10.3.2.3 Radiation detectors

10.3.2.3.1 Photographic detection

Photographic detection and *photographic intensity measurement* are not included in this edition of the compendium. IUPAC nomenclature on this topic can be found in "Nomenclature, symbols, units and their usage in spectrochemical analysis - Part I, General atomic emission spectroscopy", prepared by Commission V-4 under the chairmanship of V.A. Fassel and published in Pure and Applied Spectroscopy, *30* (1972) 658.

10.3.2.3.2 General properties of radiation detectors

The *radiation input*, i.e. the quantity to be measured by a *radiation detector* may be *radiant power* ϕ, *irradiance* E, *radiant energy* Q, or *radiant exposure* H (see Part I). The respective SI units are [W], [W m^{-2}], [J], [J m^{-2}].

The input of a detector may consist of either monochromatic or polychromatic radiation. With monochromatic radiation the respective radiation quantity is contained in a narrow wavelength band $d\lambda$. Polychromatic radiation covers a certain wavelength range and has a characteristic distribution as a function of wavelength. The corresponding radiation quantities are defined as *spectral power* $\phi_\lambda = d\phi(\lambda)/d\lambda$ (units: W nm^{-1}), and *spectral irradiance* $E_\lambda = dE(\lambda)/d\lambda$ (units: W m^2 nm^{-1}), *spectral radiant energy* $Q_\lambda = dQ(\lambda)/d\lambda$ (units: J nm^{-1}), and *spectral radiant exposure* $H_\lambda = dH(\lambda)/d\lambda$ (units: J m^{-2} nm^{-1}). In many cases it is appropriate to describe the radiant power by means of the number of *photons* or *quanta* arriving per unit time. If the energy of one quantum is $J_q = hv = hc/\lambda$ (units: J), where h is the Planck constant, v the frequency, λ the wavelength and c the velocity of propagation of the radiation in vacuum, then the number, N, of quanta of a given radiant energy is $N = Q/J_q = Q/hv = Q\lambda/hc$. If Q has a spectral distribution characterized by the spectral radiant energy Q_λ, then the number of quanta for a given interval is $dN = (Q_\lambda \lambda/hc)d\lambda$ and the total number is

$$N = (\frac{1}{hc})\int Q_\lambda \lambda d\lambda$$

The *photon flux* is the number of photons per unit time, $\phi_p = dN/dt$ (units: s^{-1}). Similarly, the *photon irradiance* is defined as photon flux per unit area dA, $E_p = d\phi_p/dA$ (units: s^{-1} m^{-2}).

10.3.2.3.3 Types of detectors

A *radiation detector* is a device in which *incident radiation* produces a measurable effect. If this effect is a rise in temperature it is called a *thermal detector*. If it is a rise in pressure it is called a *photoacoustic detector*. In the case where an electrical signal is produced it is called a *photoelectric detector*. Photoelectric detectors can be classified as *photo-emissive detectors* and *semiconductor detectors*. Where the radiation produces a chemical reaction, it is termed a *photochemical detector*.

A detector yielding an *output signal* that is independent of the wavelength of the radiation over a specific region is called a *nonselective detector*. Where it is wavelength specific it is a *selective detector*. A detector having a *quantum efficiency* independent of the wavelength is a *nonselective quantum counter*. Different types of detectors may be used for *integrated* and *time-resolved measurements*. Other types of detectors are used for *spatially resolved measurements*.

Certain types of detectors are able to distinguish between different quantum energies. This property is described by the *energy resolution*, ΔE, and the *energy resolving power*, $E/\Delta E$. These detectors are called *energy dispersive detectors*. In X-ray spectroscopy, the reciprocal $\Delta E/E$ is often used but this is discouraged.

10.3.2.3.4 Detector properties

Appropriate terms, symbols and units are listed in Table 10.7.

