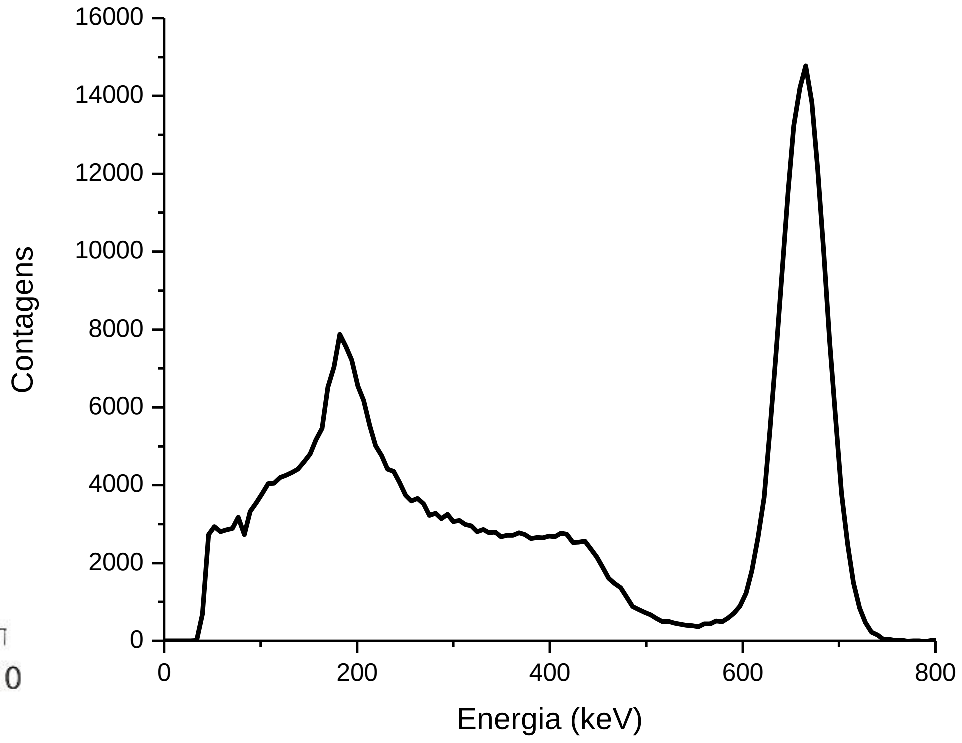
Semiconductor Detectors
Part 1

Helmuth Spieler

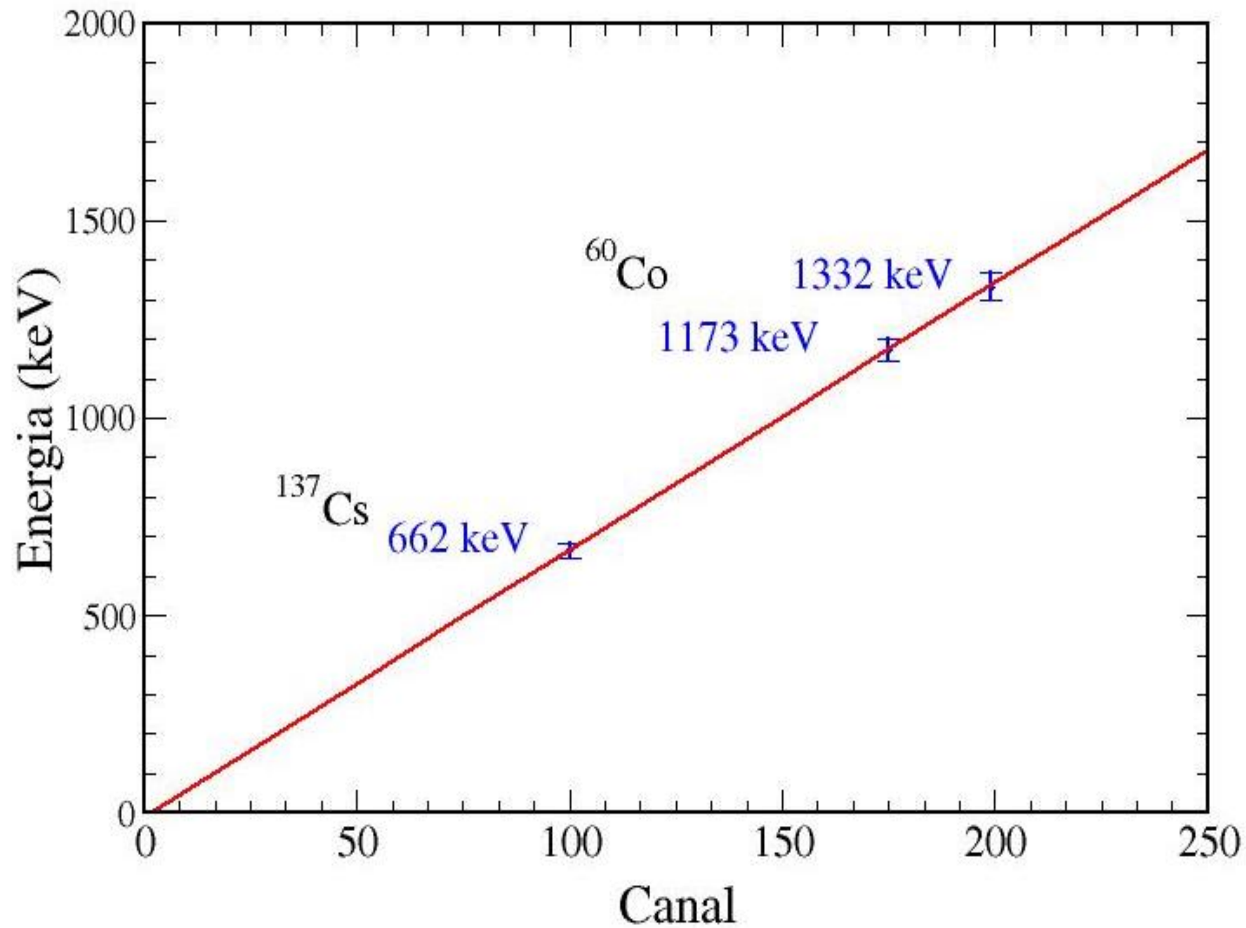
Physics Division
Lawrence Berkeley National Laboratory

Espectros de energia





Calibração de energia

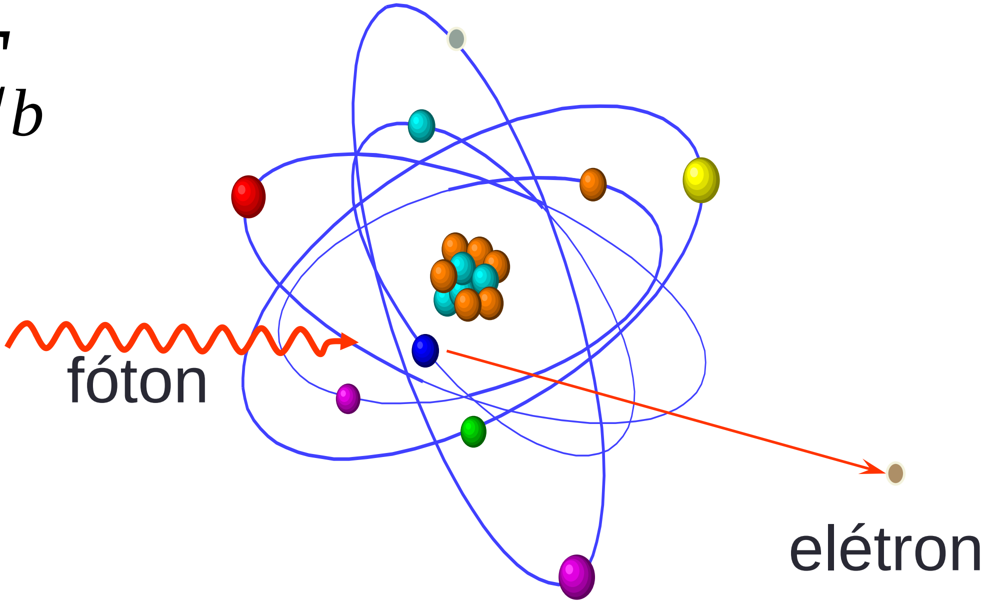


E(keV) = a + b C

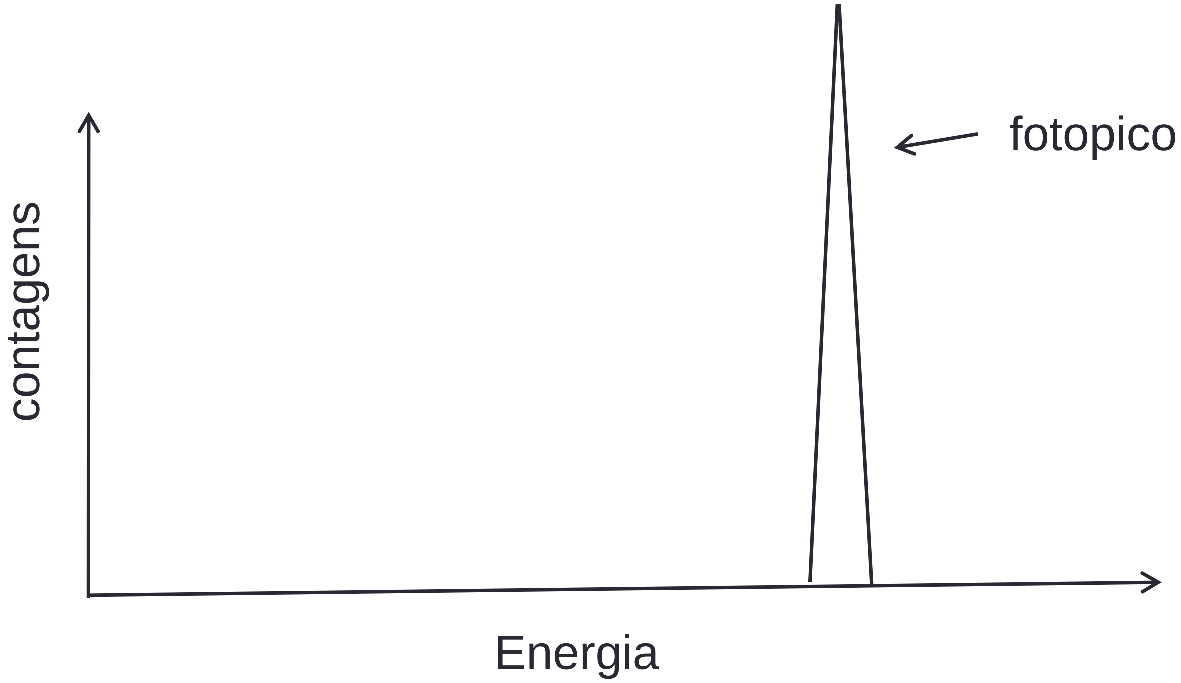
Deposição total da energia do fóton: efeito fotoelétrico

