IONIZÁLÓ SUGÁRZÁS HATÁSA AZ ÉLŐ KÖRNYEZETRE
MEASUREMENT TECHNIQUES

Szegedi Domonkos

BME Institute of Nuclear Techniques

National Institute of Oncology

- **Multiple Exposures: Chronicles of the Radiation Age**
- **487/2015. (XII. 30.) Korm. Rendelet az ionizáló sugárzás elleni védelemről és a kapcsolódó engedélyezési, jelentési és ellenőrzési rendszerről**
- **Köteles György: Sugáregészségtan**
- **Deme Sándor, Fehér István: Sugárvédelem**

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Related bibliography

Dozimetry and measurement techniques - definitions

Dose concept

- „dose” – quantity, portion (originally in medication)
- For quantitisation of ionising radiation
- Expressible in terms of basic quantities
- Beginning
  - Erythema dose – threshold dose of a deterministic effect
  - First dose limit among radiologists: 1/100 of the erythema dose per month (Mutscheller, 1924)

Absorbed dose

- **Absorbed dose:** the ratio of the radiation energy absorbed by a given volume element to the mass of that volume element

$$D = \frac{\Delta\bar{\varepsilon}}{\Delta m}$$

- The unit of measurement is the **gray** (pronounced *grey*), symbol **Gy**,

$$1Gy = 1\frac{J}{kg}$$

- In a differential approach, it can be used as a point quantity.

Dose, dose rate

- To heat 1 kg of water by 1 °C, 4200 Gy is required

  4 Gy is a semi-lethal dose for the human body

- **Dose rate (dose intensity)**

absorbed dose per unit time $\dot{D} = \frac{dD}{dt}$

unit: $\frac{Gy}{s} = \frac{J}{kg}/s$

Quantity	Radiation protection	Radiation therapy
Dose	$mGy, \mu Gy$	Gy, cGy
Dose rate	$mGy/h, \mu Gy/\mathrm{h}$	$Gy/min, cGy/min$

Biological dose concept

- The biological destructive effect of a given ionizing radiation shows variability depending, among other factors, on the type of radiation and the type of irradiated living tissue.

- **RBE – Relative Biological Effectiveness:**
  the biological destructive effect of a given radiation type/quality, compared to 250 kV peak X-rays, for the same absorbed dose.

Equvivalent dose

Equivalent dose (H): takes into account the biological effectiveness of the given type of radiation (e.g. α, β, γ)

$$H_T = \sum_r w_r D_{T,r}$$

- Where $D_{T,r}$ is the absorbed dose in tissue **T** from radiation of type **r**, and w_r is the radiation weighting factor. Its unit is the **sievert**, 1 Sv = 1 J/kg

Equivalent dose

Type of radiation	Weighting factor
Foton	1
Elekcron, muon	1
Neutron <10keV	5
10keV-100keV	10
100keV-2MeV	20
2MeV-20MeV	10
20MeV<	5
Proton	5
Alfa particles	20

Effective dose

- **Effective dose (E):** takes into account the specific radiosensitivity of a given organ or tissue

$$E = \sum_T w_T H_T$$

- Where H_T is the equivalent dose in tissue T, and w_T is the tissue weighting factor characterizing the radiosensitivity of that tissue. Its unit is the **sievert**, 1 Sv = 1 J/kg

Effective dose

Tissue	**Tissue weigthing factors**	
	ICRP 60	ICRP 103
Gonade	**0,2**	**0,08**
Marrow	0,12	0,12
Lung	0,12	0,12
Breast	**0,05**	**0,12**
Thyroid	0,05	0,05
Bone surface	0,01	0,01
Colon	0,12	0,12
Stomach	0,12	0,12
Bladder	0,05	0,05
Liver	0,05	0,05
Skin	0,01	0,01
Esophagus	0,05	0,05
Other organs, tissues	**0,05**	**0,12**

Committed dose

- **In case of incorporation, from the time of intake:**

  Dose can be expressed in integral form
- **Time dependence of dose rate:**
  - **Biological half-life** – relates to the elimination from the body
  - **Physical half-life** – decrease in activity due to radioactive decay

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_T(t)\,dt$$

Operative quantities

- Ambient dose equvialent
- Personal dose equivalent
- Directional dose equivalent to the lens and
  to the unit suface of the skin

ICRU phantom

- 76,2% oxigen
- 11,1% carbon
- 10,1% nitrogen
- 2,6% hidrogen

1g/cm^3 density, tissue-equivalent plastic phantom

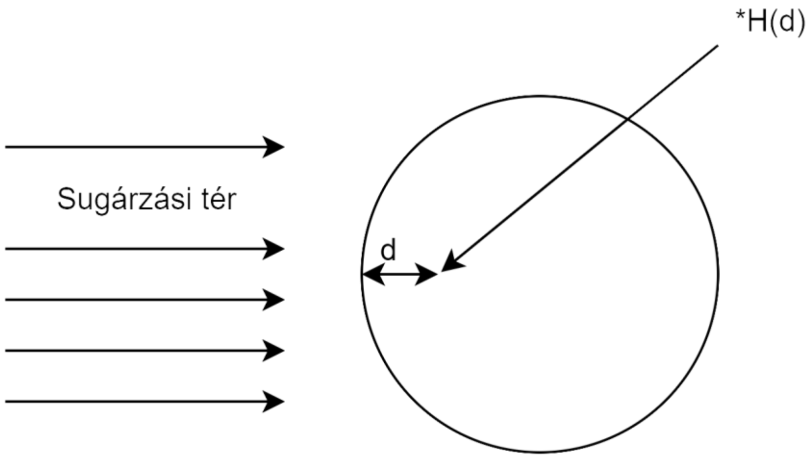
300 mm diameter sphere phantom

(300x300x150) mm^3 phantom

Ambient dose equivalent

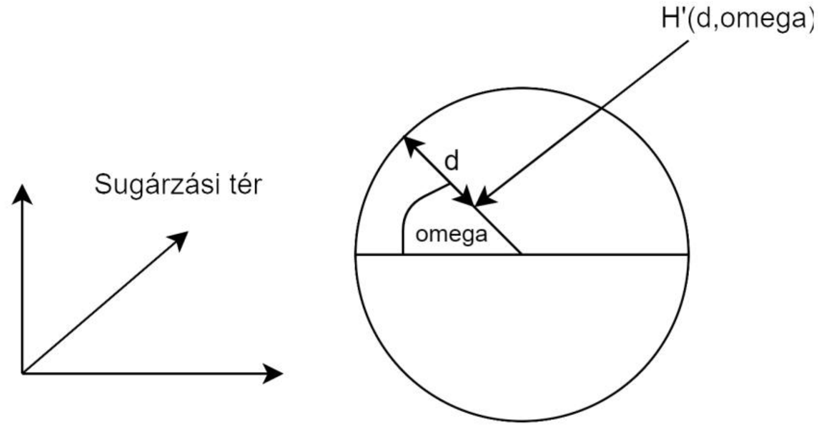
That dose equivalent at a given point in the radiation field which, **at a depth *d* in the ICRU sphere**, would be produced by the expanded and aligned radiation field corresponding to the dose equivalent, measured along the radius of the sphere opposite to the direction of the aligned beam.

High LET radiation: d = 0,07 mm
Low LET radiation: d = 10 mm



Directional dose equivalent

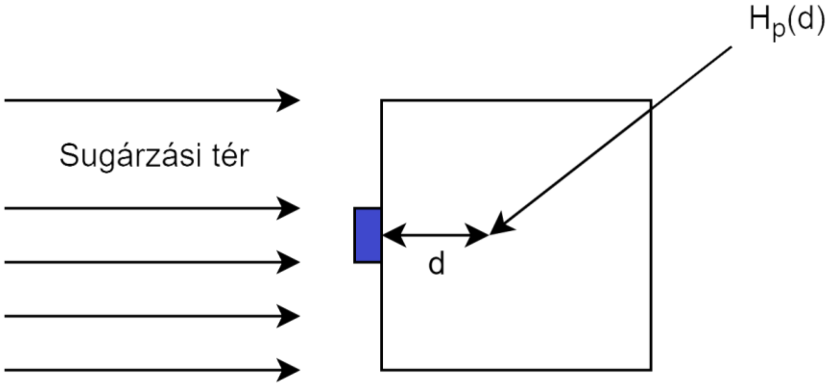
That dose equivalent at a given point (P) in the radiation field which, at a depth *d* in the ICRU sphere, would be produced by the expanded radiation field corresponding to the dose equivalent, measured along the radius of the sphere in the specified direction Ω.