The *detector input* can be e.g. radiant power, irradiation, or radiant energy. It produces the measurable *detector output* which may be e.g. an electrical charge, an electrical current or potential or a change in temperature. The ratio of the detector output and the detector input is defined as the *responsivity*, $\Re$. It is given in e.g. ampere/watt, volt/watt. The responsivity is a special case of the general term *sensitivity*. *Dark current* is the term for the output of a detector in the absence of input. This is a special case of the general term *dark output*. For photoconductive detectors the term *dark resistance* is used. If the responsivity is normalized with regard to that obtained from a reference radiation the resulting ratio is called *relative responsivity*. For measurements with monochromatic radiation at a given wavelength λ the term *spectral responsivity* $\Re(\lambda)$ is used. In some cases the *relative spectral responsivity*, where the spectral responsivity is normalized with respect to the responsivity at some given wavelength, is used. The dependence of the spectral responsivity on the wavelength is described by the *spectral responsivity function*. The *useful spectral range* of the detector should be given as the wavelength range where the relative responsivity does not fall below a specified value. *Linearity of responsivity* describes the extent to which the output of the detector is proportional to the incident radiant power at a given wavelength and at constant irradiation geometry.

A figure of merit related to the responsivity is the *quantum efficiency* $\eta(\lambda)$. It describes the number of elementary events, e.g. electrons or pulses produced by one incident photon. In

TABLE 10.7 Terms, symbols and units for measurable quantities for radiation detectors

Term	Symbol	Practical Unit	Notes
Responsivity	$\mathfrak{R}$	e.g. A W^{-1}	
Spectral Responsivity	$\mathfrak{R}(\lambda)$	e.g. A $W^{-1}nm^{-1}$	
Noise-equivalent-power	ϕ_{N}	W	
Detectivity	D	W^{-1}	$D = 1/\phi_{\mathrm{N}}$
Normalized detectivity	D^*	W^{-1}mmHz–	$D^*=D(A\Delta f)^{½}$
Detector sensitive area	A	mm^2	
Detector quantum efficiency at wavelength λ	$\eta(\lambda)$	1	
Detector sensitive volume	V	mm^3	
Frequency bandwidth	Δf	Hz	
Dark current	i_d	A	
Signal current	i_s	A	
Mean square noise current	$\sqrt{\bar{i}^{\,2}_{N}}$	A	
Load resistance	R_{L}	W	
Multiplier gain	G	1	
Signal-to-noise ratio	r_{SN}	1	$r_{\mathrm{SN}} = i_S /\sqrt{\bar{i}}$
Dark resistance	R_{d}	W	
Time constant	τ_{c}	s	
Rise time	τ_{r}	s	
Fall time	τ_{f}	s	
Response time	τ_{R}	s	$\tau_{\mathrm{R}} = \tau_{\mathrm{r}} + \tau_{\mathrm{f}}$

the case of photoelectric detectors where the output is a current the quantum efficiency is related to the spectral responsivity by means of $\eta(\lambda) = (\mathfrak{R}(\lambda)/\lambda)(hc/e)$ where e is the elementary charge. The responsivity of a detector may depend on the degree of polarization of the incident radiation giving rise to a *polarization effect*.

All signals exhibit undesirable fluctuations that are called *noise*. The frequency distribution of noise is characterized by a *power spectrum*. Two different types of noise can be observed, *periodic* and *nonperiodic noise*. The periodic noise is usually observed as *high-frequency proportional noise*. The nonperiodic noise can be divided into noise observed only at low frequencies, the *excess low-frequency noise*, and noise independent of the frequency, the *white noise*. When the excess low-frequency noise is proportional to the reciprocal of the frequency, i.e. to $1/f^{\alpha}$ (with α close to 1), the noise is called *flicker noise*. *Drift* can be considered as noise with a slow fluctuation period. A noise is generally represented by a root mean square value (RMS) of the fluctuation, which is equivalent to a standard deviation provided a Gaussian distribution can be assumed.

Detector noise originates in the detector and can be classified as:

Thermal or Johnson noise (see Note 1) due to the thermal agitation of current carriers in a resistive element.

Temperature noise (mainly for semiconductor detectors) due to the statistical processes of heat exchange between the detector and its surroundings, which produce a fluctuation of the electric signal. It is especially important in the case of thermal detectors (see Note 2) (see section 5).

Generation-recombination noise due to the statistical nature of charge carrier generation and recombination processes.

