DETECTORS OF RADIATION

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Summary

This article focuses on the detection of gamma and X-radiation. It provides an introduction to the interaction of gamma and X-radiation with matter. Then it describes the principles of the most widely applied detector types, varying from ionization chambers and semiconductor detectors to scintillation detectors and microcalorimeters. The state of the art of these detectors, and their availability, is presented. Practical aspects related to the use and fields of application of the various detector types are discussed. Performance indicators are given for detectors used in X-ray and gamma-ray spectroscopy. Where relevant, it examines the spin-off of recent innovations.

1. Introduction

A detector is a device that responds informatively to the phenomena to which it is exposed. Detection of (nuclear and X-) radiation starts with the interaction of the radiation with matter, resulting in a conversion of the energy of the radiation into the generation of photons (light), electrical charge, or heat. Henri Becquerel discovered the phenomenon radioactivity in 1896 using the photographic plate. Soon after, Pierre and Marie Curie used the first simple ionization chambers based upon a parallel-plate condenser connected to an electrometer for their measurements of radioactivity in chemicals and natural materials. Rutherford in his early work in the 1900s used a gold-leaf electroscope, invented in 1777 by Abraham Bennet for his studies on static electric charge. Silver-activated zinc-sulfide crystals were shown by Crookes in 1903 to scintillate if bombarded by α-particles. It was not until 1947 that Kallmann and Bell showed that single crystals of naphthalene and anthracene could be used as scintillators for detection of ionizing radiation, and in 1948 Hofstadter demonstrated the capabilities of the thallium-activated sodium-iodide crystals. Jaffe showed in 1932 that certain solids could serve as base materials for solid-state ionization detectors, but it took until about 1960 before silicon and germanium of sufficient size and properties became available to allow the construction of radiation detectors.

This article focuses on the detection of gamma and X-radiation. The principles of the most widely applied detector types are described, as are the state of the art, detector availability, and practical aspects related to detector use and fields of application. Where relevant, there's a discussion of spin-off innovations.

2. Gamma and X-Radiation

This section provides background and overview information on gamma and X-radiation. It then describes interactions of gamma and X-radiation with matter, focusing on the photoelectric effect, the Compton effect, and the pair production process, all of which are principal contributors to the probability that a photon interacts in an absorber.

2.1. Introduction

Gamma (γ) and X-radiation are, like visible light, types of electromagnetic radiation. Gamma radiation is often also denoted as photons. The principal difference between gamma and X-radiation is that gamma radiation originates from transitions between excited states of the atomic nucleus whereas X-radiation results from energy loss of electrons, either by slowing-down processes or by transitions to an electron shell closer to the atomic nucleus. Shell transitions of electrons in the outer electron shells also result in visible light: this phenomenon is called scintillation.

Gamma and X-radiation are characterized by their energy E or wavelength λ, which are related by

$$E = h \times \frac{c}{\lambda} \qquad (1)$$

in which E is energy of the radiation, in keV, h (Planck's constant) is $4.135\ 669 \times 10^{-15}$ eV Hz^{-1}, λ is the wavelength, in m, and c (velocity of light in a vacuum) is $2.997.926 \times 10^{8}$ m s^{-1}.

Scintillation photons and visible light have energies up to a few eV. X-radiation has energies varying between less than 1 keV and about 150 keV. This energy range overlaps with the energy range typical for gamma radiation, which varies between 10 keV to 10 MeV. It should be noted that cosmic gamma rays have energies that are orders of magnitude higher, and may vary between 1 MeV to even > 10^{8} MeV. This type of radiation is not considered here.