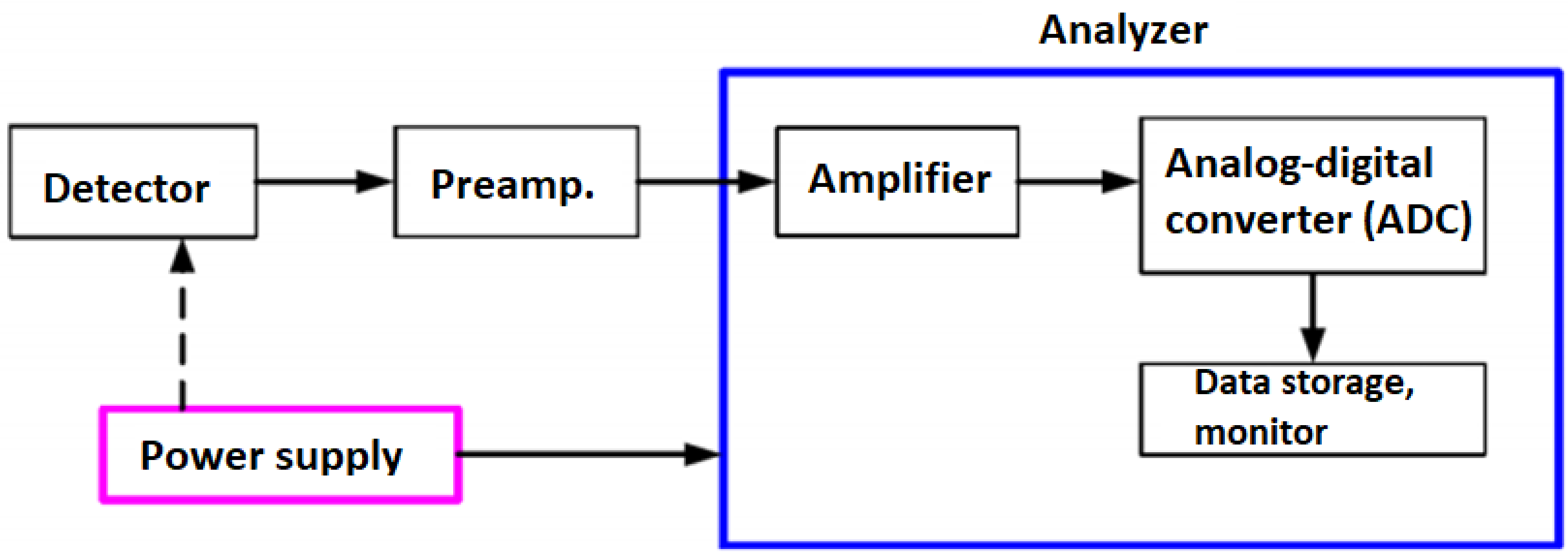
Personal dose equivalent

The dose equivalent in soft tissue located at a depth *d* below a specified point on the body surface.

The quantity used as the basis for workplace monitoring to estimate personal doses.



Detector systems



Parts of the measurement system

- **Detector**
- **Analog signal processing** (e.g., preamplification)
- **ADC (Analog-to-Digital Converter)**
- **Digital signal processing** (e.g., amplification)
- **Counting and data storage**
- **Optional: data processing with a multi-channel analyzer**

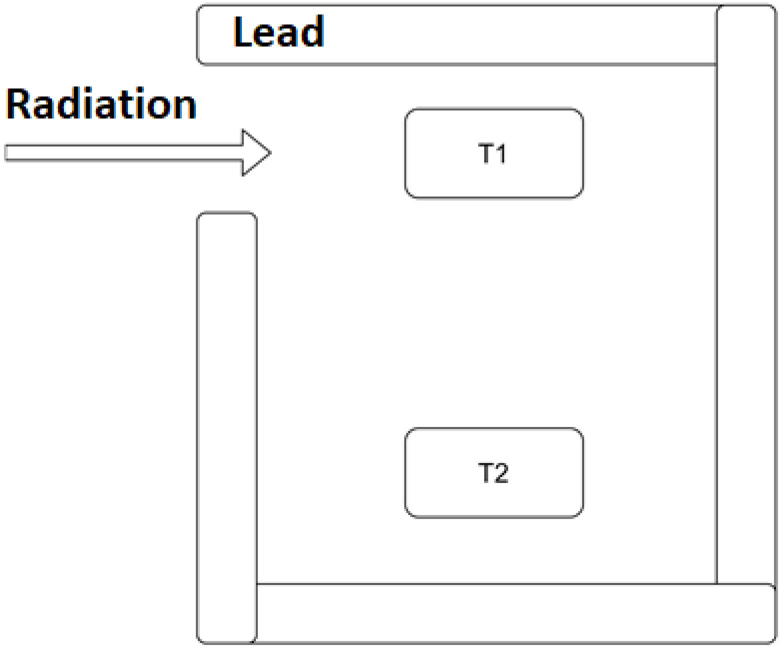
The type of detector determines the required electronics (e.g., photomultiplier), detection capabilities (e.g., qualitative analysis, dose measurement), and measurement conditions (e.g., cooling, additional shielding, underwater measurement).

Detection of ionizing radiation

- Calorimeters
- Gas-filled (ionization) detectors
- Semiconductor detectors
- Scintillation detectors
- Thermoluminescent detectors

Calorimeters

- **For standard dose measurement**
- Used in **“primary” laboratories** for primary dose measurements
- **Secondary measuring instruments** can be calibrated against these
- Suitable **only for measuring high doses**
- Measurement is based on **thermal effect**
- Applicable to **any type of radiation**