- Efeito Fotoelétrico
  - Deposição total de energia
  - Elétron colocado em movimento

$$E_{e^-} = h\nu - E_b$$

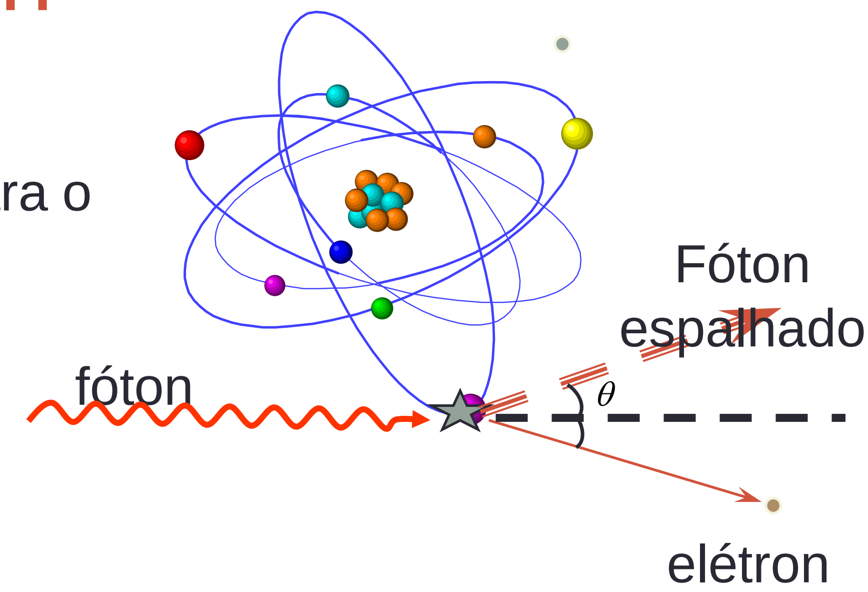


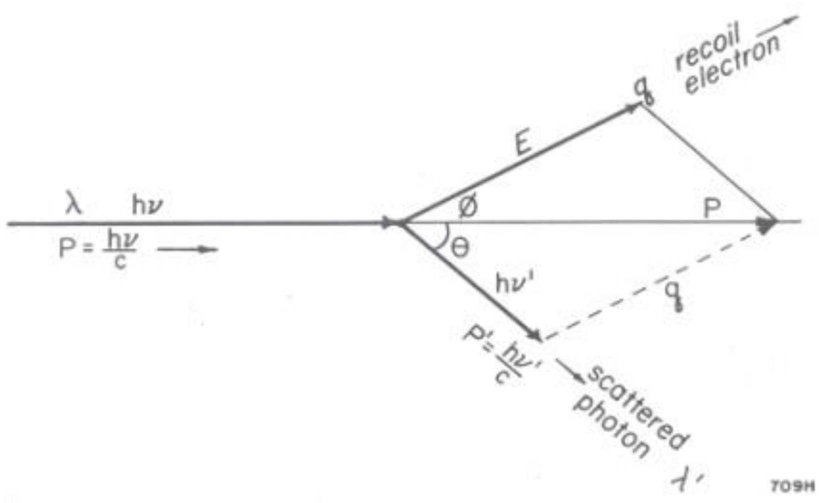
Deposição total da energia do fóton: efeito fotoelétrico



Deposição parcial de energia: Espalhamento Compton

- Compton
  - Transferência parcial de energia para o elétron
  - Fóton espalhado residual





$$h\nu' = \frac{h\nu}{1+\left(h\nu/m_0c^2\right)(1-\cos\theta)}$$

$$E_{e^-} = h\nu\left[\frac{\left(h\nu/m_0c^2\right)(1-\cos\theta)}{1+\left(h\nu/m_0c^2\right)(1-\cos\theta)}\right]$$

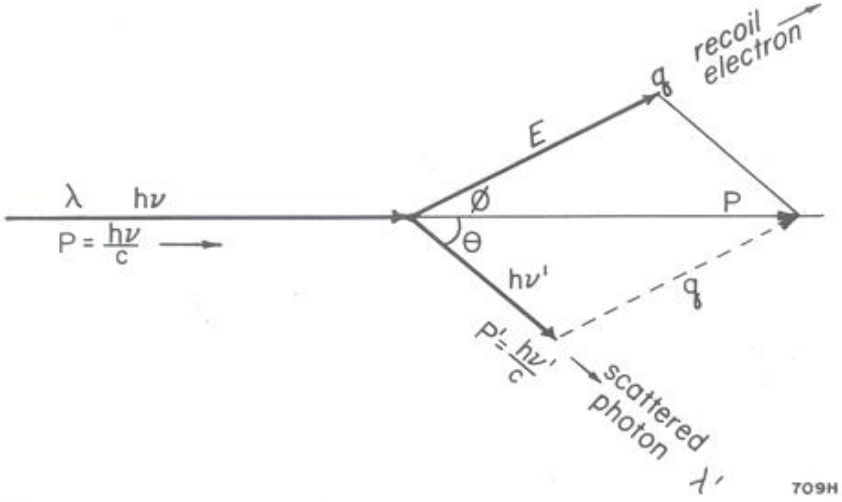
Deposição parcial de energia: Espalhamento Compton

- Choque frontal

$$\theta \approx \pi \qquad \phi \approx 0$$

$$h\nu'\big|_{\theta=\pi} = \frac{h\nu}{1 + 2\left(h\nu / m_0c^2\right)}$$

$$E_{e^-}\big|_{\theta=\pi} = h\nu\left[\frac{2\left(h\nu / m_0c^2\right)}{1 + 2\left(h\nu / m_0c^2\right)}\right]$$