The energies of gamma and X-radiation are well defined, and their emission accompanies most nuclear reactions and nuclear decays. Röntgen, using a gas discharge tube, discovered X-radiation in 1895. Other types of electromagnetic radiation with energies in the range of gamma and X-radiation are annihilation radiation and *Bremsstrahlung*. Annihilation radiation results from the reaction of a positron with an electron, and consists of two photons of 511 keV each that are emitted in opposite directions. *Bremsstrahlung* is a German word meaning "slowing-down radiation." This radiation is produced by the interaction of fast electrons with the Coulomb field of the nucleus. Its production is usually associated with lightly charged particles, e.g.,

energetic electrons in absorbers of high atomic number. The energy spectrum is continuous with a maximum value close to the energy of the charged particle, but with a lower average value.

Gamma radiation, X-radiation, and other electromagnetic radiation are ionizing radiation and hidden from direct (visual) observation. Indirect observation is possible, if the radiation interacts with matter. Then the products resulting from that interaction can be detected and recorded by physical and/or electronic means (see *Radioactivity, Atomic Model, Röntgen*).

2.2. Interaction of Gamma and X-radiation with Matter

When ionizing radiation passes through matter, an interaction may occur with the atoms, electrons, and atomic nuclei. The interaction process is easier to understand by referring to the radiation as incident photons, and by considering the particles with which they interact as target particles. More than ten different ways of interacting can be distinguished, but in the energy region of gamma and X-radiation resulting from decaying radionuclides and nuclear reactions, the most important interactions are the photoelectric effect, the Compton effect, and pair production. Although the interaction of electromagnetic radiation with matter is independent of the origin of the radiation (gamma radiation, X-radiation, annihilation radiation, and *Bremsstrahlung*), only the term gamma radiation will be used (see *Radioactivity, Interaction of Radiation with Matter*).

2.3. The Photoelectric Effect

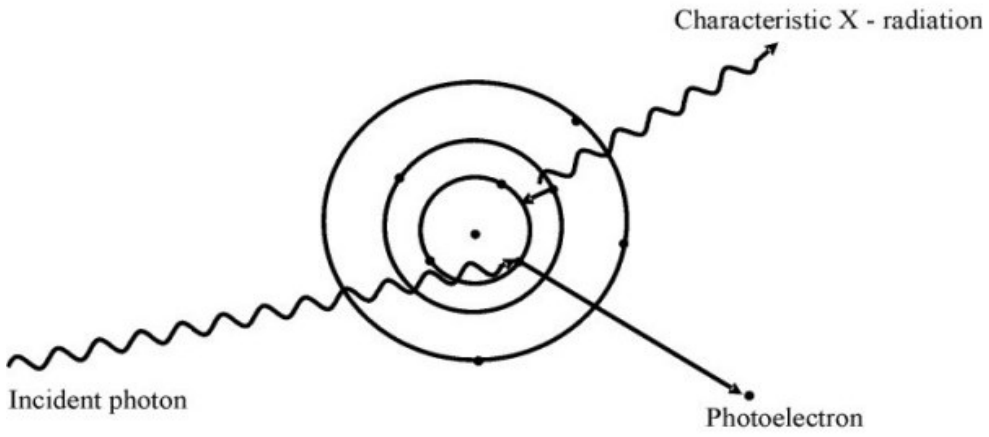

Figure 1. Schematic representation of the photoelectric effect

The photoelectric effect is a process in which the total energy Eγ of a photon is transferred to an atomic electron, preferably from an inner shell (see Figure 1).

The probability that a photon will undergo photoelectric interaction is expressed as a cross section, $\sigma_{pe.}$ The value of this cross section depends on the atomic number *Z* of the absorber material, and the energy E_γ of the radiation. An exact dependence cannot be given, but in a first approximation these relationships may serve:

$$\text{for } E_\gamma < \sim 500 \text{ keV:} \qquad \sigma_{pe} \div \frac{Z^{4.5}}{E_\gamma^{-3.5}} \tag{2}$$

$$\text{for } \sim 500 \text{ keV} < E_\gamma < \sim 1000 \text{ keV} : \quad \sigma_{pe} \div \frac{Z^{4.5}}{E_\gamma^{-2}} \tag{3}$$

$$\text{for } E_\gamma > \sim 1000 \text{ keV: for } > E_\gamma \sim 1000 \text{ keV} : \sigma_{pe} \div \frac{Z^{4.5}}{E_\gamma^{-1}} \tag{4}$$

