Section 4.5 X-RAY DETECTORS

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A wide variety of x-ray detectors is available, some counting single photons, some providing only measurements of count rate or total flux, others measuring the energy, position, and/or incidence time of each x-ray. Table 4-2 provides typical values for useful energy range, energy resolution, dead time per event, and maximum count rate capability for common x-ray detectors. For special applications, these specifications can often be substantially improved.

Table 4-2. *Properties of common x-ray detectors; ΔE is measured as FWHM.*

Detector	Energy range (keV)	$\Delta E/E$ at 5.9 keV (%)	Dead time/event (μs)	Maximum count rate (s^{-1})
Gas ionization (current mode)	0.2–50	n/a	n/a	10^{11}[a]
Gas proportional	0.2–50	15	0.2	10^6
Multiwire and microstrip proportional	3–50	20	0.2	$10^6/mm^2$
Scintillation [NaI(Tl)]	3–10,000	40	0.25	2×10^6
Energy-resolving semiconductor	1–10,000	3	0.5–30	2×10^5
Surface-barrier (current mode)	0.1–20	n/a	n/a	10^8
Avalanche photodiode	0.1–50	20	0.001	10^8
CCD	0.1–70	n/a	n/a	n/a
Superconducting	0.1–4	< 0.5	100	5×10^3
Image plate	4–80	n/a	n/a	n/a

[a] Maximum count rate is limited by space-charge effects to around 10^{11} photons/s per cm^3.

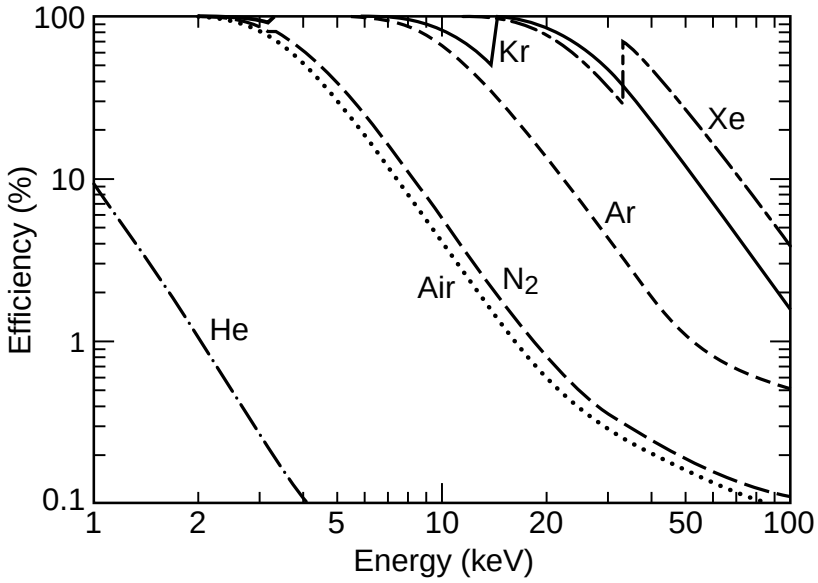

Fig. 4-10. *Efficiency of a 10-cm-long gas ionization chamber as a function of energy, for different gases at normal pressure.*

A. GAS IONIZATION DETECTORS

Gas ionization detectors are commonly used as integrating detectors to measure beam flux rather than individual photons. A typical detector consists of a rectangular gas cell with thin entrance and exit windows. Inside the detector, an electric field of about 100 V/cm is applied across two parallel plates. Some of the x-rays in the beam interact with the chamber gas to produce fast photoelectrons, Auger electrons, and/or fluorescence photons. The energetic electrons produce additional electron-ion pairs by inelastic collisions, and the photons either escape or are photoelectrically absorbed. The electrons and ions are collected at the plates, and the current is measured with a low-noise current amplifier. The efficiency of the detector can be calculated from the active length of the chamber, the properties of the chamber gas, and the x-ray absorption cross section at the appropriate photon energy. Figure 4-10 shows, for different gases at normal pressure, the efficiency of a 10-cm-long ion chamber as a function of energy. Once the efficiency is known, the photon flux can be estimated from chamber current and the average energy required to produce an electron-ion pair (Table 4-3).