distribuição angular

$$0 \le \theta \le 180^0$$

$$0 \le \phi \le 90^0$$

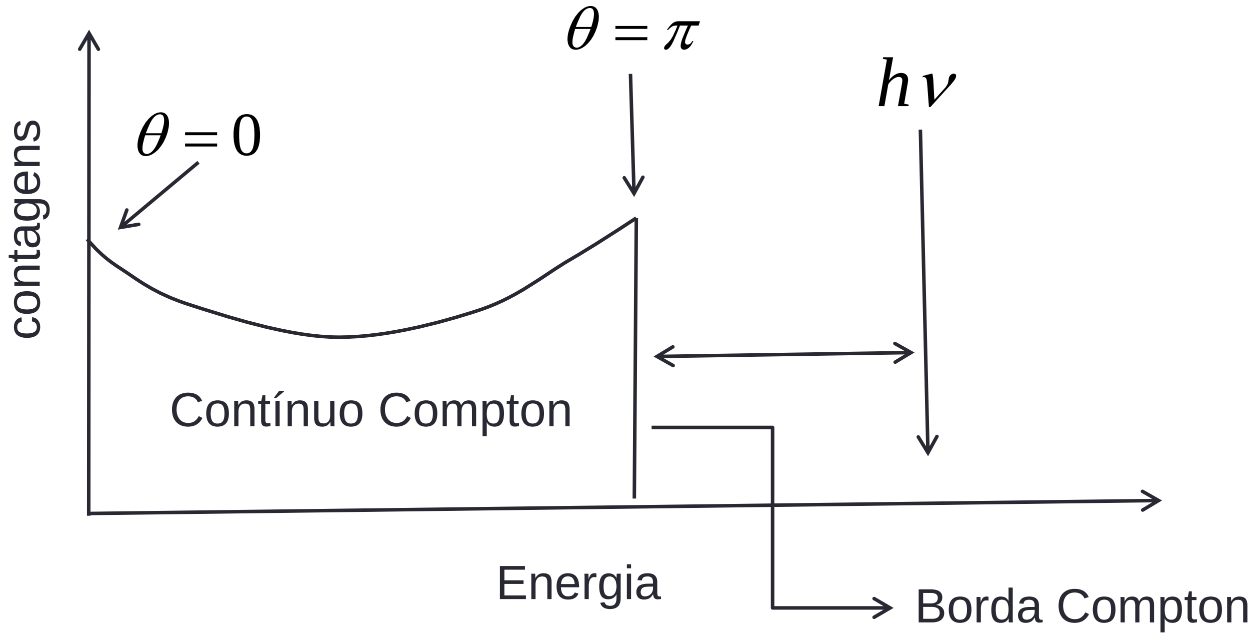
- Choque leve

$$\theta \approx 0 \quad \phi \approx 90^o$$

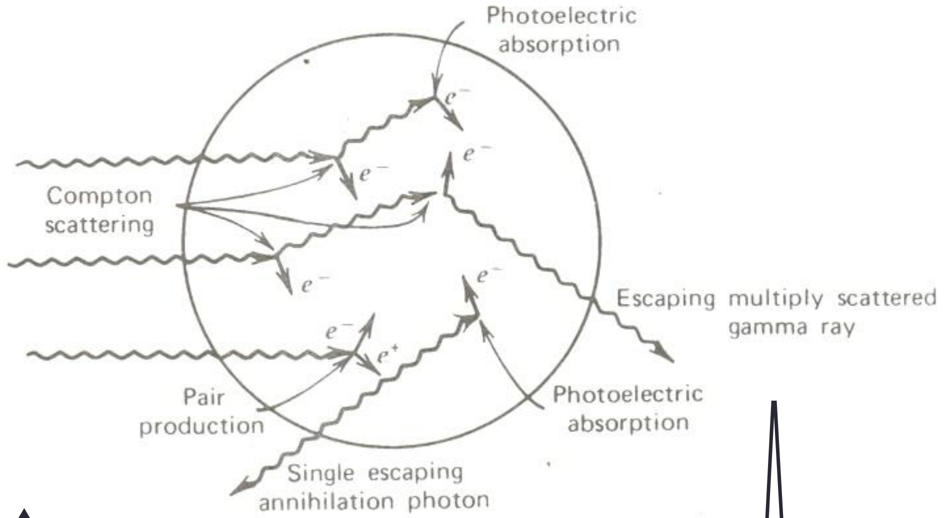
$$E \approx 0$$

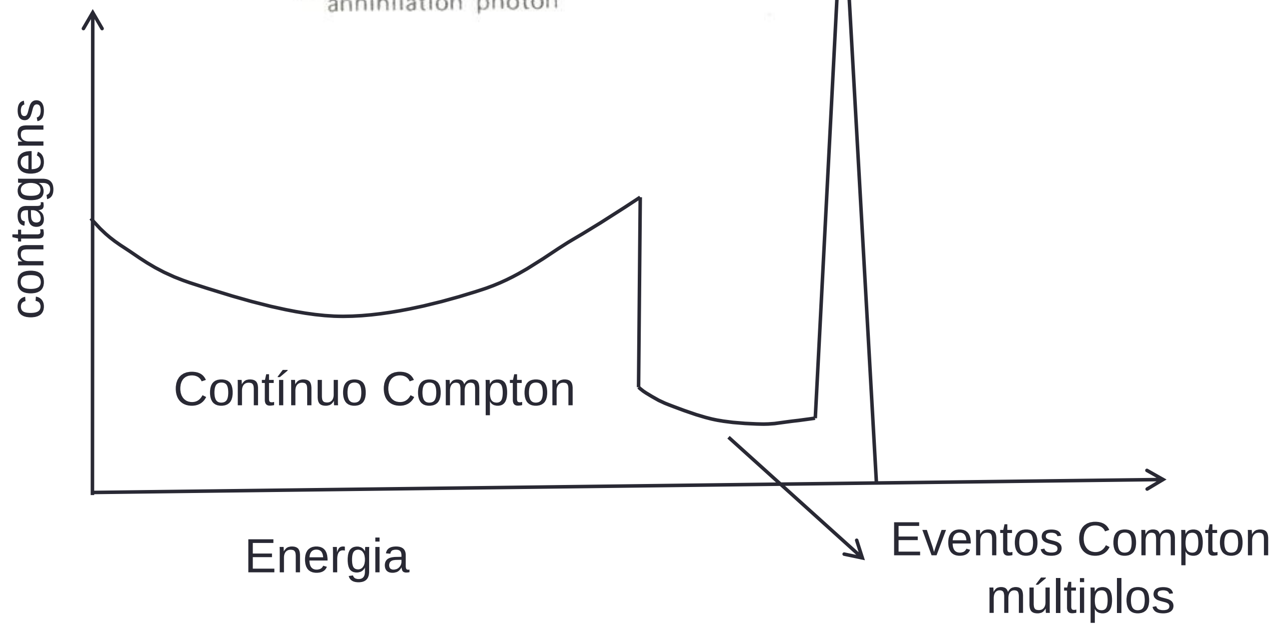
$$h\nu' \approx h\nu$$

Borda Compton

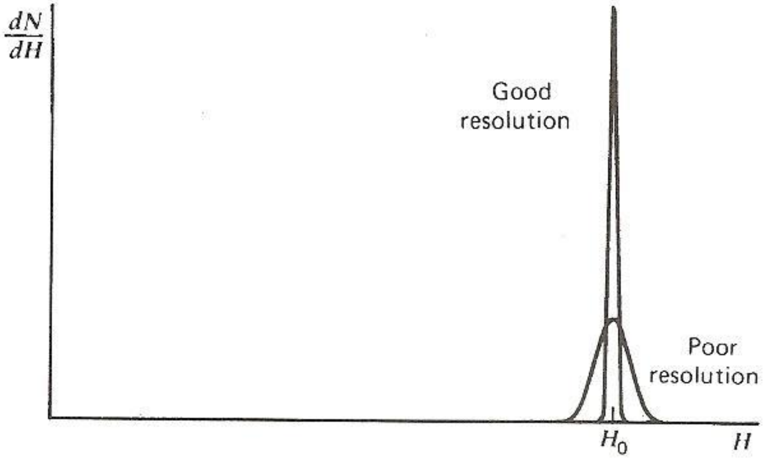


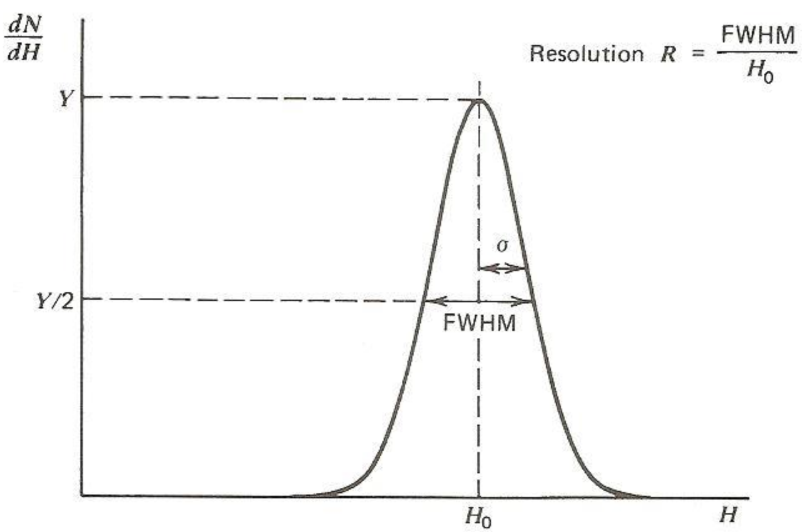
Eventos Compton múltiplos

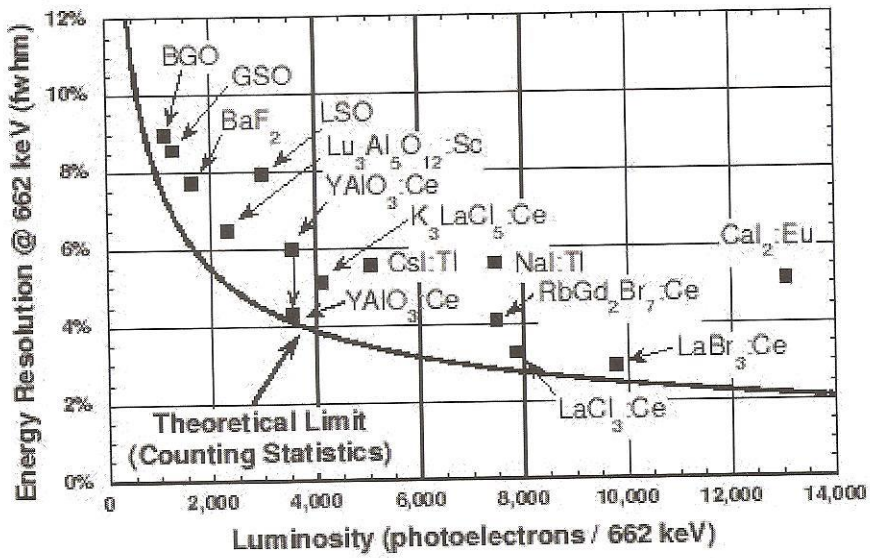




Produção de luz/cargas *vs* resolução energética

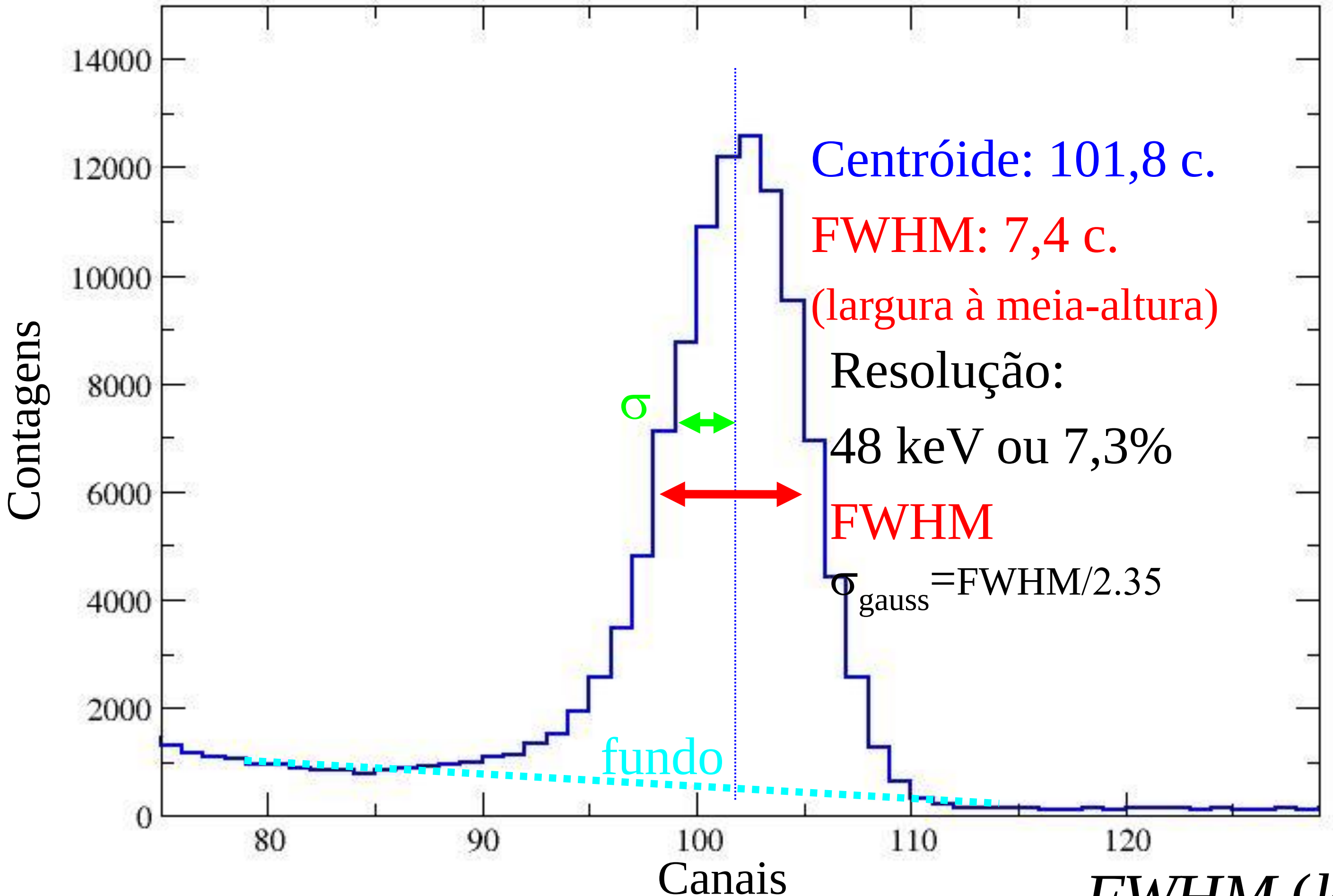






Resolução em energia

Ex: ^{137}Cs - 662 keV



$$R(\%) = \frac{FWHM\,(keV)}{Fotopico(keV)} \times 100$$

Resolução energética

$$R(\%) \equiv \frac{FWHM}{E_{fotopico}} = K\frac{\sqrt{E}}{E} = \frac{K}{\sqrt{E}}$$