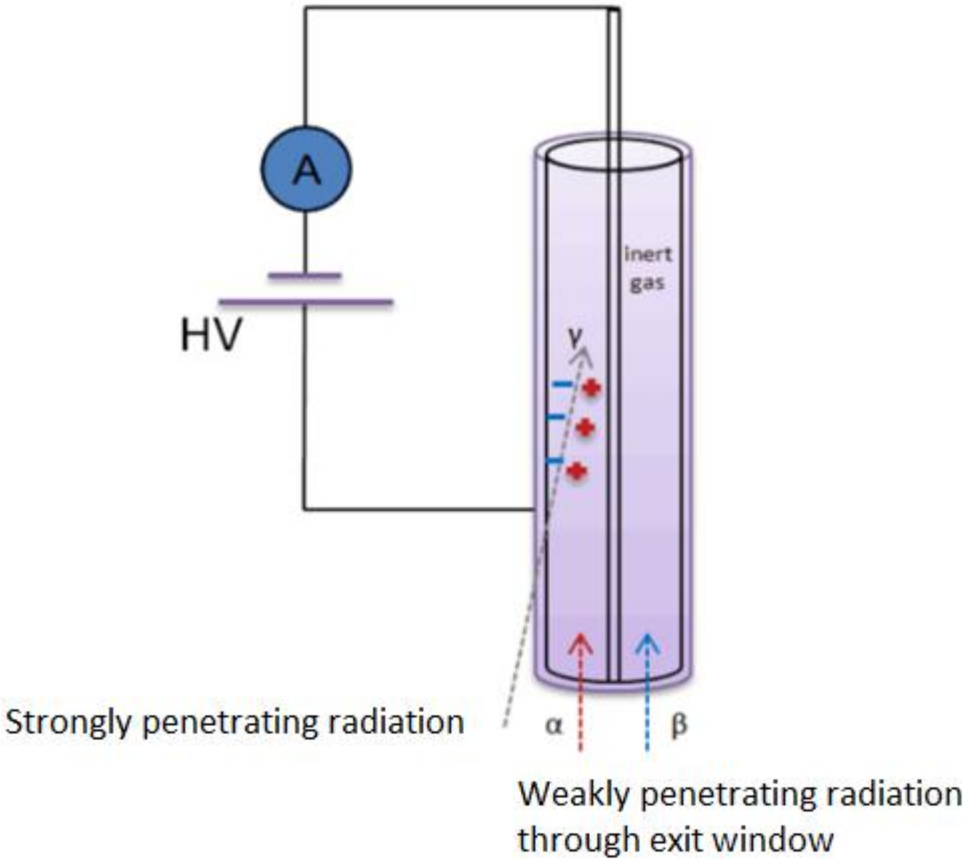


D~ T1-T2

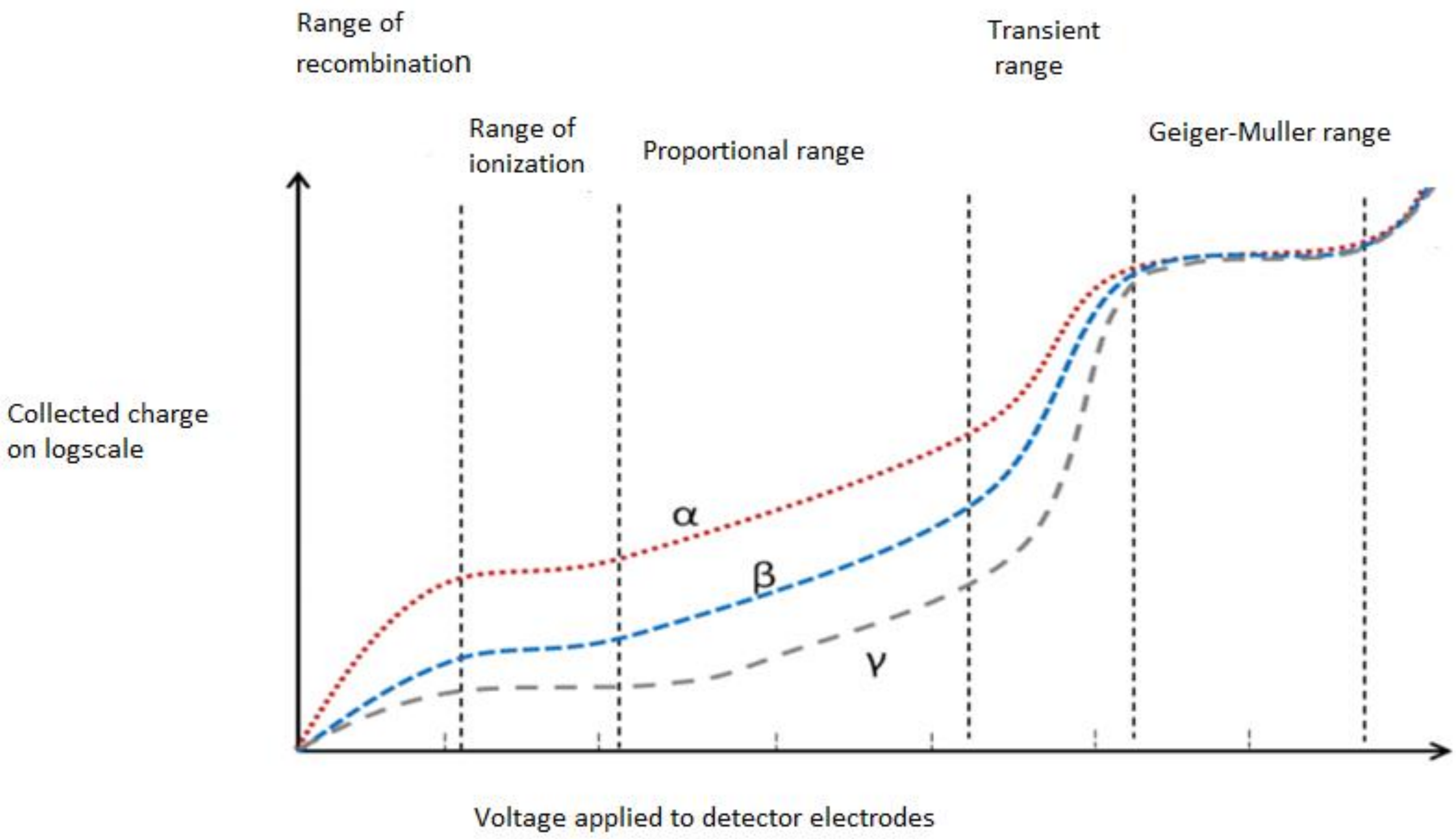
Gas-filled detectors

- Gas-filled volume (~cm^3)

- Voltage applied to electrodes (~100 V)
- Electronics for measuring collected charge (~pA)
    - Electrometer



Gas-filled detector measurement ranges



Range of ionization chamber mode

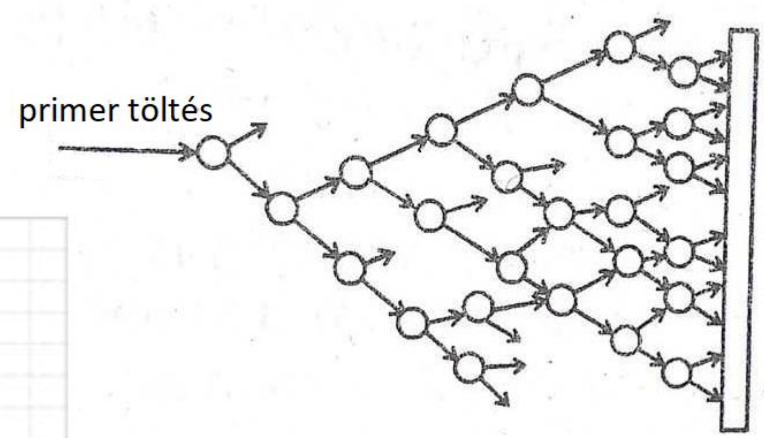
- Due to the voltage applied to the electrodes, the anode is able to collect the charges produced during ionization before they recombine.
- The measured charge is proportional to the number of ion pairs produced, which depends on the dose absorbed in the volume over the given time.
- The instantaneous current is therefore a function of the dose rate.
- Suitable for measuring **higher (therapeutic) doses/dose rates**.

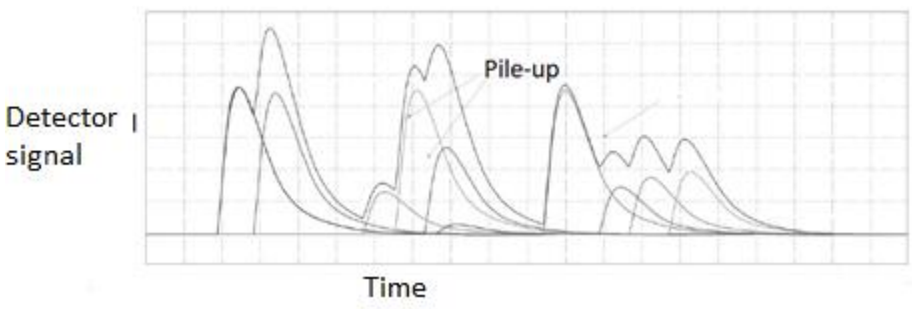
Ionization chambers

	Victoreen 451P	PTW 31013 (+ Unidos)
Sensitive volume	230 cm^3	0.3 cm^3
Temperature Range	-20°C .. +50°C	10° - 40°C
Humidity range	0 to 100%	10 - 80 %
Energy range (γ)	>25 keV	40 keV - 50 MeV
Maximal dose rate	50 mSv/h	28 Gy/s
Application	Radiation protection	Radiation therapy

Proportional counter

- **Gas amplification occurs**
- The current pulse is proportional to the number of primary ion pairs, which depends on the radiation energy.
- With a **discriminator** and **multi-channel analyzer**, it can also be used for measuring spectral data.
- **Pile-up** may occur in higher intensity fields.