Table 4-3. *Average energy required to produce an electron-ion pair in several gases*

Element	Energy (eV)
Helium	41
Nitrogen	36
Air	34.4
Neon	36.3
Argon	26
Krypton	24
Xenon	22

B. GAS PROPORTIONAL COUNTERS

Gas proportional detectors consist of a small-diameter anode wire in an enclosed gas volume. They are usually used to count single photon events. When a photon interacts in the gas, some gas atoms are ionized, and the electrons are attracted to the positive anode wire. Near the anode wire, the electrons are accelerated by the high electric field, producing a cascade of electrons that result in a large electrical pulse. The output is coupled to a low-noise preamplifier to give usable pulses. The pulse height resolution of the detector (about 20% at 6 keV) can be used for some energy discrimination, and the output counting rate can be as high as 10^6 counts per second.

C. MULTIWIRE AND MICROSTRIP PROPORTIONAL CHAMBERS

Multiwire and microstrip proportional chambers are widely used as position-sensitive detectors of both photons and charged particles. Multiwire chambers use a grid of fine wires spaced about 2 mm apart as the anode plane in a gas proportional chamber. Microstrip detectors use a patterned anode plane. The spatial resolution can be as good as 30 μm. Recently gas electron multiplying (GEM) detectors have been developed that have improved spatial resolution and lower operating voltages [1].

D. SCINTILLATION DETECTORS

Scintillation detectors work by converting x-rays to optical photons in special materials and then detecting the light with a photomultiplier tube or a photodiode. The scintillator materials can be either organic scintillators, single crystals of thallium-activated sodium iodide [commonly referred to as NaI(Tl)], single crystals of sodium-activated cesium iodide [CsI(Na)], or single crystals of bismuth germanate (BGO). Since the light output is low (about 200–300 eV is required for each optical photon), the energy resolution is also low. Organic scintillators have very poor energy resolution, whereas the NaI(Tl), CsI(Na), and BGO crystals have energy resolutions of about 40% at 10 keV. These detectors can have a time resolution of better than 1 ns and a count rate capability up to 2×10^6 photons per second. For a scintillator thickness of more than 5 mm, for both NaI and CsI, the detection efficiency between 20 and 100 keV is essentially unity.

Gas scintillation detectors combine the operation of gas ionization chambers and photon detectors to give improved performance. Electrons generated from photon or charged-particle interactions in a gas (usually pure xenon or argon with 1% xenon) are accelerated in a high-field (~3 kV/cm) region, where they produce UV scintillation light. This light is usually wave-shifted and then detected by a photomultiplier. These detectors have an energy resolution about two to three times better than conventional proportional chambers.

E. ENERGY-RESOLVING SEMICONDUCTOR DETECTORS

Silicon and germanium detectors can make excellent energy-resolving detectors of single photons (about 150 eV at 5.9 keV). They are basically large, reverse-biased n^+–i–p^+ diodes. When a photon interacts in the intrinsic region, tracks of electron-hole pairs are produced (analogous to electron– positive ion pairs in a counting gas). In the presence of the electric field, these pairs separate and rapidly drift to the detector contacts. The average energy required to generate an electron-hole pair is 3.6 eV for silicon and 2.98 eV for germanium. To keep the leakage current low, the detector must have very few electrically active impurities. For example, germanium detectors are made from zone-refined crystals that have fewer than 10^{10} electrically

active impurities/cm^3. They are usually cooled to reduce the thermal leakage current. The count rate capability with an energy resolution of <200 eV is limited to about 2×10^5 per second. To handle the high counting rates available at synchrotrons, multielement arrays of 4–30 elements have been developed for fluorescent EXAFS experiments.