$$\ln(R) = \ln(K) - \frac{1}{2}\ln(E)$$

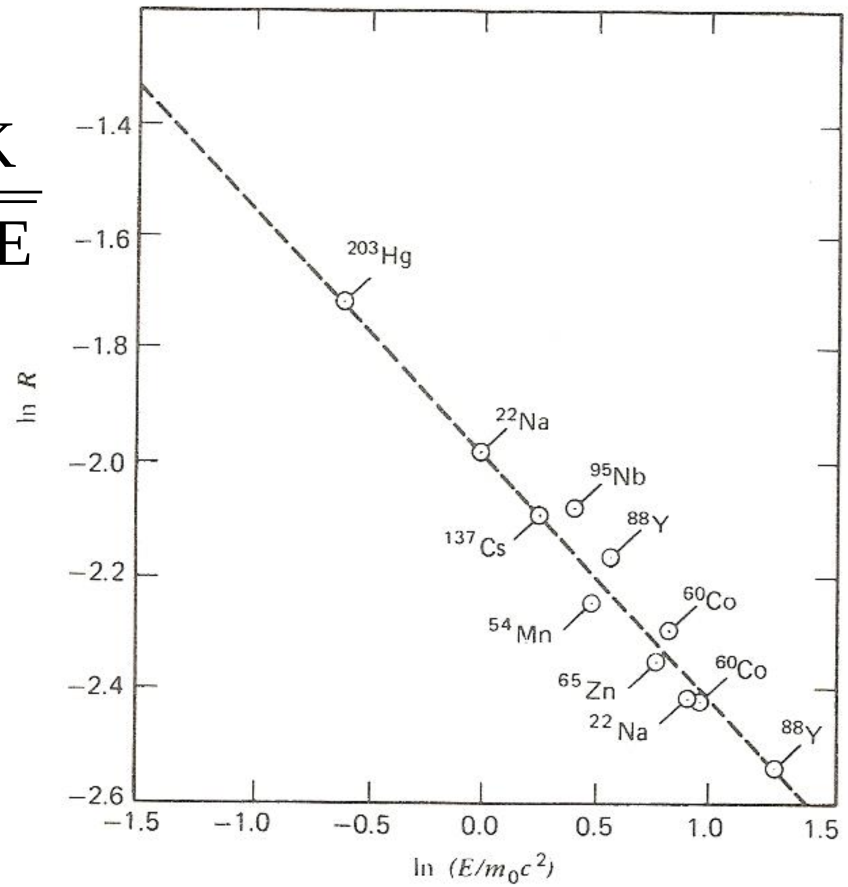
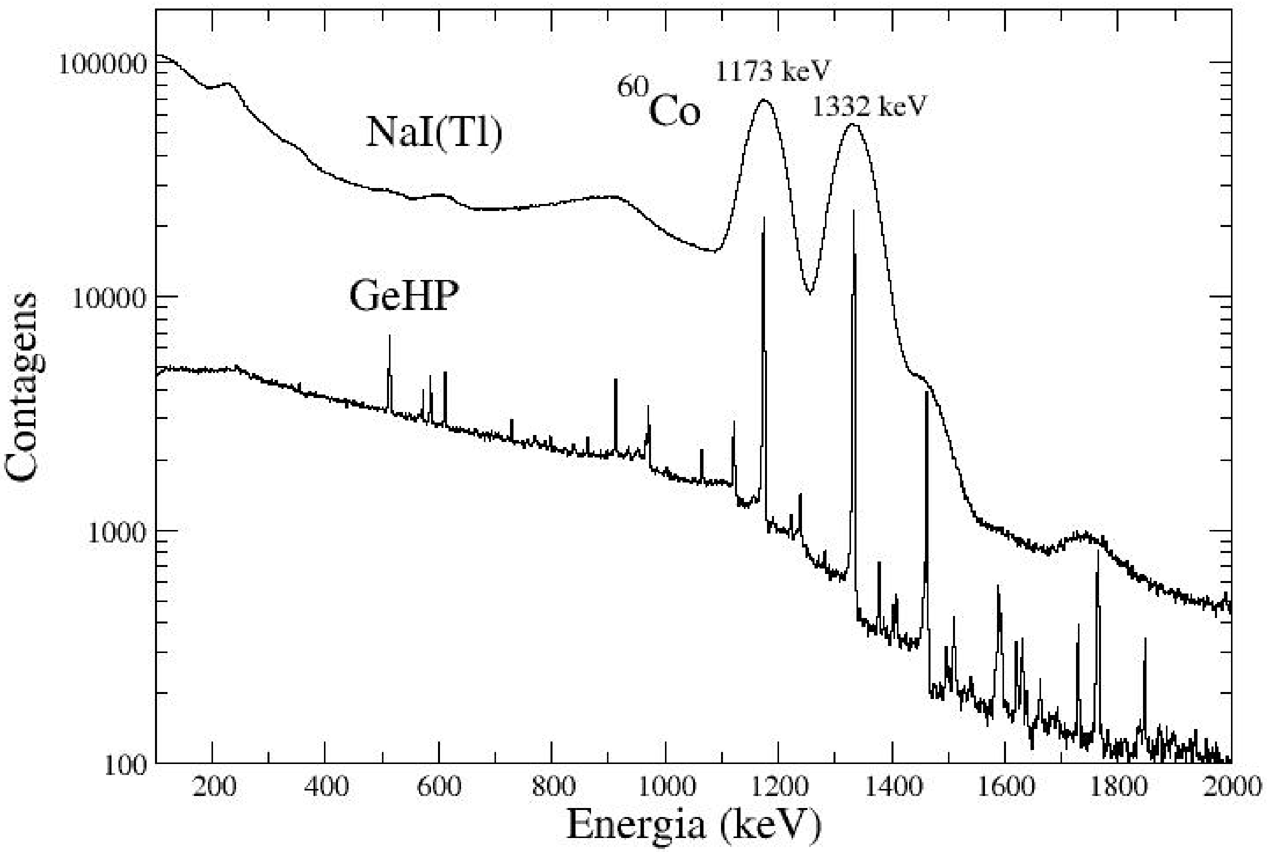
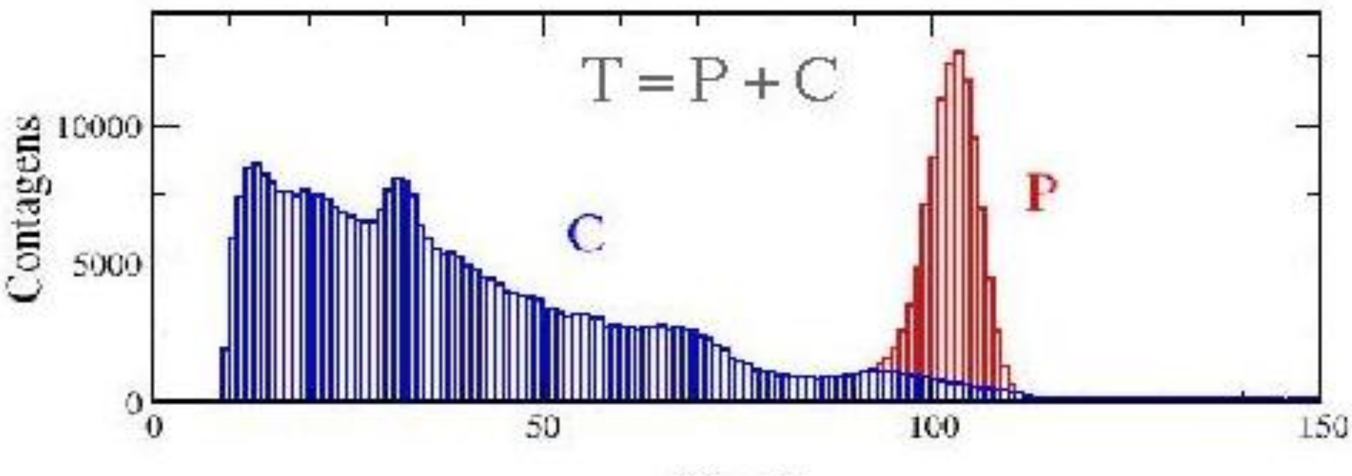


Figure 10.17 Experimentally measured resolution R from a NaI(Tl) scintillation detector for various gamma-ray energies E. (From Beattie and Byrne.[16])

Espectros de raios γ de uma fonte de ^{60}Co obtidos com um cintilador de NaI(Tl) e com um detector semicondutor de germânio (GeHP).



Eficiência de detecção



$$f = \frac{P}{T}$$

Correção para Eficiência do detector

Contagens brutas

$$C_c(E) = \frac{C_b(E)}{e(E)}$$

Eficiência

Contagens corrigidas

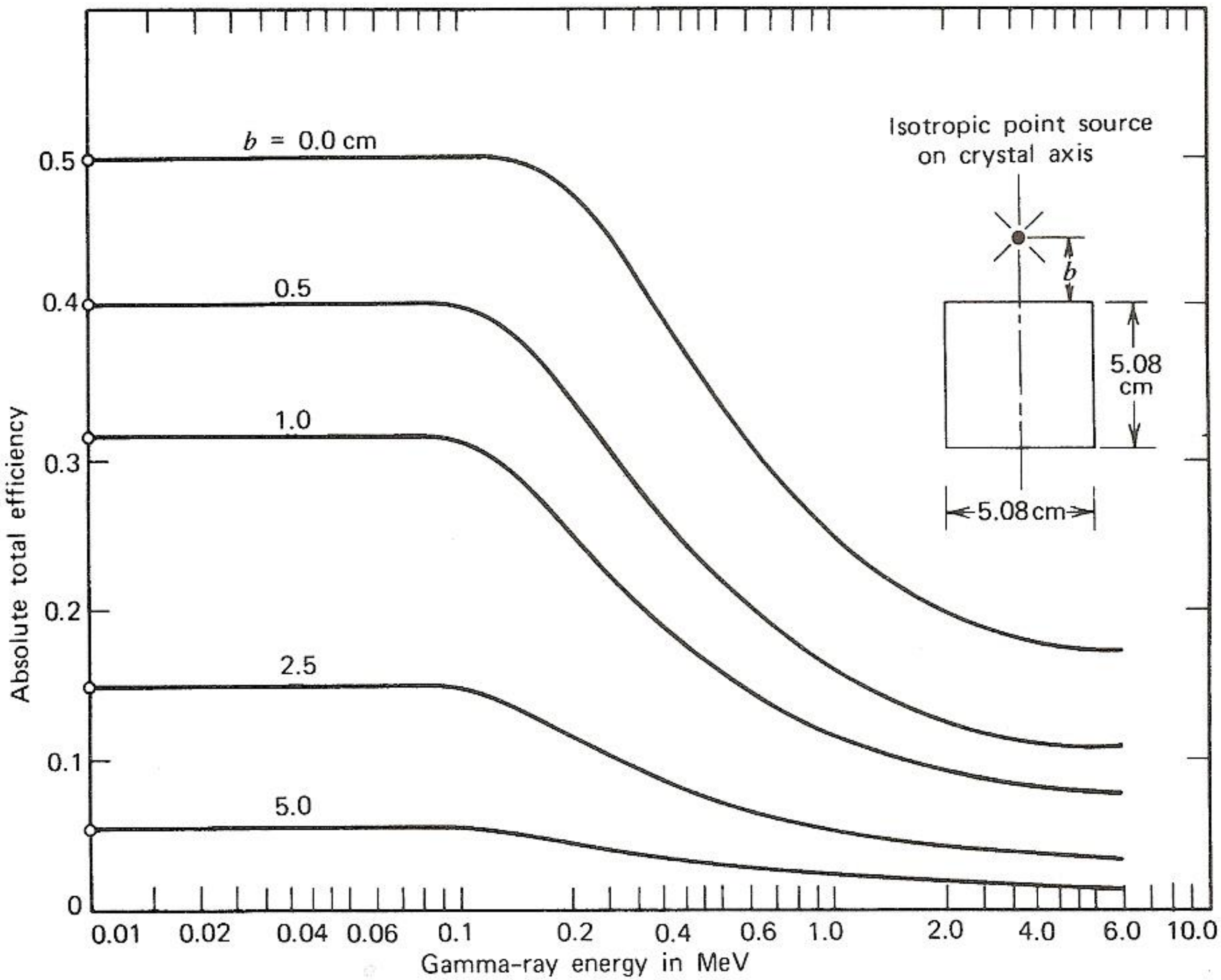


Figure 10.22 The absolute total efficiency calculated for a 5.08 cm × 5.08 cm solid cylindrical NaI(Tl) scintillator. Different values of the source location are shown. (From Snyder.[28])