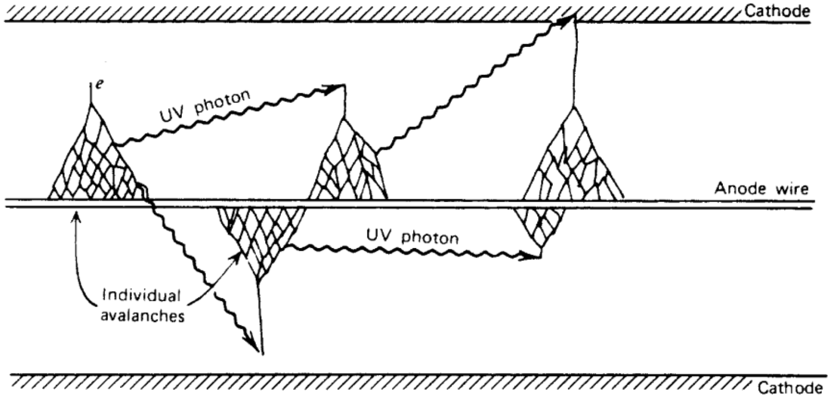


FH 40 G-L10 proportional counter

- **Energy-filtered proportional detector**
- **Energy range for photons:** 30 keV – 4.4 MeV
- **Measured quantity:** Ambient dose equivalent H*(10)
- **Measurement range:**
  - Dose rate: 10 nSv/h -100 mSv/h
  - Dose: 0,1 μSv – 1 mSv

GM tube

- Each individual particle produces a separate discharge, appearing as a uniform current pulse.
- **Self-sustaining gas amplification** occurs.
- Quenching is required in the detector volume.
- Due to the discharge processes, **dead time** occurs.
- Mostly suitable for measuring **lower dose rates**.



GM tube discharge

- **External quenching:** via electronic means
- **Internal quenching:** using a quench gas, capable of absorbing the resulting ultraviolet radiation through internal conversion
- Organic gases (methane, alcohol)
- **Finite lifetime**
- **Halogen quench gas** is capable of recombination

Scintillator detector

- Detection based on light phenomena
- The measured light intensity is proportional to the energy deposited by the detected particle.
- Photocathode: photon → electron
- Photomultiplier: signal amplification ~10^3

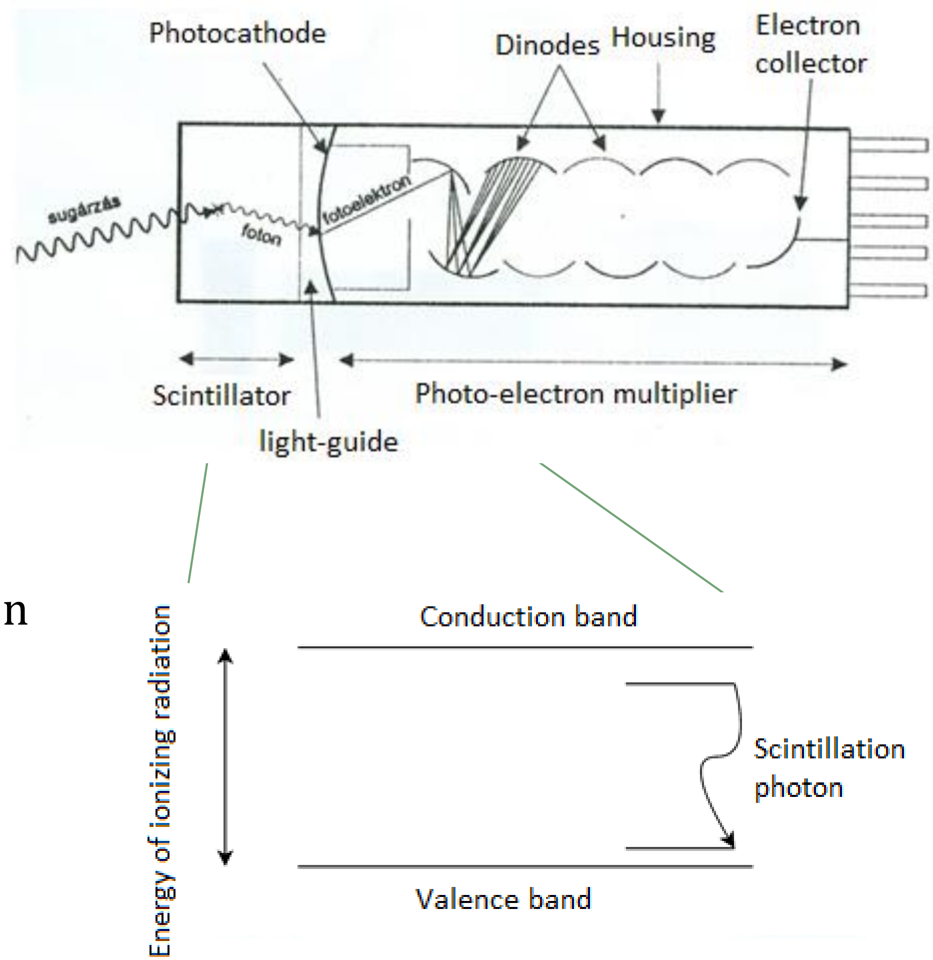
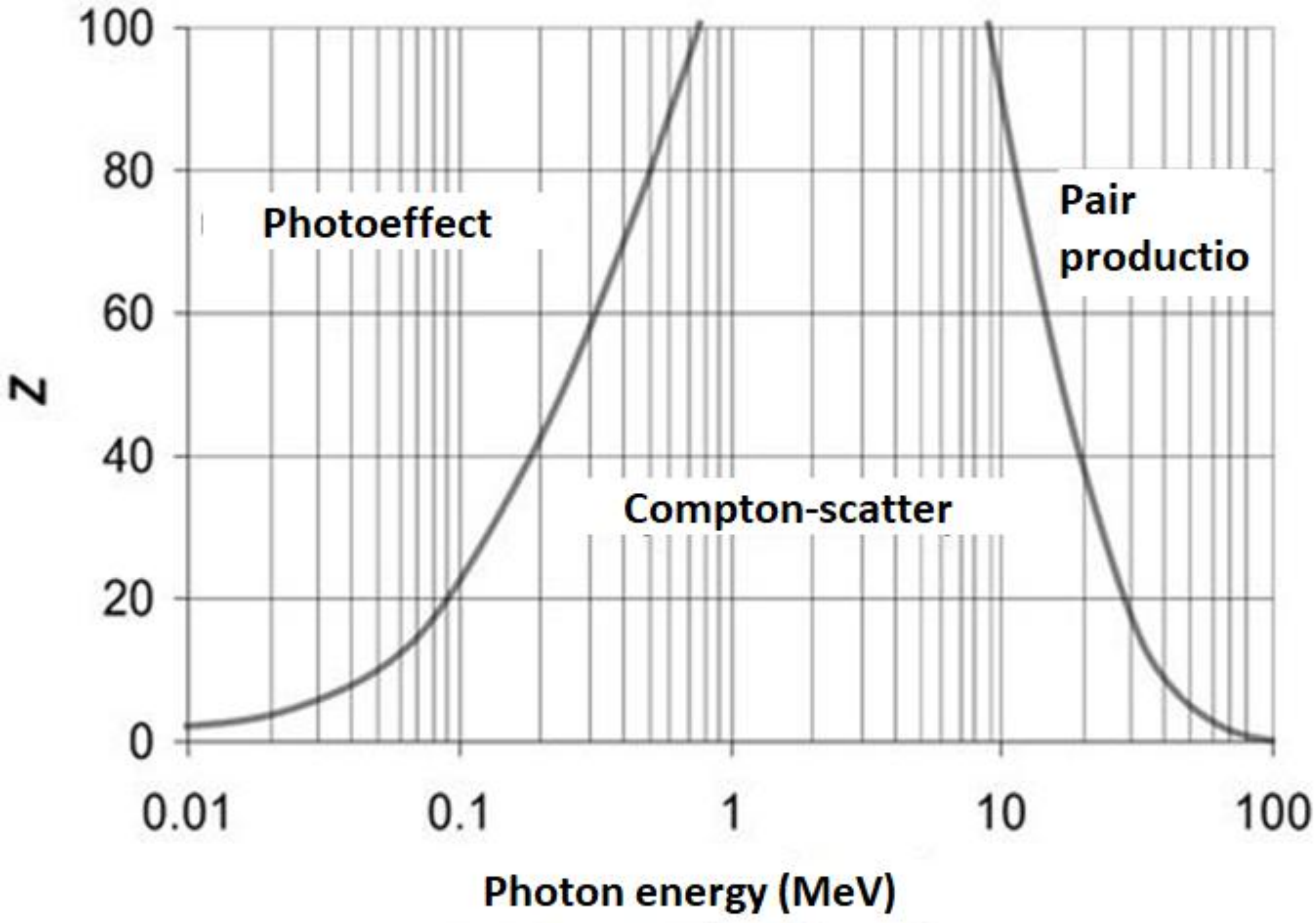
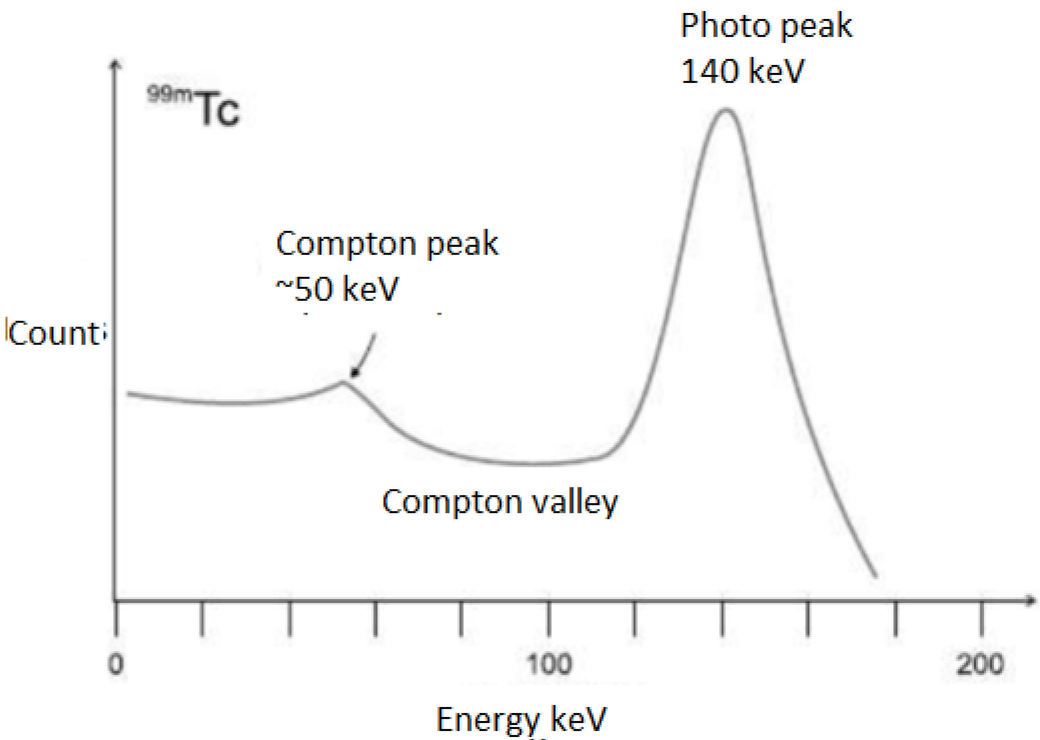
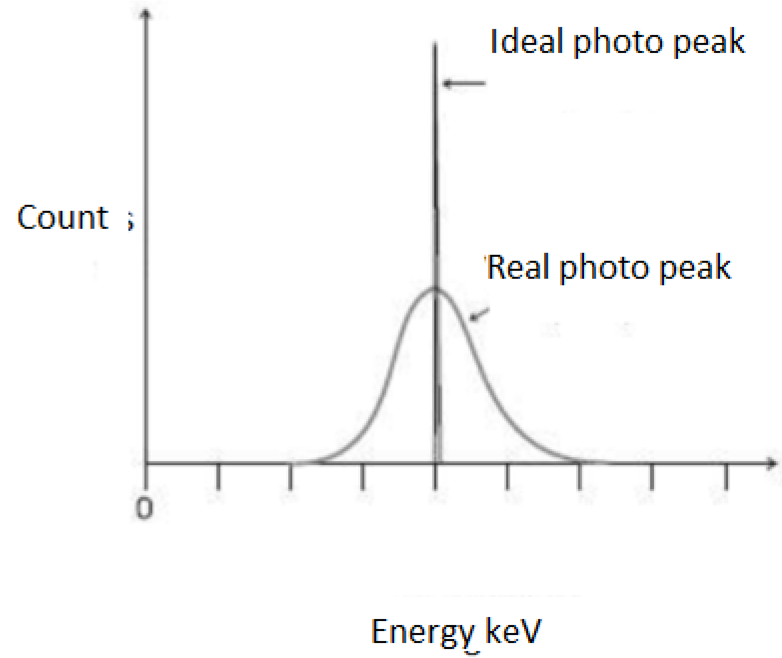