F. CURRENT-MODE SEMICONDUCTOR DETECTORS

Semiconductor diodes are also used in current mode to measure x-ray flux. They have very linear responses and are available with thin entrance windows. Surface-barrier detectors are good beam monitors when used with low-noise current amplifiers. In addition, silicon avalanche detectors are now available in which the silicon is biased so that there is an internal avalanche of electron-hole pairs for each interacting photon. These devices can be used at lower beam intensities in a pulse-counting mode and in current mode at higher photon fluxes. They have excellent time resolution but limited energy resolution.

G. CCD DETECTORS

CCD detectors are now used in a variety of ways for x-ray imaging. They are available with up to 4096×4096 pixels, with pixel sizes of $12\ \mu m \times 12\ \mu m$ and readout times of less than 1 s. In most scientific applications, CCD detectors are cooled to below –30°C to reduce background noise. In most systems, a thin phosphor screen converts the incident x-rays into optical photons, which the CCD detects. A commonly used phosphor is $Gd_2O_2S(Tb)$, which has a high efficiency and a light decay time of a few hundred microseconds. When used as a detector for macromolecular crystallography, a large phosphor screen (up to 300 mm^2) is usually coupled to the CCD with a tapered optical fiber [2]. On the other hand, for high-spatial-resolution x-ray imaging, a 5- to 20-μm-thick sapphire scintillation screen is optically coupled with a high-quality microscope lens to give a spatial resolution of around 1 μm [3]. For imaging with x-rays below 1 keV, direct exposure of back-thinned CCD detectors is used.

H. OTHER X-RAY DETECTORS

X-ray detectors operating at superconducting temperatures (0.1–4 K) have recently been developed; these devices achieve excellent energy resolution (12 eV at 700 eV). They are currently very small and very inefficient for x-rays above 1 keV, and they have maximum count rates of only about $5 \times 10^3\ s^{-1}$. With further development, however, they may make very useful x-ray spectrometers [4].

Microchannel plate detectors are compact, high-gain electron multipliers, which are often used as efficient electron or low-energy photon detectors. A typical MCP consists of about 10^7 closely packed lead-glass channels of equal diameter. Typically, the diameter of each channel, which acts as an independent, continuous dynode photomultiplier, is ~10 μm.

Image plate detectors are available that have many of the characteristics of film but with the advantage of excellent dynamic range, efficiency, and large area [5]. They are made with a plate containing a photosensitive material that on exposure to x-rays creates color centers that can be read out in a scanning mode with a laser as a digital image.

For high-speed x-ray imaging experiments, x-ray streak cameras have been developed that have time resolutions of around 350 fs.

Finally, photographic film is also available for quick x-ray–imaging experiments; however, because of the need for processing after exposure, it is no longer commonly used for scientific measurements. Special films are available that give improved efficiency, contrast, or resolution.

I. CALIBRATION OF X-RAY BEAM MONITORS

Measurement of the relative intensity of x-ray beams is usually done with a gas ionization chamber or a thin silicon diode in the beam path. Another technique is to place a thin foil (usually plastic) in the beam and to measure the scattered photons with a scintillation detector. The approximate efficiency of a gas ionization detector can be estimated from its active length and the properties of the chamber gas at the energy of the x-ray beam. However, calibration of these detectors to measure absolute x-ray intensity is more difficult. One calibration technique is to use a well-characterized single-photon detector as a standard and to establish the x-ray flux–to–detector current calibration of the beam monitor at a reduced beam flux where the single-photon counter response is linear.

At photon energies below 1000 eV, silicon photodiodes are available that can be used as absolute beam monitors [6]. At higher energies, avalanche photodiodes are now available with very wide dynamic ranges. Since they can be used in both single-photon and current-measuring modes, they can be easily calibrated once their efficiency as a function of energy is known (either from the device specifications or by direct measurement) [7].

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