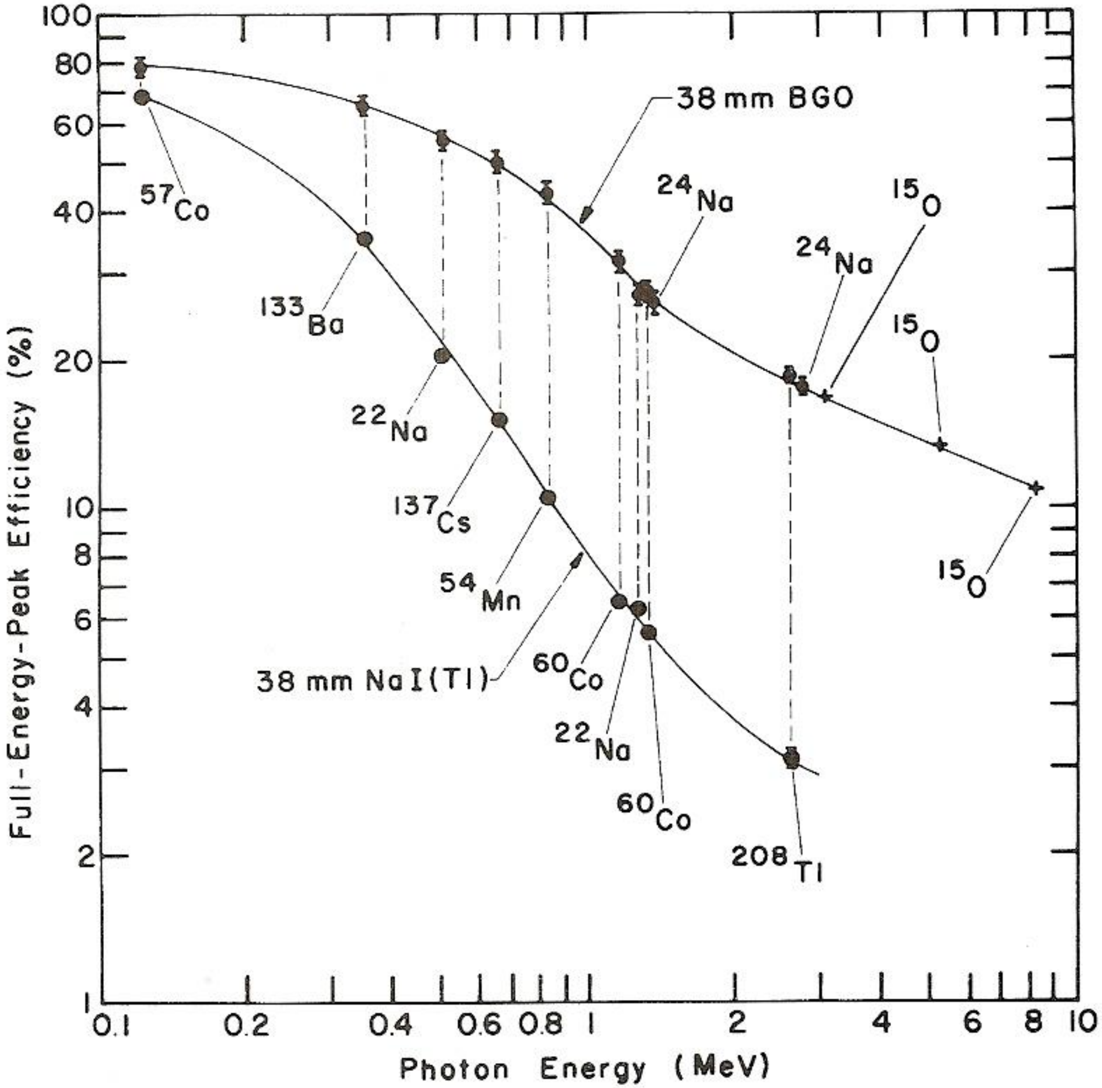


Figure 10.28 Intrinsic peak efficiencies for BGO and NaI(Tl) scintillators of equal 38 mm × 38 mm size. Radioisotope sources used for various photon energies are indicated. (From Evans and Orndoff.[40])

Metodologia experimental para medições de espectros de raios X em mamografia:

- Espectrômetro de raios X

Fonte: Josilene Santos, exame de qualificação, IFUSP 2016

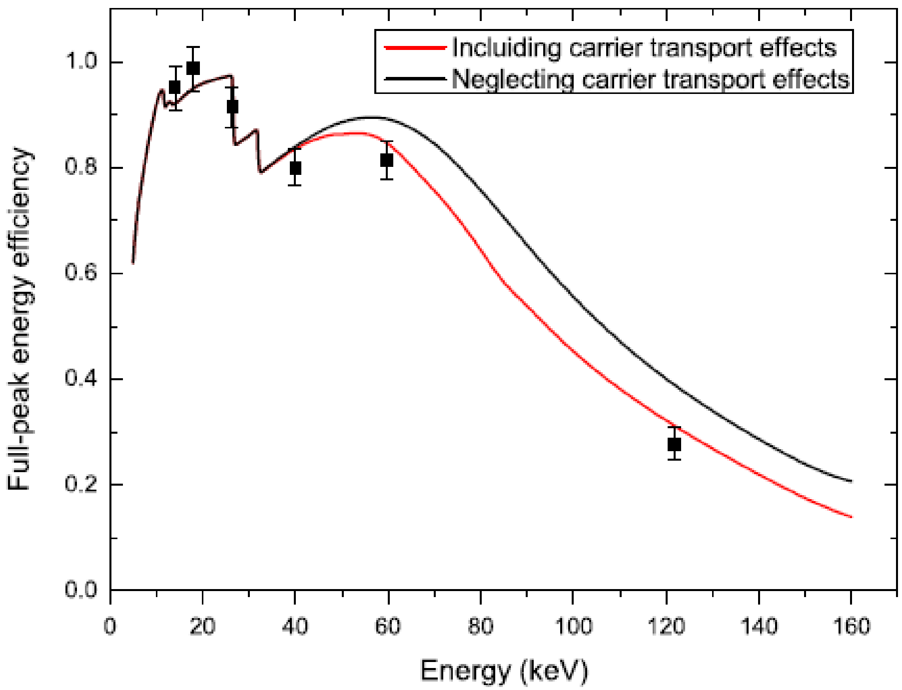


Fig. 3. Simulated and experimental full-energy peak efficiencies for the CdTe detector.

GRUPO DE
DOSIMETRIA
DAS RADIAÇÕES
e FÍSICA MÉDICA

IFUSP - Instituto de Física da USP

Applied Radiation and Isotopes 100 (2015) 32–37

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Monte Carlo simulation of the response functions of CdTe detectors to be applied in x-ray spectroscopy

CrossMark

A. Tomal [a,*], J.C. Santos [c], P.R. Costa [c], A.H. Lopez Gonzales [c], M.E. Poletti [b]

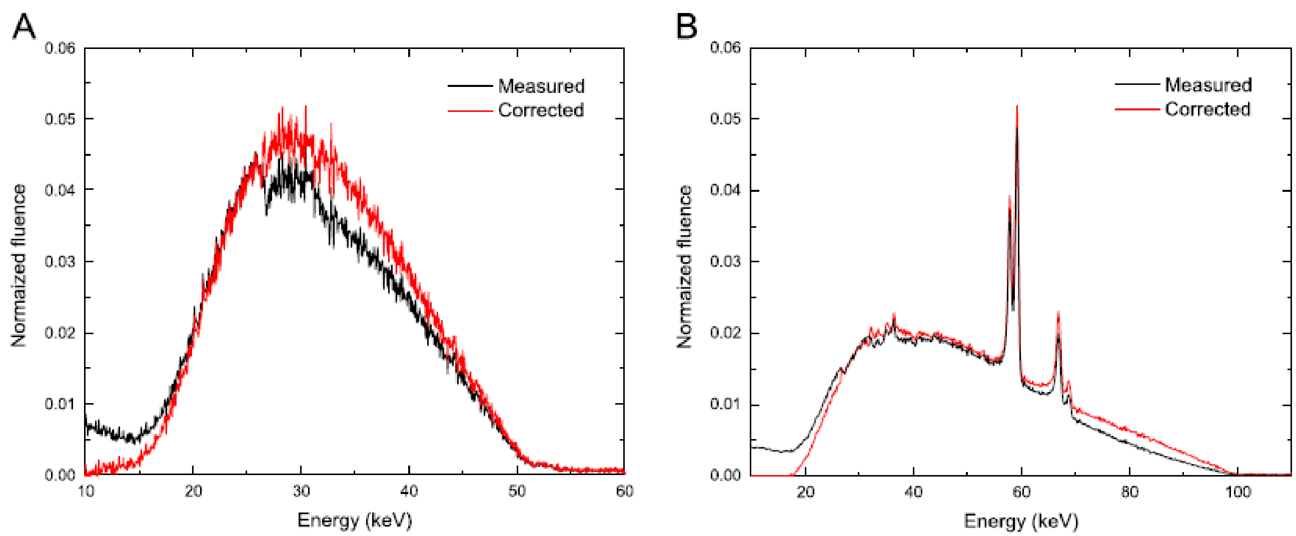
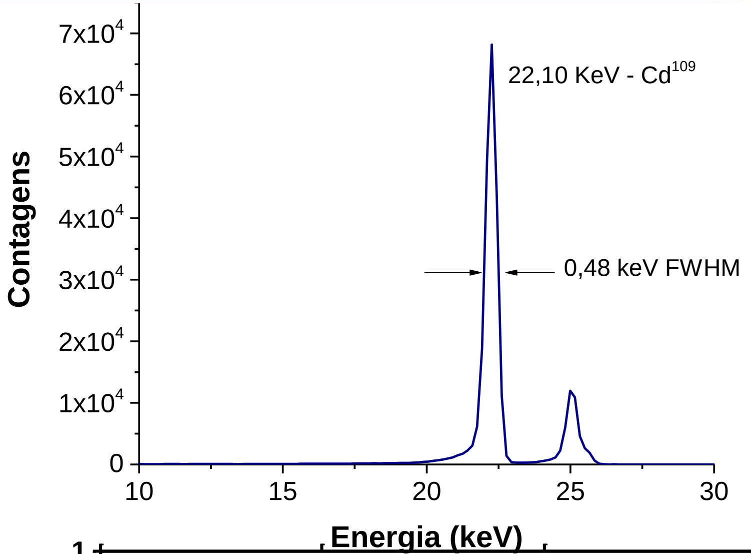


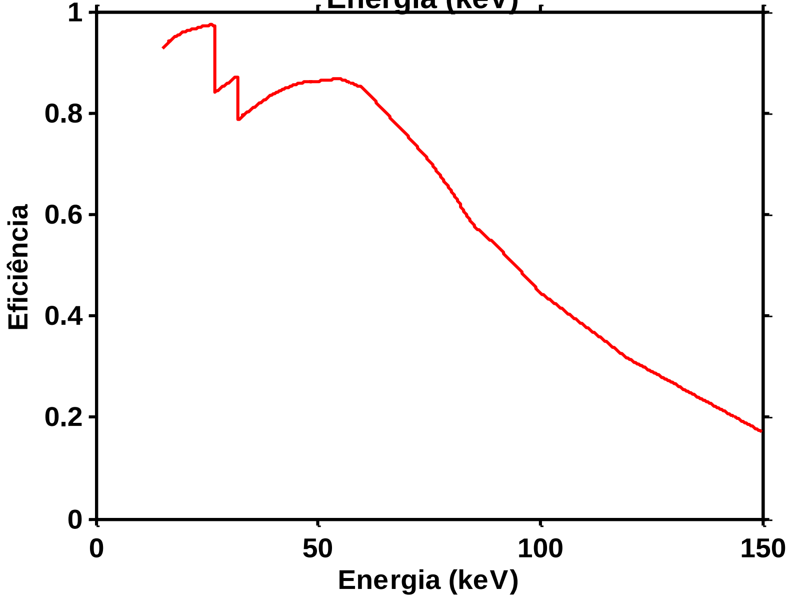
Fig. 5. Measured and corrected x-ray spectra obtained with CdTe detectors for (a) 50 kVp and (b) 100 kVp.