Diagram of interactions



Spectrum of scintillator detectors





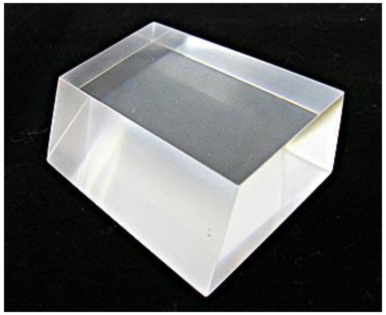
Broadening in spectrum

- Radiation → photon conversion efficiency
- Photon collection efficiency
- Photon → photoelectron conversion efficiency
- Photomultiplier: $\times 10^3$ amplification, statistical noise

At the same time:
- Even a single particle can be detected
- Wide measurement range in energy

Common scintillator chrystals

Scintillator material	Density g/cm3	Effective Z	Probability of photoeffect (%)	Photon yield (photon/MeV)
BGO	7,1	75	40	9 000
LSO	7,4	66	32	30 000
NaI:Tl	3,67	51	17	41 000
LYSO	7,1	75	32	32 000
YAP	5,5	33,5	4,2	17 000



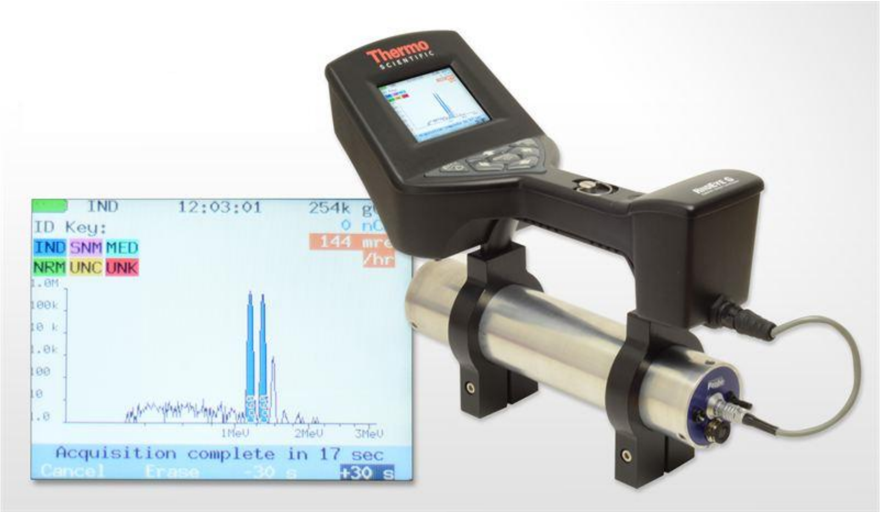
Scintillator detector

- Radiation type: Gamma
- Energy range: 20 keV – 3 MeV
- Temperature range: -20° to 50°C
- Nuclide library: ANSI
- Detector dimensions:

