12. PARTICLE DETECTORS

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In this section we give various parameters for common detector components. The quoted numbers are usually based on typical devices, and should be regarded only as rough approximations for new designs. A more detailed discussion of detectors can be found in Ref. 1. In Table 12.1 are given typical spatial and temporal resolutions of common detectors.

Table 12.1: Typical detector characteristics.

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10 to 150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	$\geq 300\ \mu$m[b,c]	50 ns	200 ns
Drift chamber	50 to 300 μm	2 ns[d]	100 ns
Scintillator	—	150 ps	10 ns
Emulsion	1 μm	—	—
Silicon strip	$\dfrac{\text{pitch}}{3\text{ to }7}$[e]	[f]	[f]
Silicon pixel	2 μm[g]	[f]	[f]

[a] Multiple pulsing time.
[b] 300 μm is for 1 mm pitch.
[c] Delay line cathode readout can give $\pm 150\ \mu$m parallel to anode wire.
[d] For two chambers.
[e] The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim 25\ \mu$m) with pulse-height-weighted center finding.
[f] Limited at present by properties of the readout electronics. (Time resolution of ≤ 15 ns is planned for the SDC silicon tracker.)
[g] Analog readout of 34 μm pitch, monolithic pixel detectors.

12.1. Plastic scintillators

The photon yield in the frequency range of practical photomultiplier tubes is ≈ 1 photon per 100 eV of charged particle ionization energy loss in plastic scintillator [2]. One must take into account the light collection efficiency ($\lesssim 10\%$ for typical 1-cm-thick scintillator), the attenuation length (1 to 4 m for typical scintillators [3]), and the quantum efficiency of the photomultiplier cathode ($\lesssim 25\%$ when folded with a typical scintillator emission spectrum).

12.2. Inorganic scintillators

Table 12.2 gives a partial list of commonly-used inorganic scintillators in high-energy and nuclear physics [4–11]. These scintillating crystals are generally used where high density and good energy resolution are required. In a crystal which contains nearly all of the energy deposited by an incident particle, the energy resolution is determined largely, but not totally, by the light output. The table gives the light output of the various materials relative to NaI, which has an intrinsic light output of about 40000 photons per MeV of energy deposit. The detected signal is usually quoted in terms of photoelectrons per MeV produced by a given photodetector. The relationship between photons/MeV produced and p.e.'s/MeV detected involves factors for light collection efficiency (typically 10–50%, depending on geometry) and the quantum efficiency of the detector ($\sim$ 15–20% for photomultiplier tubes and $\sim$ 70% for silicon photodiodes for visible wavelengths). The quantum efficiency of the detector is usually highly wavelength dependent and should be matched to the particular crystal of interest to give the highest quantum yield at the wavelength corresponding to the peak of the scintillation emission. The comparison of the light output given in Table 12.2 is for a standard photomultiplier tube with a bialkali photocathode. For scintillators which emit in the UV, a detector with a quartz window should be used.

Table 12.2: Properties of several inorganic crystal scintillators.

	NaI(Tl)	BGO	BaF_2	CsI(Tl)	CsI(pure)
Density (g/cm^3)	3.67	7.13	4.89	4.53	4.53
Radiation length (cm)	2.59	1.12	2.05	1.85	1.85
Molière radius (cm)	4.5	2.4	3.4	3.8	3.8
dE/dx (MeV/cm) (per mip)	4.8	9.2	6.6	5.6	5.6
Nucl. int. length (cm)	41.4	22.0	29.9	36.5	36.5
Decay time (ns)	250	300	0.7^f 620^s	1000	$10, 36^f$ $\sim 1000^s$
Peak emission λ (nm)	410	480	220^f 310^s	565	305^f $\sim 480^s$
Refractive index	1.85	2.20	1.56	1.80	1.80
Relative light output	1.00	0.15	0.05^f 0.20^s	0.40	0.10^f 0.02^s
Hygroscopic	very	no	slightly	somewhat	somewhat

f = fast component, s = slow component

12.3. Čerenkov detectors

Čerenkov detectors utilize one or more of the properties of Čerenkov radiation discussed in the Passages of Particles through Matter section (Sec. 10 of this *Review*): the existence of a *threshold* for radiation; the dependence of the Čerenkov cone half-angle θ_c on the *velocity* of the particle; the dependence of the *number of emitted photons* on the particle's velocity. The presence of the refractive index n in the relations allows tuning these quantities for a particular experimental application (*e.g.*, using pressurized gas and/or various liquids as radiators).

The number of photoelectrons (p.e.'s) detected in a given device or channel is

$$N_{\text{p.e.}} = L\frac{\alpha^2 z^2}{r_e\, m_e c^2}\int \epsilon_{\text{coll}}(E)\, \epsilon_{\text{det}}(E) \sin^2\theta_c(E) dE \ , \tag{12.1}$$

where L is the path length in the radiator, ϵ_{coll} is the efficiency for collecting the Čerenkov light, ϵ_{det} is the quantum efficiency of the transducer (photomultiplier or equivalent), and $\alpha^2/(r_e\, m_e c^2) =$ 370 cm^{-1}eV^{-1}. The quantities ϵ_{coll}, ϵ_{det}, and θ_c are all functions of the photon energy E, although in typical detectors θ_c (or, equivalently, the index of refraction) is nearly constant over the useful range of photocathode sensitivity. In this case,

$$N_{\text{p.e.}} \approx LN_0 \left\langle \sin^2\theta_c \right\rangle \tag{12.2}$$

with

$$N_0 = \frac{\alpha^2 z^2}{r_e\, m_e c^2} \int \epsilon_{\text{coll}}\, \epsilon_{\text{det}} dE \ . \tag{12.3}$$

We take $z = 1$, the usual case in high-energy physics, in the following discussion.

Threshold Čerenkov detectors make a simple yes/no decision based on whether the particle is above/below the Čerenkov threshold velocity $\beta_t = 1/n$. Careful designs give $\langle\epsilon_{\text{coll}}\rangle \gtrsim 90\%$. For a photomultiplier with a typical bialkali cathode, $\int \epsilon_{\text{det}} dE \approx 0.27$, so that

$$N_{\text{p.e.}}/L \approx 90\ \text{cm}^{-1} \left\langle \sin^2\theta_c \right\rangle \qquad (i.e.,\ N_0 = 90\ \text{cm}^{-1}) \ . \tag{12.4}$$

Suppose, for example, that n is chosen so that the threshold for species a is p_t; that is, at this momentum species a has velocity $\beta_a = 1/n$. A second, lighter, species b with the same momentum has velocity β_b, so $\cos\theta_c = \beta_a/\beta_b$, and

$$\frac{N_{\text{p.e.}}}{L} \approx 90\ \text{cm}^{-1}\, \frac{m_a^2 - m_b^2}{p_t^2 + m_a^2} \ . \tag{12.5}$$

For K/π separation at $p = 1$ GeV/c, $N_{\text{p.e.}}/L \approx 16$ cm^{-1} for π's and (by design) 0 for K's.