Espectrômetro de raios X

GRUPO DE DOSIMETRIA DAS RADIAÇÕES e FÍSICA MÉDICA
IFUSP - Instituto de Física da USP

- Detector de telureto de cádmio (CdTe) de 9 mm^2
- É um aparelho compacto e não necessita de refrigeração criogênica.
- resfriamento termoelétrico (célula Peltier)
- PX4: processamento, MCA, Interface USB, fonte
- Software ADMCA
- Kit de colimadores de 25 - 2000μm





Fonte: Josilene Santos, exame de qualificação, IFUSP 2016

DETECTORES DOSIMÉTRICOS

Calorímetro

- Maneira mais direta de avaliar dose
  - Isolamento térmico do material irradiado
    - Toda a energia absorvida foi utilizada para aumentar a energia

$$\Delta T = \frac{E_{ab}(1-\delta)}{mc} = \frac{\bar{D}(1-\delta)}{c}$$

Energia média absorvida (E_{ab})

Dose absorvida média ($\bar{D}$)

Calor específico (c)

Defeito térmico (δ): Fração da energia absorvida que não se transforma em calor

Termoluminescência

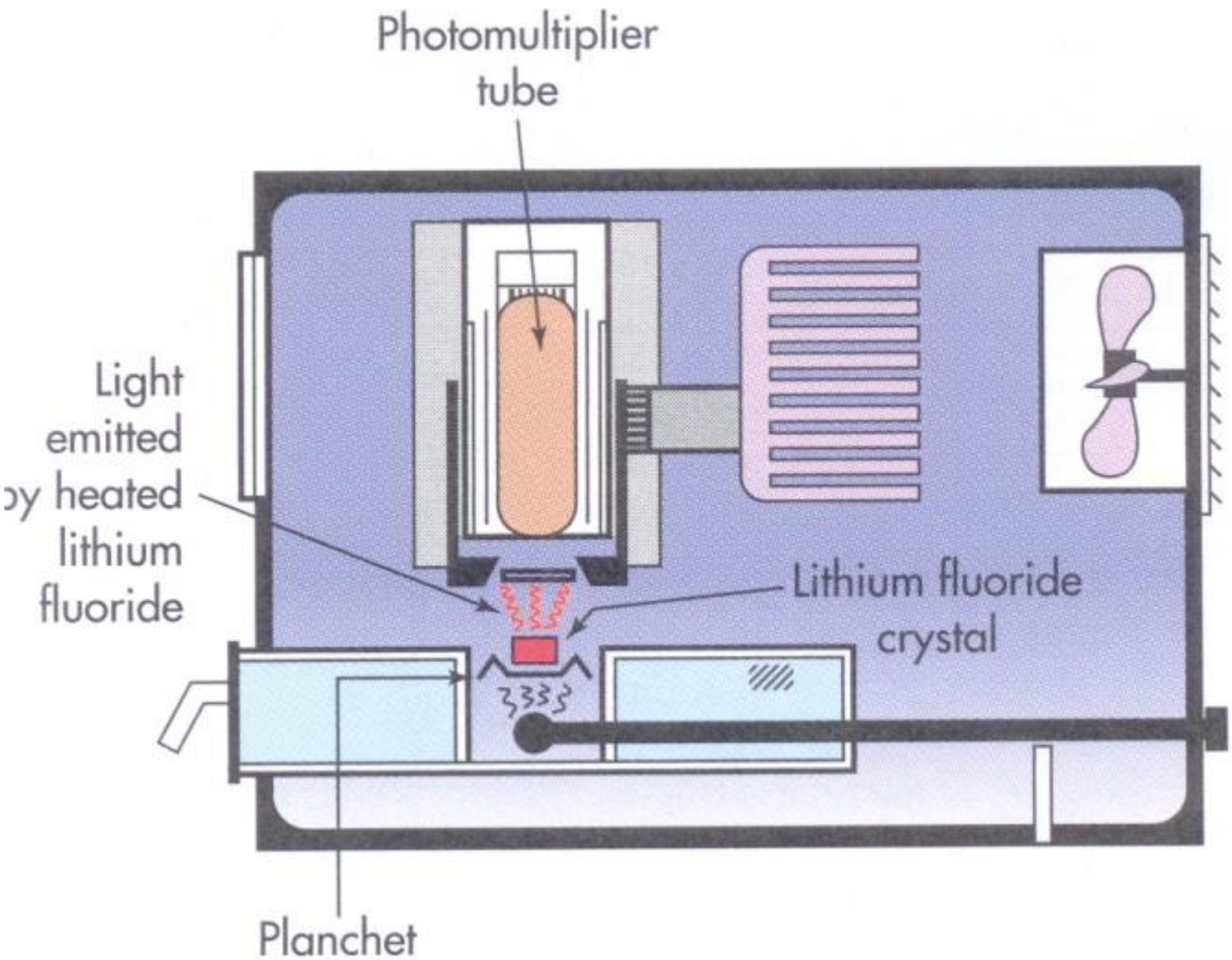
- Termoluminescência
  - Emissão de luz após aquecimento
    - Emissão de luz proporcional à dose
    - Fosforescência com tempo de vida muito grande à temperatura ambiente
  - Vantagens
    - Tamanho pequeno
    - Grande faixa dinâmica (μGy – kGy)
    - Boa repetibilidade

Termoluminescência

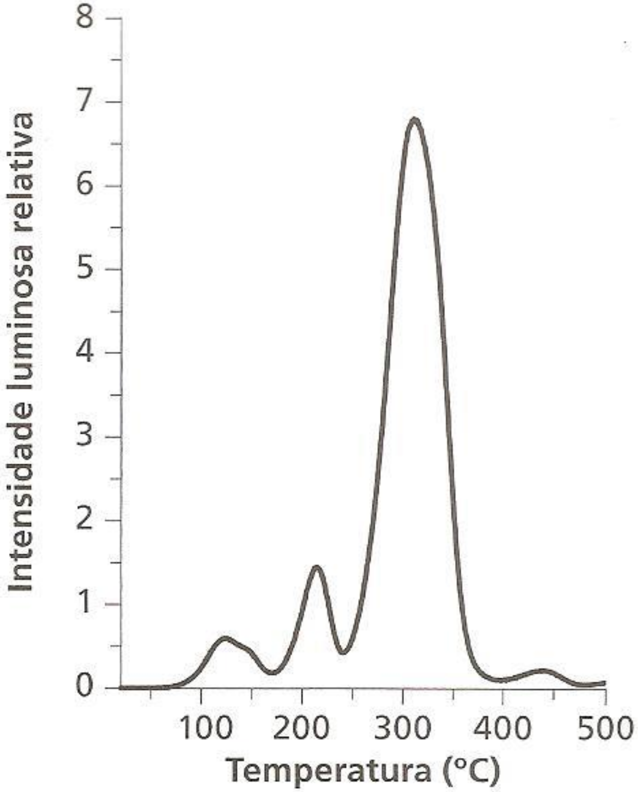
- Exemplos
  - Fluoreto de Lítio (LiF)
    - Impurezas: Mg,Ti,Cu,P
  - Fluoreto de Cálcio (CaF)
  - Sulfato de Cálcio ($CaSO_4$)

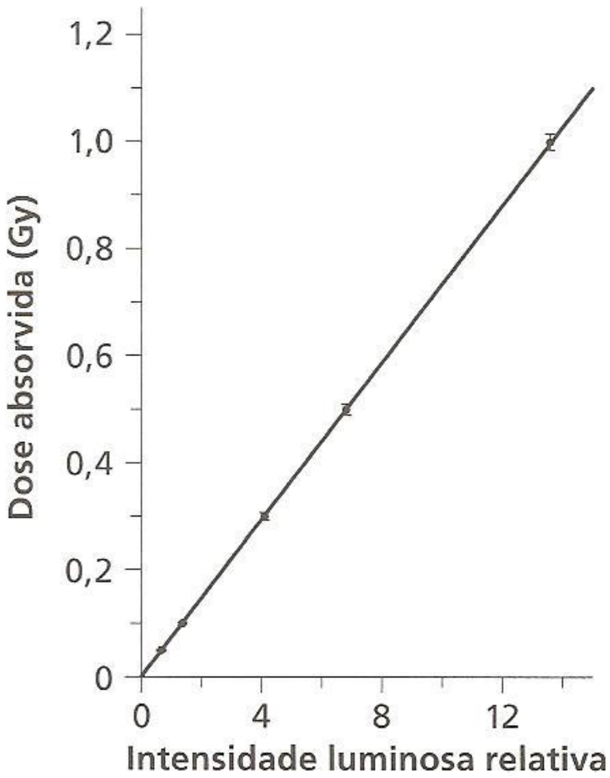
- Aplicações
  - Monitoração pessoal
  - Dosimetria de procedimentos médicos
  - Dosimetria ambiental
  - Dosimetria industrial