  2 inch x 2 inch NaI

  1.5 inch x 1.5 inch LaBr

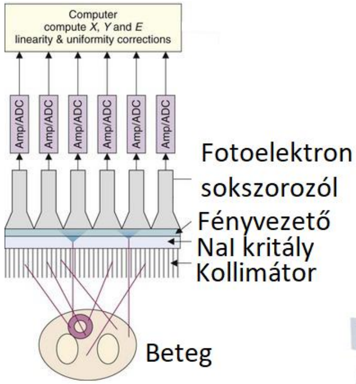
  3 inch x 3 inch NaI



Application of scintillator detectors

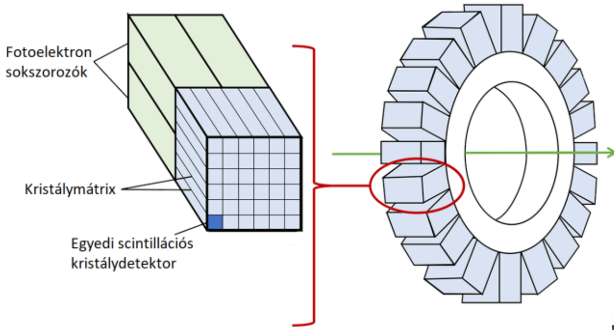
Gamma camera

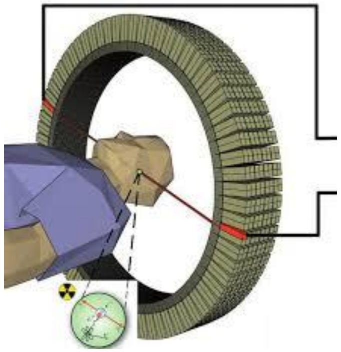
Single crystal + position-sensitive photomultiplier



PET detector

Crystal matrices + photomultiplier per unit

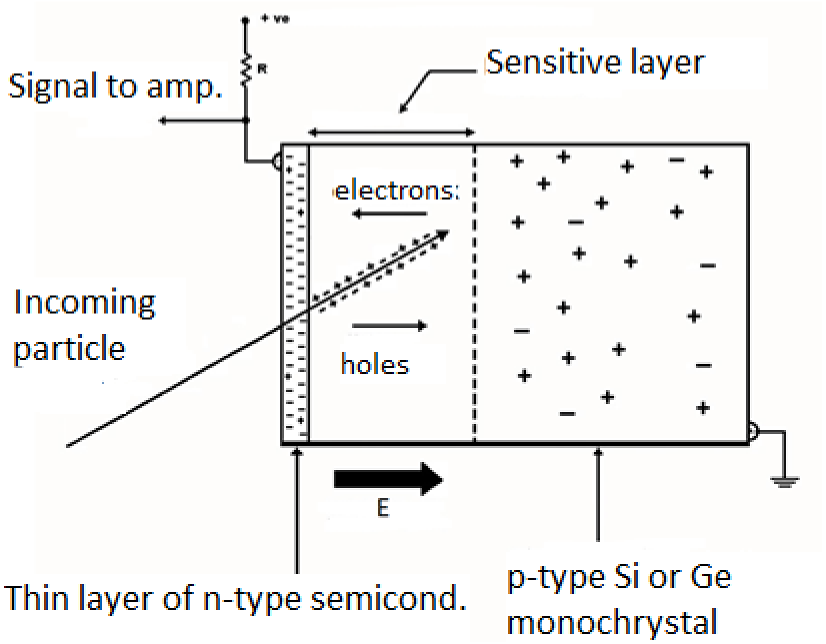




Semiconductor detectors

In a reverse-biased diode, electron-hole pairs are generated in the depleted layer and are collected.

- Energy-selective detection → spectral information
- High density, good detection efficiency
- Small energy gap in the forbidden band

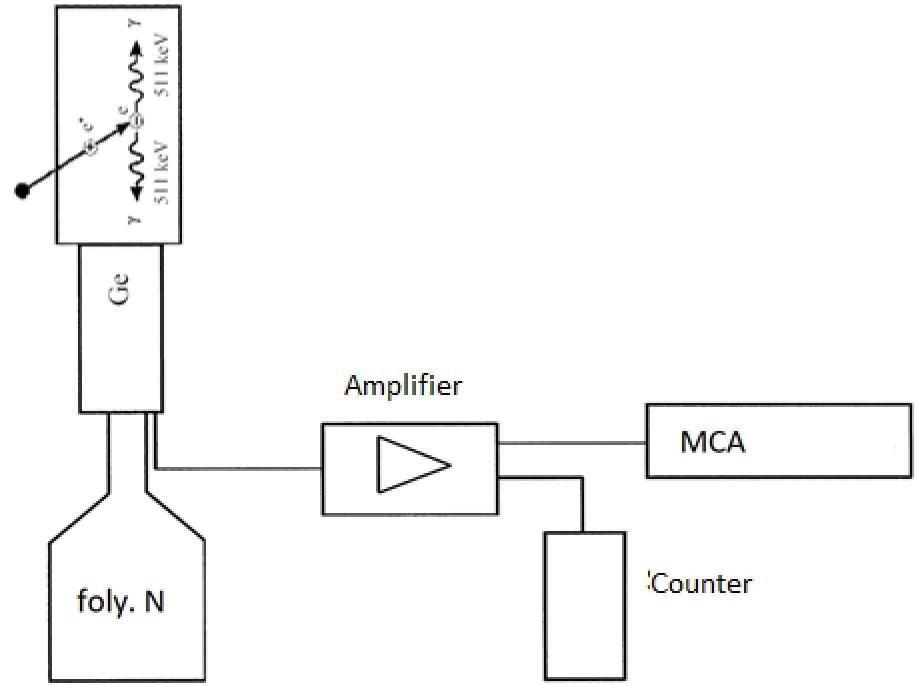


Si and Ge semiconductor detectors

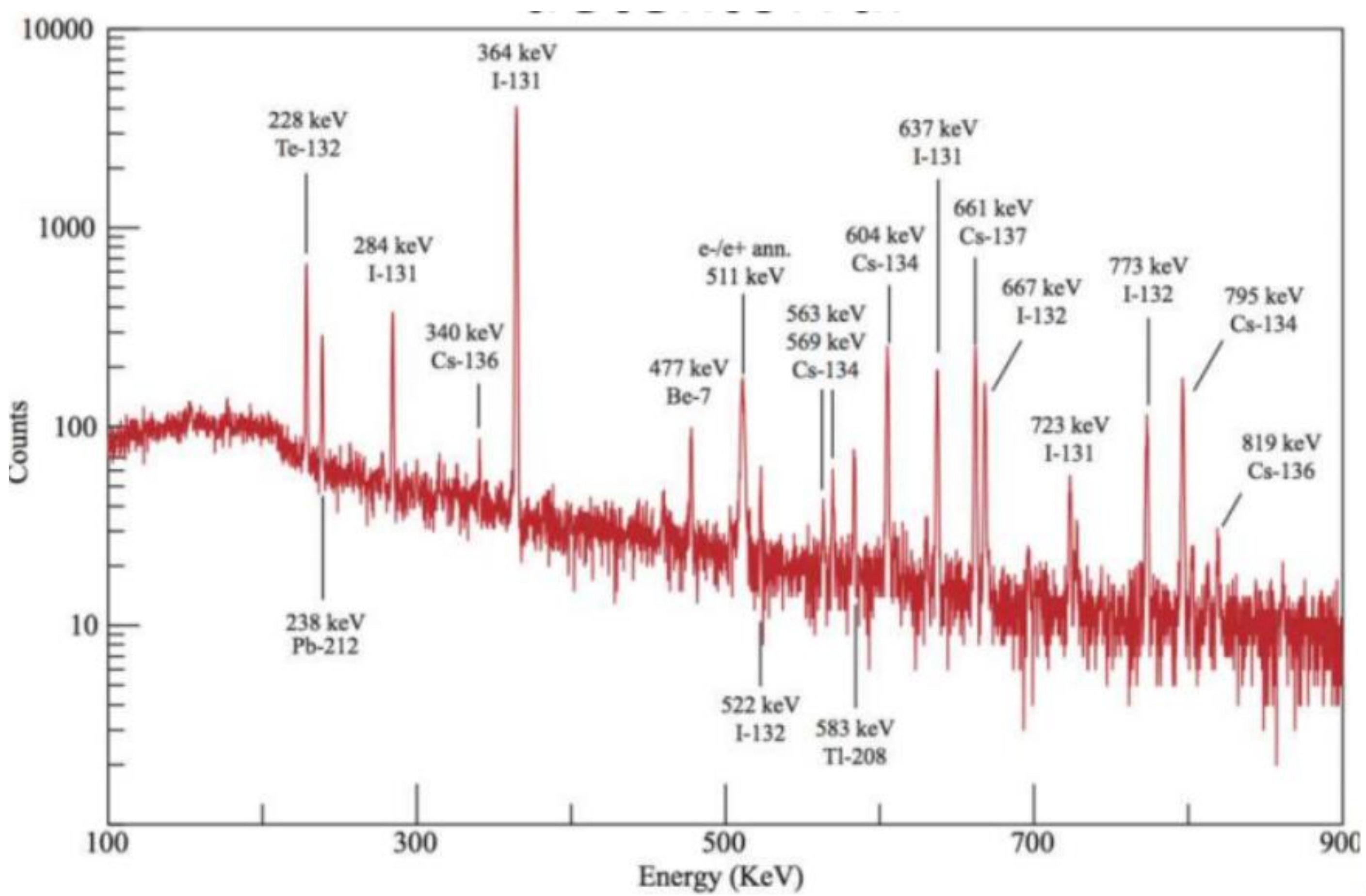
	Ge	Si
Z	32	14
Relative atomic number	72,6	28,1
Density at room temp. [g/cm^{-3}]	5,33	2,33
Energy of e-hole production [eV]		
At room temperature	-	3,76
At 77 K	2,96	3,62

For NaI crystals, this value is around 40 eV, meaning that **10 times more primary charges** are generated in semiconductor detectors when detecting a particle of the same energy.