Contact noise due to current fluctuations across electrical contacts.

Radiation noise due to statistical fluctuations in the "arrival" of the photons.

Dark current noise due to the sum of noise currents in the absence of a signal, including fluctuations of thermionic emission, of leakage current, of corona discharge charge carriers and other physical effects.

Shot noise is the sum of the radiation noise and the statistical component of the dark current noise.

The smallest signal that can be determined is limited by noise. The noise equivalent power ϕ_N is the incident radiant power resulting in a signal/noise ratio of 1 within a bandwidth of 1 Hz and at a given wavelength. The reciprocal of the noise equivalent

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Note 1 The term Nyquist noise has been used. The term Johnson noise is preferred.

Note 2 Consequently, the detectivity of thermal detectors increases on cooling, whereas the pyroelectric detector functions in a different way and its detectivity is not affected by temperature noise.

power is defined as *detectivity*, *D*. It is useful to normalize the detectivity by referring it to the sensitive area *A* of the detector and the *frequency bandwidth*, Δf, of the measurement, resulting in the *normalized detectivity*, *D**, which is defined by means of the following equation:

$$D^* = D(A\ \Delta f)^{1/2}$$
$$= (1/\phi_N)(A\ \Delta f)^{1/2} \text{ (units: } W^{-1} \text{ mm } s^{-}\text{–)}$$

It is recommended that D^* be reported in the form D^* (500 K, 900, 1) = ... or D^*_λ (5 mm, 900, 1) = ... These refer respectively to the value of D^* for a 500 K black body, or a 5 mm narrow-band source as measured at 900-Hz chopping frequency, and a 1-Hz noise bandwidth.

Every detector has a time constant. If the output changes exponentially with time, the time required for it to change from its initial value by the fraction $(1-\exp(-t/\tau_c)$(for $t = \tau_c$) of the final value, is called *time constant* τ_c. The *response time*, τ_R, is the time required for the detector output to go from the initial value to a percentage (e.g., 99%) of the final value. In the case of an exponential behaviour of the detector, τ_R, can be related to τ_c. The *rise time*, τ_r, is the time required for the detector output to vary between given percentages (e.g., from 10% to 90%) of the final value. Similarly, the *fall time*, τ_f, is the time required for the detector output to vary between given percentages (e.g., from 90% to 10%) of the initial value. The *delay time* and the response time of the detector may be due to the *transit time* of *charge carriers* within the detector. The detector response to a hypothetical Dirac function input exhibits a final bandwidth, defined by *spread time*, τ_{sp}, which is due to τ_r and τ_f.

For constant input the output, and hence the responsivity, can change with time. If this change of responsivity with time is reversible it is called the *fatigue effect*. It may also be the cause of *hysteresis*. If, however, the change is irreversible, one speaks of *aging*. If an operating parameter e.g. the supply electric potential is changed, the responsivity may need time, i.e. the *settling time*, to reach the new final value.

The *detector sensitive area* is that area of the detector where an incident radiant power results in a measurable output. The *detector sensitive volume* of the detector is that volume of the detector where an incident radiant power produces a measurable output. *Detector homogeneity* is specified by the *effective sensitive area* or the *effective sensitive volume* where the responsivity is homogeneous to within specified limits. The dependence of a detector on temperature can be described by the *temperature coefficient of responsivity* and is expressed as percentage change in output per °C. In the case of a nonlinear dependence the temperature and the temperature range for which the temperature coefficient of responsivity is applicable should also be stated.

10.3.2.3.5 Thermal detectors

Thermal detectors ideally exhibit a wide wavelength-independent response. Thermal detectors are amenable to absolute calibration. Thermal detectors so calibrated are called *absolute radiometers*. A *thermocouple* is based on the *thermoelectric effect*, by which two junctions between dissimilar conductors (metallic or heavily doped semiconductors) kept at different temperatures generate an electric potential. This potential depends on the amount of radiant energy absorbed by the *active junction*, while the *compensating junction* serves as a reference. A *thermopile* consists of several thermocouples connected in series to increase the magnitude of the electric potential. A *bolometer* is a detector constructed from a material having a large *temperature coefficient of resistance*. Absorption of radiation gives rise to a change in resistance. A bolometer is named according to its active component, e.g. *thermistor bolometer*, *semiconductor bolometer*, *superconductor bolometer*.