Termoluminescência



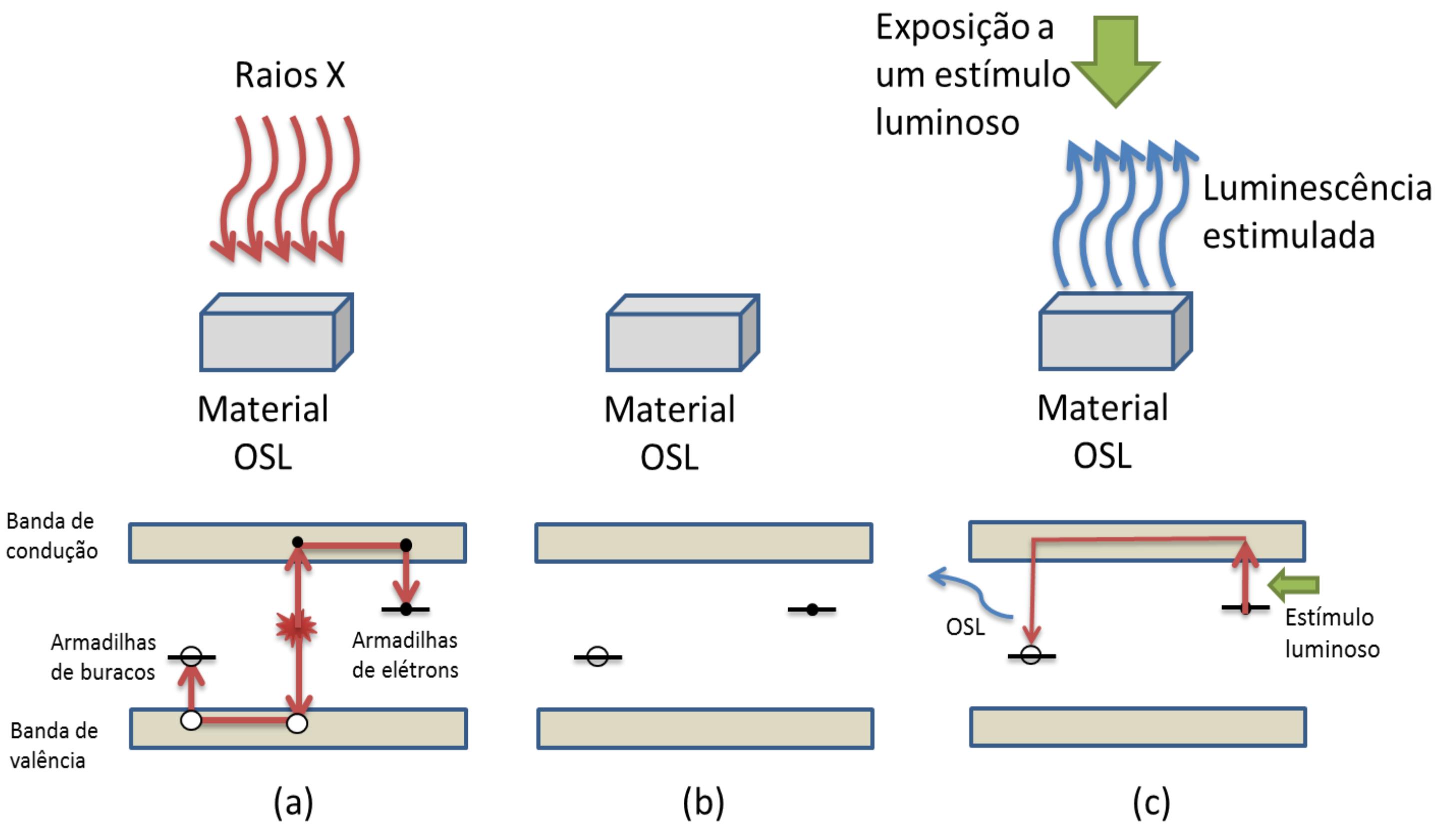
Termoluminescência





Luminescência opticamente estimulada

- Usa-se luz ao invés de aquecimento

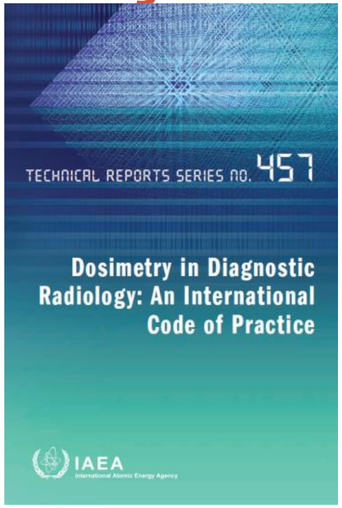


Ver também

- http://slideplayer.com/slide/4888351/

- https://humanhealth.iaea.org/HHW/MedicalPhysics/TheMedicalPhysicist/Studentscorner/HandbookforTeachersandStudents/Chapter_21.pdf

Correções em câmaras de ionização



$$K = M_Q \, N_{K,Q_O} \prod_i k_i$$

$N_{K,Qo}$: coeficiente de calibración de un LSCD (o LPCD) y alude a las condiciones de referencia, Q_0 T_0, P_0 etc.

M_Q : la lectura del instrumento en ciertas condiciones, por ejemplo, para *P*, *T*, *etc*. Una medición se lleva a cabo generalmente en condiciones diferentes a las de referencia

k_i : factores de corrección que corrigen el efecto de una magnitud de influencia

Correções em câmaras de ionização

RASTREABILIDADE

LPCD → **LSCD** → **Usuario**

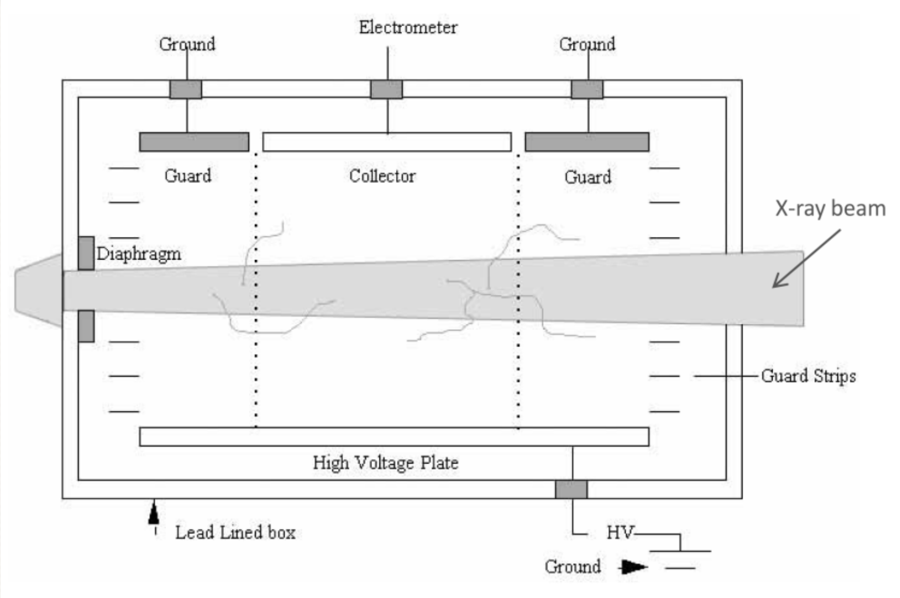
21.6. DOSIMETER CALIBRATION

All instruments used for dosimetric measurement in the clinical environment should have a calibration traceable to a recognized dosimetry standard

- The measurement of a dosimetric quantity, such as air kerma, prerequisites that there is a SI that determines the quantity and its unit
- Primary Standards Dosimetry Laboratories (PSDLs) employ free air ionization chambers for the measurement of absorbed dose traceable to the fundamental SI absorbed dose unit of Gray (Gy)
- Secondary Standards Dosimetry Laboratories (SSDLs) calibrate their reference class instruments at PSDLs and use these as their local dosimetry standards
- Therefore the traceability of the measurements to the specific PSDL is maintained. The main role of the SSDL is to bridge the gap between PSDL and dosimeter user

21.6. DOSIMETER CALIBRATION

21.6.1. Standard free air ionization chamber



Free air ionization chambers are often used by PSDLs as the primary standard for the determination of air kerma against which the secondary standard chambers from SSDLs are calibrated

The charge liberated by X rays in the mass of the air inside the chamber volume is measured

The air kerma is deduced according to its definition $K = \frac{dE_{tr}}{dm} = \frac{dQW_{air}}{dm}$

from measurements of basic physical quantities (charge and mass) and applying physical constants and relative correction factors

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Correções em câmaras de ionização

Magnitudes de influencia

Se definen como magnitudes que no son el objeto de la medición pero pueden tener influencia en el resultado de la medición.

Ejemplos: energía del haz de rayos X, P, *T*, tamaño del campo, corriente de fuga del electrómetro, etc.

k_i : corrige el efecto de las magnitudes de influencia; por ejemplo k_Q, k_{TP}, …

Condiciones de referencia

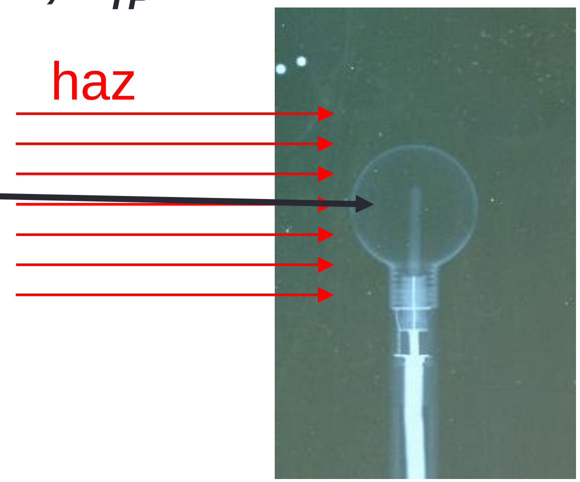
Las condiciones de referencia representan un conjunto de valores (valores de referencia) de las magnitudes de influencia para el cual, es válido el coeficiente de calibración sin más correcciones

Ejemplos : P_0 = 101.3 kPa, θ_0 = 20ºC, FCD=100cm, *Q*=RQR5 (70kV)

Correções em câmaras de ionização

Corrección de la densidad del aire, k_{TP}

$$K = \frac{\varepsilon}{m}$$



$$P \cdot V = \frac{m}{MW} \cdot R \cdot T$$

$$k_{TP} = \frac{P_0 \cdot T}{P \cdot T_0} = \frac{P_0 \cdot (273.2 + \theta)}{P \cdot (273.2 + \theta_0)}$$