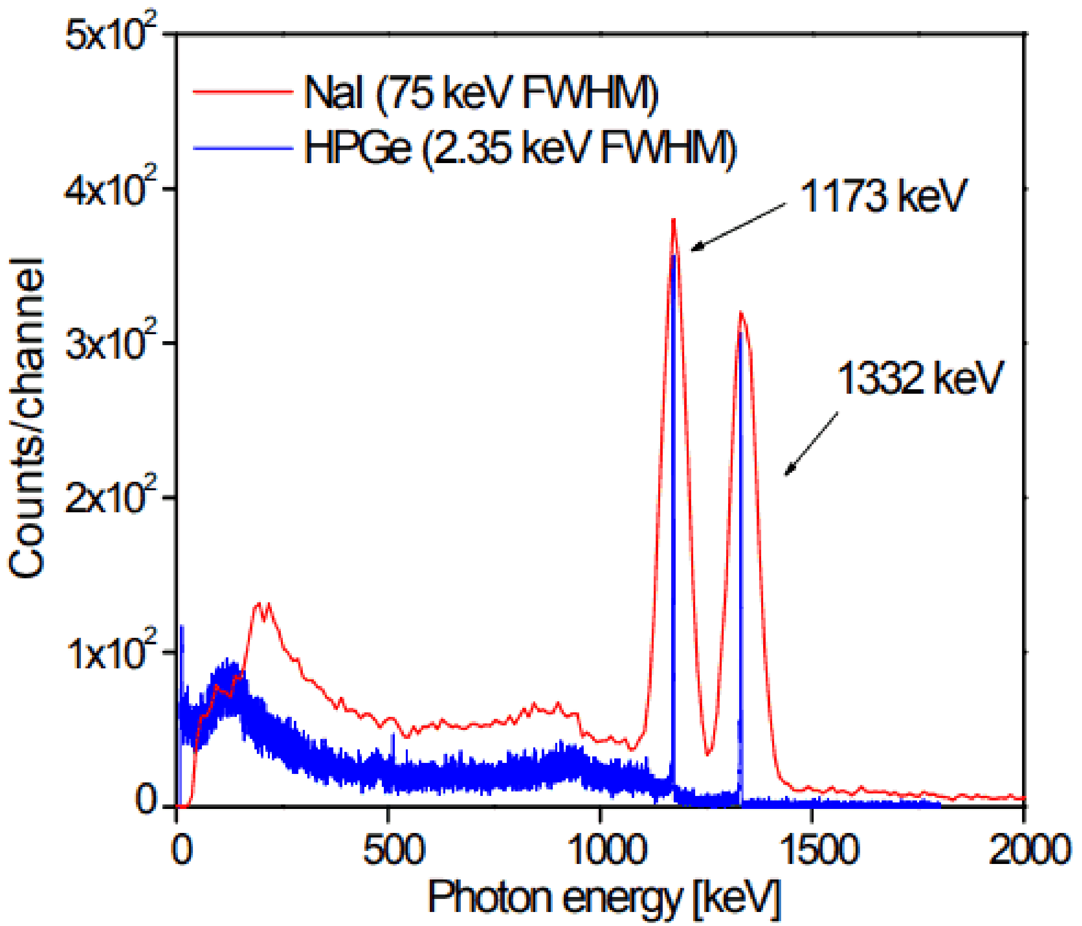
HPGe detector



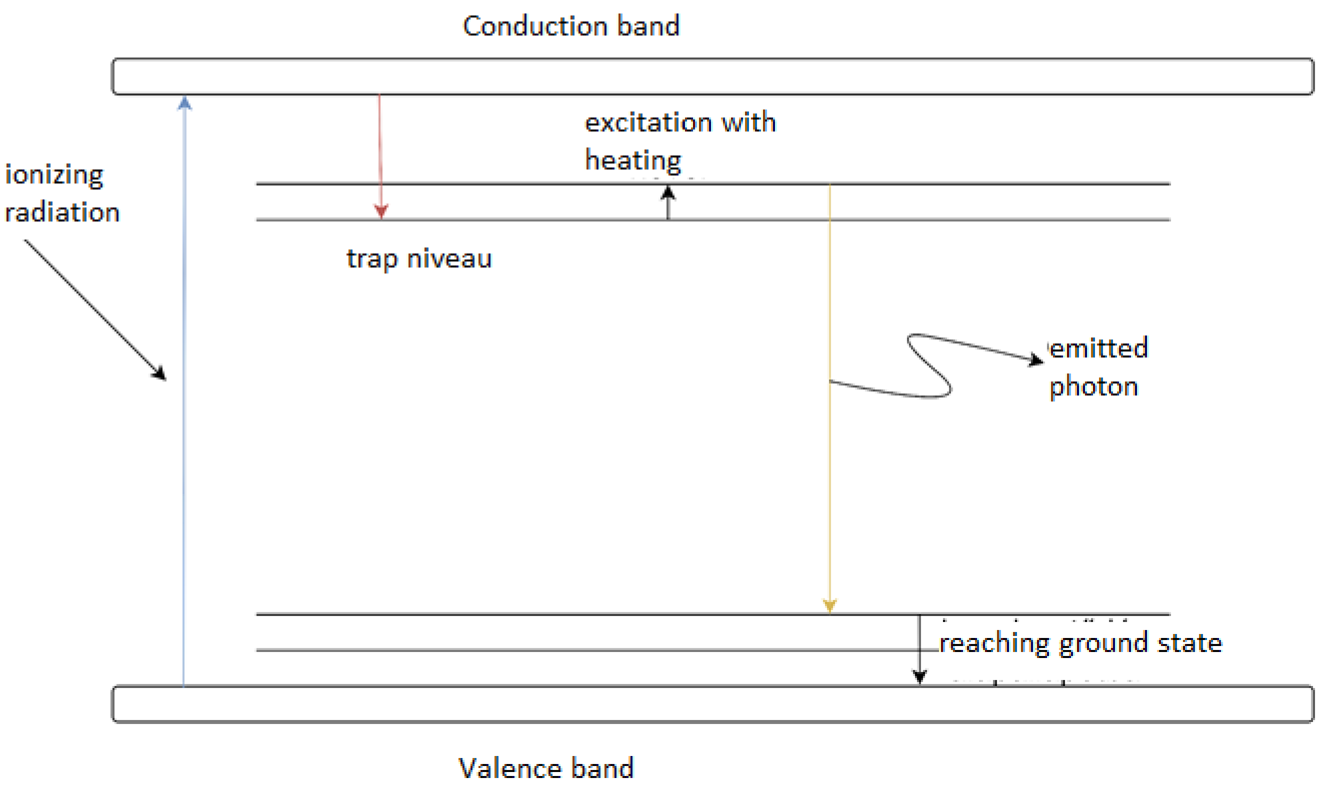
Spectrum of semiconductor detector



Boadening for NaI and HPGe detectors



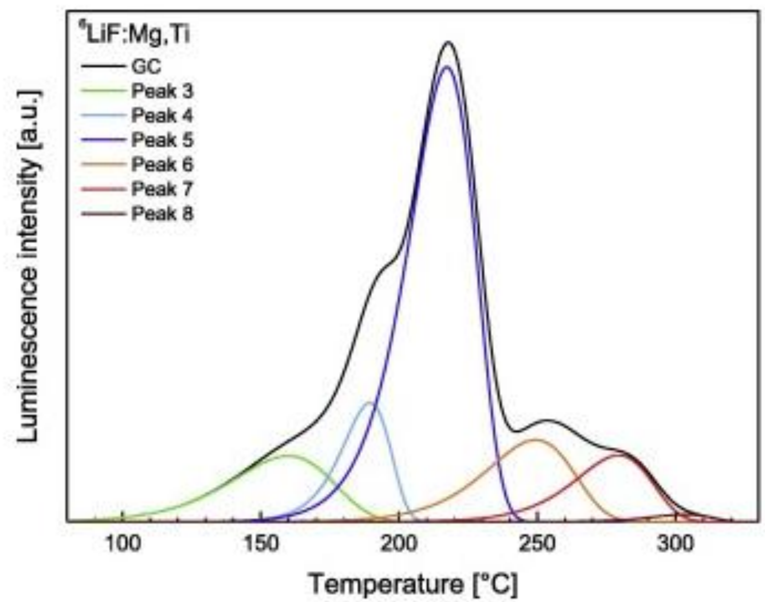
Thermoluminescent dosimeters



Thermoluminescent dosimeters

- Small size
- Low cost
- Reusable
- In vivo dosimetry

- Measurement data is erased, one chance to read out
- Post hoc results
- Time-consuming
- Calibration and preparation required



Glow curve

TLD in personal dosimetry

- **Passive detectors**
- **Cumulative dose**
- Dose accumulation over **2 months**
- Evaluated by the **National Personal Dosimetry Service**
- Can be retrieved from the **National Personal Dosimetry Registry**

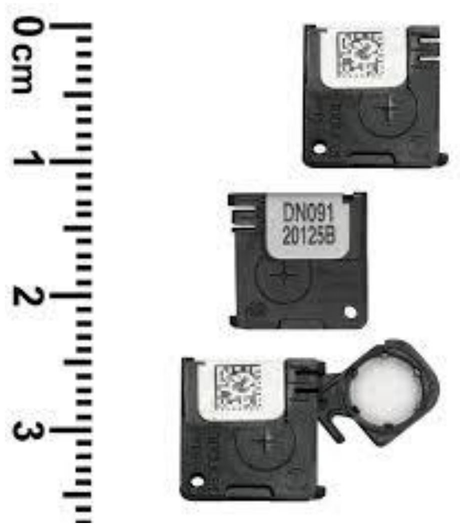
Personal dosimeter- UD802AT

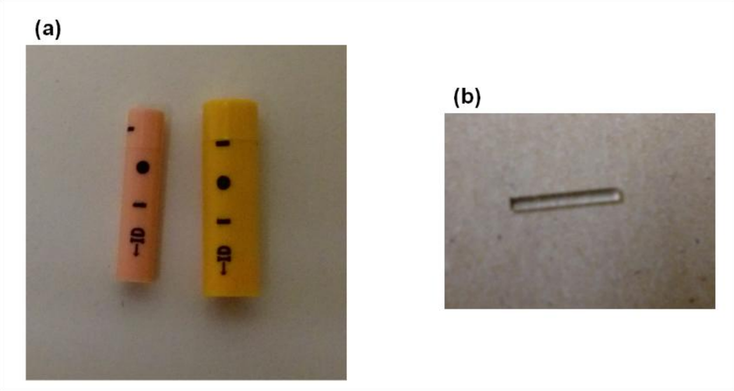
Dosimeter	UD802AT
# of TL detectors with filters	4 db
Gamma energy	10 keV ... 10 MeV
Dose range	10 µSv ... 10 Sv
Detection limit	1,6 µSv
Cycles of readouts	> 1000
Fading	5% / év

TLD alternatives

OSLD – Optically Stimulated Luminescence Dosimetry
RPLD – RadioPhoto Luminescence Dosimetry

- Luminescence stimulated by light – instead of heating
- Measurement results can be read multiple times





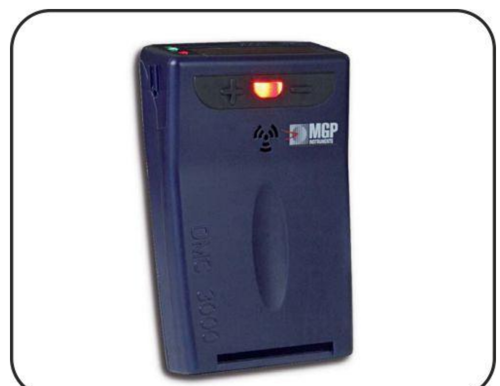
Alternatives for personal dosimetry

Film dosimeters

- Cumulative dose
- Selectivity achievable with filters
- Can be read multiple times in the short term
- However, cumbersome storage and evaluation procedure

Electronic dosimeters

- Cumulative dose, suitable even for monitoring very short operations
- Possibility to store data
- Application of warning levels
- Electronic auxiliary functions (reset, close-range data transfer, etc.)



Surface contamination measurement

Contamination detection

- End-window GM tube
- Some proportional counters
- Low-activity gamma contamination is poorly measurable

Qualitative analysis of contamination

- With a proportional counter
- With a scintillation detector

RadEye AB100

- Dual-phosphor scintillator
- ZnS scintillator for alpha particle detection