The following relationship exists between the photoelectric absorption cross section σ_{pe} and the photoelectric linear attenuation coefficient $\mu_{pe,l}$ (cm^{-1})

$$\mu_{ph,l} = \sigma_{pe} \times \rho \times \frac{N_{Av}}{A} \tag{5}$$

with ρ = the density of the absorbing material in $kg.m^{-3}$, N_{Av} (Avogadro's number) = $6.023.10^{29}$ $atoms.m^{-3}$, and A = the atomic mass of the absorbing material.

It is generally assumed that photoelectric absorption results in complete absorption of the energy carried by the photon. The photoelectron will successively lose its energy E_γ-E_b in the absorber. During filling of the vacancy in the electron shell, E_b is released through emission of X rays or Auger electrons. The energy carried by the low energy Auger electron will be transferred completely to the absorber. As a result of the subsequent process, the energy deposited in the absorber amounts to

$$E_\gamma - E_b + E_b = E_\gamma \tag{6}$$

However, when considering an absorber of limited dimensions or in case of interaction near the surface of the absorber, the X-radiation may "escape" from the absorber, limiting the total amount of energy deposited to (in case of a K X ray, energy E_K)

$$E_\gamma - E_b + E_b - E_K = E_\gamma - E_K \tag{7}$$

2.3.1. The Compton Effect

In the Compton effect a photon interacts with a free or loosely bound electron in the absorbing material. In this interaction, only a part of the photon energy is transferred to the Compton electron (Figure 2).

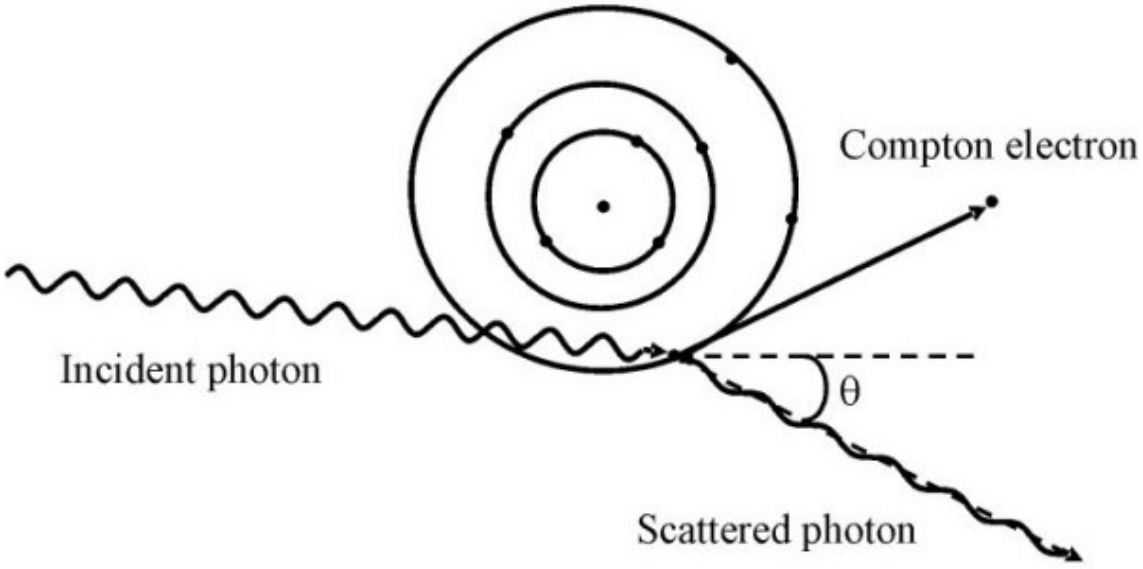

Figure 2. Schematic representation of the Compton effect

The distribution of the photon energy E_γ between the Compton electron e^-_c and the remaining Compton photon γ_c depends on the initial photon energy and the angle θ between the directions of the primary photon and the Compton photon:

$$E_{\gamma_c} = \frac{E_\gamma}{1+\alpha(1-\cos\theta)} \tag{8}$$

where

$$\alpha = \frac{E\gamma}{m_e \ c^2} = \frac{E\gamma}{511} \tag{9}$$

in which m_e = the mass of the electron, and E_χ is expressed in keV.
The Compton scattering absorption cross section σ_c is related to the absorber material and the photon energy. If calculated per unit mass, the cross section is almost independent of the atomic number and

$$\sigma_C = f(E_\gamma) \tag{10}$$

which function is approximated by the Klein-Nishina equation.

The (linear) Compton scattering attenuation coefficient $\mu_{c,l}$ follows from

$$\mu_{c,l} = C \times \rho \times f(E_\gamma) \tag{11}$$

where C is constant.

2.3.2. The Pair Production Process

Above a threshold of 1022 keV, the incident photon may interact with the electric field of the atomic nucleus. This results in the conversion of the photon into an electron-positron pair. The photon is completely absorbed in this process (Figure 3).

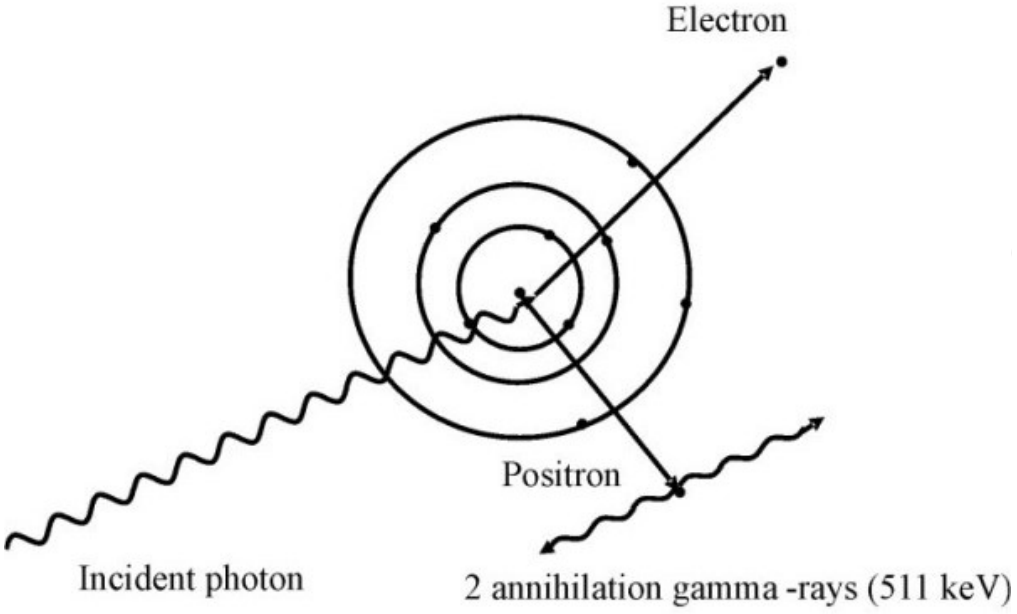

Figure 3. Schematic representation of the pair production process

The threshold energy arises from the energy required to create the electron-positron pair, which is equivalent to $2m_e c^2$ = 1022 keV. The excess energy of E_γ-1022 keV is carried by the two electrons as kinetic energy. Initially this energy is transferred to the absorber. When the positron has lost its kinetic energy it will meet an electron and annihilate, resulting in two annihilation photons of 511 keV each. These photons can escape or deposit their energy partially or totally in the absorber. The net energy absorbed as a consequence of pair production is therefore:

- if 2 annihilation photons escape, E_γ – 1022 keV;
- if 1 annihilation photon escapes, E_γ – 511 keV; and
- if both annihilation photons undergo photoelectric effect and absorption, E_γ keV.