A *pyro-electric detector* is based on the temperature dependence of *pyro-electricity*. The material forms the dielectric in a small capacitor, and the change in surface potential is detected as the detector is intermittently irradiated.

A pressure change as a result of the absorption of radiation is used for a *pressure-sensitive detector*. A *pneumatic detector* is based on the pressure increase of a gas. A special type is the *Golay cell* where the pressure change is detected by observing the deflection of one of the chamber walls. A *photo-acoustic detector* is used to detect intermittent radiation absorbed in a black body or in the sample concerned. The resulting rapid temperature change produces a *transient pressure gradient* that is observed with the help of a *microphone*, or a *piezoelectric device*.

10.3.2.3.6 Photo-emissive detectors

In a *photo-emissive detector*, a photon interacts with a solid surface, the *photocathode*, or with a gas, releasing a photoelectron. This process is called the *external photoelectric effect*. The photoelectrons are collected by an electrode at positive electric potential, i.e. the *anode*.

The *vacuum phototube* (PT) is a photo-emissive detector inside an evacuated envelope with a transparent window. The useful spectral range is determined by the spectral responsivity function or by the quantum efficiency function of the photocathode (often characterized by a so-called S-number) and the spectral transmittance of the window material. A special type, the *solar blind detector*, is insensitive to radiation of wavelengths longer than some specified wavelength (e.g. 320 nm) in the UV range. The photo-tube may have a *detector window* but for UV wavelengths and X-rays for which there is no transparent window material available the detector is operated as a *windowless detector*.

Biplanar vacuum phototubes consist of a plane wire mesh anode and plane opaque cathode separated by a few mm. Operated at electric supply potentials of up to 5 kV they have response times in the nanosecond range and are capable of delivering high pulse currents. They are used in pulsed laser applications.

A *photomultiplier tube* (PMT) is a vacuum phototube (See Note 3) with additional amplification by *electron multiplication*. It consists of a photocathode, a series of *dynodes*, called a *dynode chain* on which a secondary-electron multiplication process occurs, and an *anode*. According to the desired response time, transit time, gain or dark current, different types of dynode structures have been developed, e.g. *circular cage structure*, *linear focused structure*, *venetian blind structure*, *box and grid structure*. Some special dynode structures permit combination with additional electric or magnetic fields. The *gain* of the photomultiplier is $G = k\sigma^{\mathrm{n}}$, where k is the efficiency of collection of photoelectrons on the first dynode, σ is the secondary emission ratio, i.e. the number of secondary electrons emitted for each electron incident on the dynode, and n is the number of dynodes. The PMT is a high-impedance current generator.

The *strip dynode photomultiplier* tube consists of a photocathode followed by thin dynode material on an insulating substrate. In a *continuous-strip photomultiplier*, two strip dynodes are arranged in parallel. In a *resistance-strip magnetic photomultiplier*, a uniform magnetic field is applied to the planes of the strips, so that the electrons travel in the crossed electric and magnetic fields. A *channel photomultiplier tube* (See Note 4) consists of a photocathode, a *channel electron multiplier* (CEM) system for the photoelectrons, and an anode to collect the final electron current. A number of small channels called *microchannels* can be constructed in arrays for imaging applications.

The *scintillation counter* consists of a *scintillator* coupled to a photomultiplier tube. Incident X-ray photons are converted in the scintillator into bursts of *visible light photons*, some of which fall on the photocathode and can be measured. For incident photons having energies higher than the absorption edge of the elements contained in the scintillator, an *escape peak* can be observed.

A *gas-filled phototube* is similar in construction to a vacuum phototube except that it is filled with a noble gas (usually Ar) at a pressure of about 10 Pa. Photoelectrons accelerated by the anode electric potential ionize gas atoms. The additional electrons provide a substantial intrinsic gain.

Note 3 All terms related to PT in this section also refer to PMT, eg *solar-blind PMT*.

Note 4 Use of the term channeltron is discouraged.