- Plastic scintillator for beta particles

  Field measurement auxiliary options:
- Headphones for noisy environments

  >1000 hours battery life
- Audio signal for alpha and beta particles, with increasing frequency proportional to the count rate

RadEye B20

Similar mobile measurement support functions

Extension rod for higher activity

Use of filters for selectivity

Application	Contamination $\alpha\beta\gamma$	Contamination $\beta\gamma$	Dose Rate $H^*(10)$	Dose Rate $H'07$
Autodetection Filter	No Filter	Alpha Blocker 425068581	H*(10)Filter 425068582	H'07 Filter 425068583
RadEye B20 / B20-ER				
Filter Code displayed at the LCD	No Code	(α Blocker)	(H*(10))	(H'07)
Related Units	cps cpm Bq/cm² Bq dpm dps	cps cpm Bq/cm² Bq dpm dps	Sv/h rem/h	Sv/h rem/h

Neutron detection

- **Difficult to detect** due to the low interaction probability,

  especially for fast neutrons.

  Neutron thermalization is required for measurement.

  A **gas-filled proportional counter** surrounded by a

  moderator medium is used.

  The fill gas is mostly **BF$_3$**.

  The neutron interacts with **boron**, and the resulting photon

  can be detecte

$$
n + {}^{10}B \begin{cases} \rightarrow\ {}^{7}Li^{*} + {}^{4}He + 2{,}31\ \text{MeV} + 0{,}48\ \text{MeV}\ \gamma\ \text{foton} & (93{,}7\ \%) \\ \rightarrow\ {}^{7}Li + {}^{4}He + 2{,}79\ \text{MeV} & (6{,}3\ \%) \end{cases}
$$

$$
{}^{7}Li^{*} \rightarrow {}^{7}Li + 0{,}48\ \text{MeV}\ \gamma\ \text{foton}
$$

Neutron detectors (H*(10))

	Wedholm 2222A	Berthold LB 6411	Thermo Scientific FHT 762
Detector	BF3	3He/CH4	3He
Moderator	PE(B)	polietilen (2% carbon)	polietilen/ tungsten
Energy Range	0,025 eV- 17 MeV	0,025 eV- 20 MeV	0,025 eV – 20 MeV
Dose rate range	1 μSv/h- 1000 mSv/h	30 nSv/h- 100 mSv/h	1 nSv/h- 100 mSv/h
Dead time	1 μs	5 μs	
Sensitivity	0,35…0,5 cps/μSv/h	1,27 cps/ μSv/h	0,84 cps/ μSv/h
Average background count	0,0083 cps	<0,02 cps	
Gamma sensitivity	2 Gy/h <10μSv/h@10 mSv/h	<40 μSv/h@ 10 mSv/h	1…5 μSv/h@ 100 mSv/h
Directional dependence	significant	-30%...+30%	-20%...+20%

THANK YOU!