The cross section for pair production, σ_{pp}, depends on the photon energy and the atomic number of the absorber in a complicated way:

$$\sigma_{pp} \div Z^2 f(\ln E_\gamma) \qquad (12)$$

Unlike the photoelectric effect and the Compton effect, pair production has a cross section that slowly increases with photon energy. This type of interaction tends to be the dominant one at high photon energies, $E_\gamma > 5$ MeV.

The (linear) pair production attenuation coefficient, $\mu_{pp,l}$, is derived from this cross section similarly as for the photoelectric attenuation coefficient:

$$\mu_{pp,l} = \sigma_{pp} \times \rho \times \frac{N_A \nu}{A} \tag{13}$$

2.3.3. Total Attenuation

The three processes are the principal contributors to the probability that a photon interacts in an absorber. This probability, σ_T, follows from summing the individual interaction cross sections:

$$\sigma_T = \sigma_{pe} + \sigma_c + \sigma_{pp} \tag{14}$$

and, similarly, the total linear attenuation coefficient

$$\mu_{T,l} = \mu_{pe,l} + \mu_{c,l} + \mu_{pp,l} \tag{15}$$

and the total mass attenuation coefficient

$$\mu_{T,m} = \mu_{pe,m} + \mu_{c,m} + \mu_{pp,m} = \frac{N_A \nu}{A}(\sigma_{pe} + \sigma_c + \sigma_{pp}) \tag{16}$$

For a specific energy and atomic number of the absorber, one of the processes can be dominating (see Figures 4 and 5).