P_0 = 101.3 kPa = 1 atm

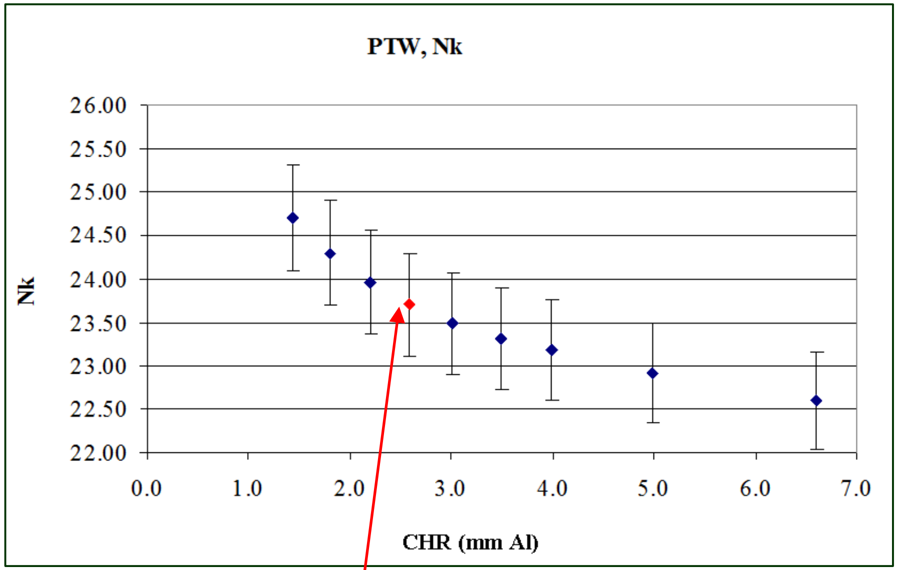
θ_0 = 20ºC ó 22ºC

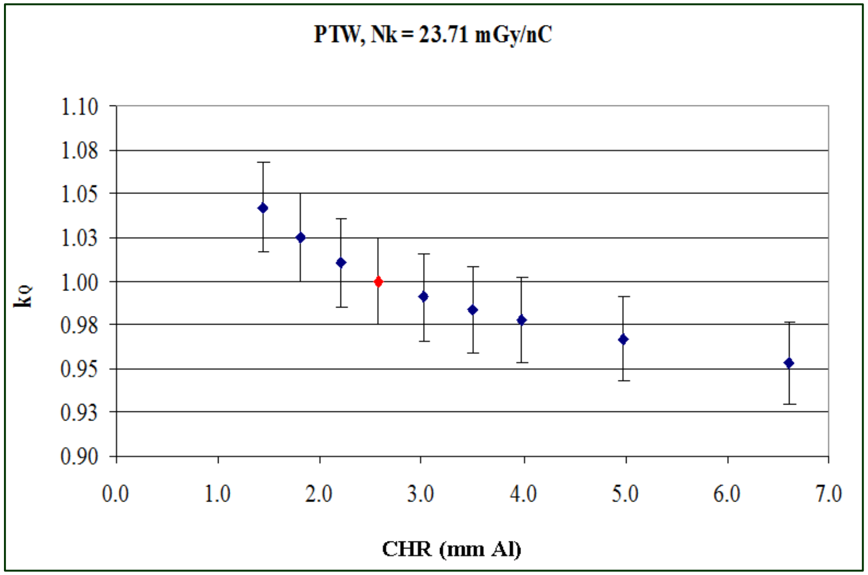
Detectores de estado sólido : k_{TP} = 1

Cámaras selladas (¿?): k_{TP} = 1

Correções em câmaras de ionização

Corrección de la calidad del haz, k_Q





$$K_Q = M_Q \; N_{K,Q_o} \; k_{Q,Q_0}$$

$$k_{Q,Q_0} = \frac{N_{K,Q}}{N_{K,Q_0}} \left(= k_Q\right)$$

donde el factor $k_{Q,Qo}$ corrige los efectos de la diferencia entre la calidad del haz de referencia, *Qo*, y la calidad real, *Q*, durante la medición

Correções em câmaras de ionização

Otras correcciones de las magnitudes de influencia

k_s : por las pérdidas por saturación o recombinación de iones

k_{dist} : por la desviación de la ubicación de la cámara de la ubicación de referencia

k_{lin} : por la no linealidad de la sensibilidad del conjunto de medición

k_{dir} : por la dirección de la radiación incidente

k_{emc} : por el efecto de la compatibilidad electromagnética

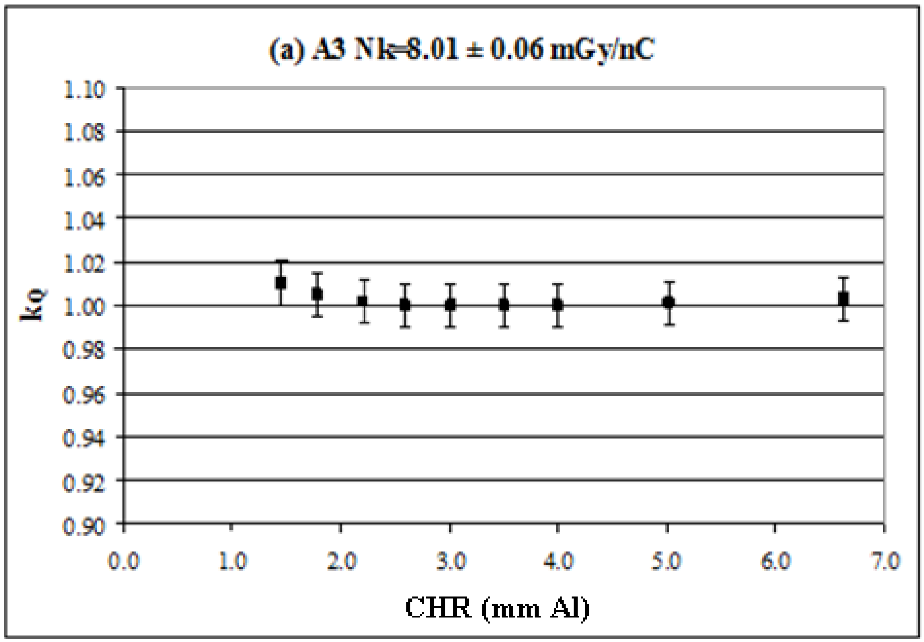
k_{fs} : por la desviación del tamaño /homogeneidad del haz de las condiciones de referencia

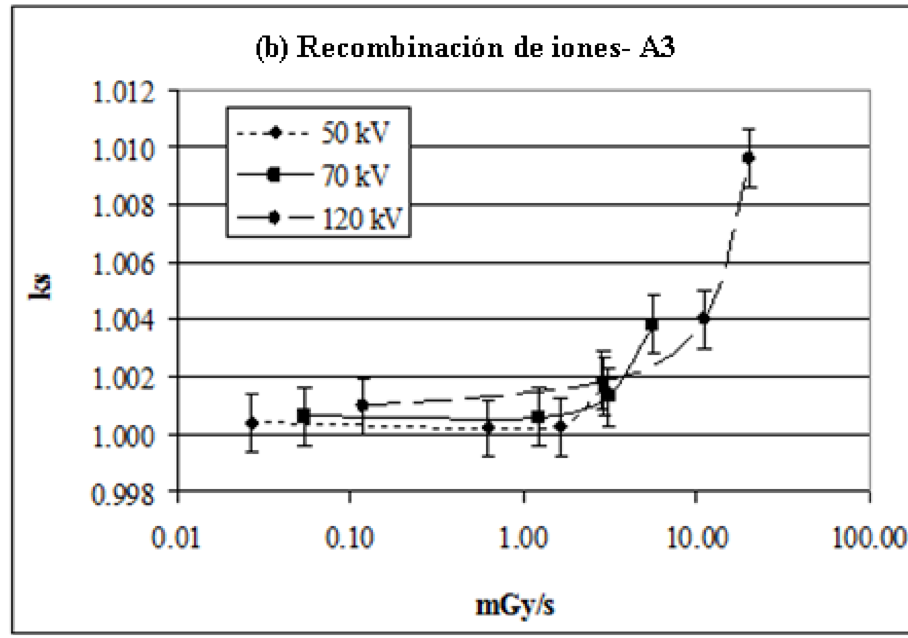
k_{lt} : por variaciones a largo plazo de la respuesta

k_{ms} : por la dependencia del instrumento de la fuente de potencial (redes o batería)

$$K = M_Q \cdot k_{TP} \cdot N_{K,Q_O} \cdot \prod_i k_i \qquad \prod_i k_i = k_Q \cdot \overbrace{\underbrace{k_S k_{dist} k_{lin} k_{dir} k_{emc} k_{fh} k_{lt} k_{ms}}_{\text{contribución a las incertidumbres}}}^{1}$$

Correções em câmaras de ionização





Dependencia energética de la respuesta

Coeficiente de saturación

21.6. DOSIMETER CALIBRATION

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21.6. DOSIMETER CALIBRATION
21.6.2. SSDL calibration

Most SSDLs apply the substitution method for the dosimeter calibration

At a given beam quality, Q, the true value of air kerma $K_Q^{"true"}$ is measured using the reference dosimeter

The reference point of the user's dosimeter is placed at the same point and the dosimeter's reading is used to derive the calibration coefficient from the ratio

$$N_{K,Q}^{user} = \frac{K_Q^{"true"}}{M_Q^{user}}$$

M_Q^{user} is the reading of the user's instruments corrected for air density

21.6. DOSIMETER CALIBRATION

21.6.2. SSDL calibration

The calibration of the diagnostic radiology dosimeters are performed at the radiation qualities which are described in the IEC 61267 standard and which are produced using appropriate tube filtration at the specified tube voltage

Depending on the application of the dosimeter, a series of different beam qualities are used. For example: series

- RQR simulates the primary beams incident on the patient
- RQT, the beam qualities used in CT
- RQA, the transmitted radiation qualities through the patient
- RQR-M, mammography beams

Each series consists of several beams with different combinations of tube voltage and filtration

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21.6. DOSIMETER CALIBRATION

21.6.2. SSDL calibration

Characterization of Radiation Quality Series RQR (according to IEC 61267, 2005) used for unattenuated beams for General Radiography Applications Spectra are for an X ray tube with a W target and Al filters

Radiation Quality	X ray Tube Voltage (kV)	First HVL (mm Al)	Homogeneity coefficient (h)
RQR 2	40	1.42	0.81
RQR 3	50	1.78	0.76
RQR 4	60	2.19	0.74
RQR 5 *	70	2.58	0.71
RQR 6	80	3.01	0.69
RQR 7	90	3.48	0.68
RQR 8	100	3.97	0.68
RQR 9	120	5.00	0.68
RQR 10	150	6.57	0.72

*This quality is generally selected as the reference of the RQR series

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21.6. DOSIMETER CALIBRATION

21.6.2. SSDL calibration

Characterization of Radiation Quality Series RQR-M (according to IEC 61267, 2005) used for unattenuated beams for Mammography Applications. Spectra are for an X ray tube with a Mo target / Mo filter

Radiation Quality	X ray Tube Voltage (kV)	First HVL (mm Al)
RQR-M 1	25	0.28
RQR-M 2 *	28	0.31
RQR-M 3	30	0.33
RQR-M 4	35	0.36

* This quality is generally selected as the reference of the RQR-M series

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21.6. DOSIMETER CALIBRATION

21.6.2. SSDL calibration

Characterization of Radiation Quality Series RQT (according to IEC 61267, 2005) used for unattenuated beams for Computed Tomography (CT). Applications Spectra are for an X ray tube with a W target and Al and Cu filters

Radiation Quality	**X ray Tube Voltage (kV)**	**First HVL (mm Al)**
RQT 8	100	6.90
RQT 9 *	120	8.40
RQT 10	150	10.1

* This quality is generally selected as the reference of the RQT series

21.6. DOSIMETER CALIBRATION

21.6.2. SSDL calibration

A general purpose dosimeter should be calibrated in terms of air kerma at the RQR (RQR 2 to RQR 10) radiation qualities

- According to common practice, the calibration coefficient, N_K of a dosimeter is obtained at the RQR 5 (70 kV)
- For the other radiation qualities of the RQR series, further correction factors (k_Q) are provided to take into account the energy dependence of the dosimeter response
- For a given radiation quality Q, k_Q is defined as the ratio of the calibration coefficients at radiation quality Q to that at the radiation quality RQR 5
- By definition k_Q equals 1 at RQR 5
- For mammography the standard beam quality is the RQR-M2 (28 kV) and for CT the RQT 9 (120 kV)

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