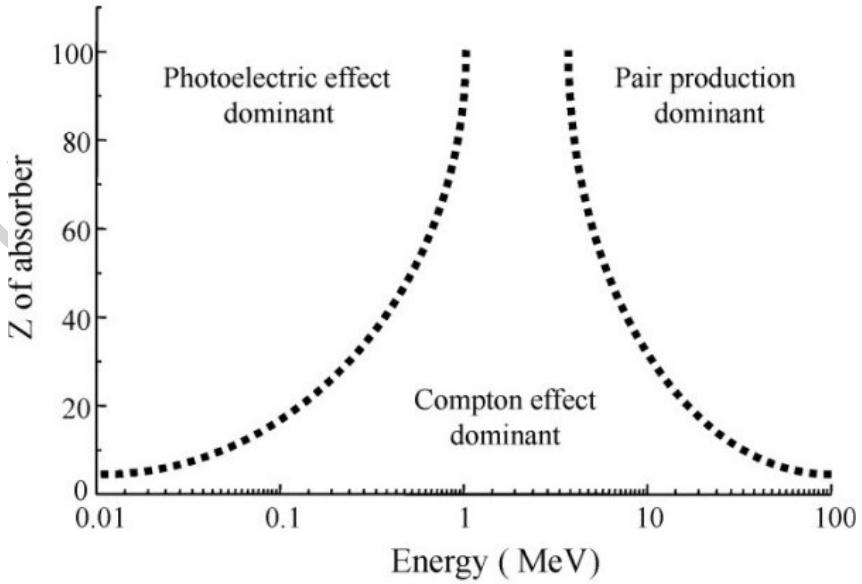

Figure 4. Relationship between photon energy and type of interaction

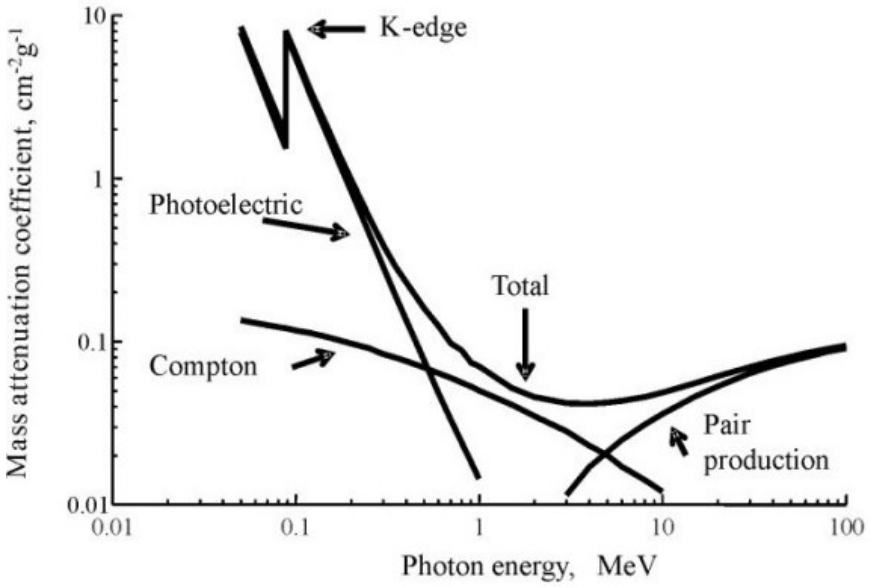

Figure 5. Relationship between attenuation coefficients and photon energy

3. Radiation Detectors

The interaction of gamma and X-radiation with matter results in, among other things, ionization processes and subsequent generation of electrical signals that can be detected and recorded. A radiation detector therefore consists of an absorbing material in which at least part of the radiation energy is converted into detectable products, and a system for the detection of these products. These ionization products can be detected directly or indirectly.

In ionization detectors such as gas-filled detectors and semiconductor detectors, the ions or the electrons are collected directly by applying an electric field over the absorbing medium and subsequently collecting the free charge carriers on the electrodes.

In scintillation detectors the ionization is measured indirectly through the secondary detection of light scintillations to which the absorbing material is transparent. The difference between direct and indirect detection of ionization products results directly in a considerable difference in statistical distribution of the observed events and thus of radiation energy resolution capability.

Eventually, the deposition of energy due to the interaction of radiation with matter results in a minute generation of heat. This process also offers an opportunity for detection of radiation, and microcalorimeters for X-ray spectrometers are based on it.
The major requirements for ionization detectors are:

- Large number of ionizations per unit absorbed energy
- Low concentration of the free-charge carriers when no radiation is absorbed
- Long life and high mobility of the electrons and ions so that the charge carriers can reach the electrodes before recombination would occur
- High probability of interaction between the radiation to be measured and the absorber material

The suitability of a scintillator for use in radiation detectors depends on the following main properties:

- High efficiency for converting the absorbed energy into light photons
- The wavelength of the emitted light close to the maximum of the spectral sensitivity of the photomultiplier tube
- The intensity of the light emitted by the scintillator after an absorption event decays exponentially with time. The related material dependent time constant should be in the range of a few ns to a few μs.
- The scintillator transparent for the emitted light

4. Ionization Detectors

This section introduces and describes three categories of ionization detectors. The first is gas-filled radiation detectors, which include ionization chambers, proportional counters, and Geiger-Müller counters. The second category is semiconductor detectors, which include surface barrier detectors, position-sensitive silicon detectors, and silicon drift chambers. The third is integrating solid state devices.

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Biographical Sketch

Peter Bode has a degree in chemical technology from Delft University of Technology, where he also got his Ph.D. He has been employed by the Interfaculty Reactor Institute since 1970 for neutron activation analysis, gamma-ray spectrometry, and other nuclear analytical techniques. He is head of the laboratory for instrumental neutron activation analysis (INAA), and the current research program focuses on, among other things, the direct analysis of large (kg-scale) samples. In 1993, the laboratory for INAA became the first accredited (EN45001) INAA laboratory in the world. Dr. Bode is listed on 100 scientific publications. As a next step after quality assurance and quality management, metrology in chemical measurements has gained his interest, and he is exploring opportunities for using neutron activation analysis and nuclear analytical techniques.