Radiological Sciences @ OUHSC

Radiation Detection and Measurement

Lecture 18

Chapter 8: Scintillation Detection Principles

Light collection and scintillator mounting

- In general on would like to have the largest possible fraction of light collection from a Scintillator, two effects arise to thwart this:
  1. Optical self absorption-the loss of light within the scintillator.
  2. Losses at the scintillator surfaces.
- Self absorption tends to be minimal for most scintillators, with the exception of large (many cm in dimension) or rarely used materials.
- For this reason we focus on losses at the interface.

Light collection and scintillator mounting

- Light collection conditions affect the energy resolution in two ways:
  1. Statistical broadening of the response function will worsen with fewer photons.
  2. Uniformity of the light collection will determine the variation of the signal pulse amplitude. Perfect uniformity would ensure that all events of the same energy anywhere on the scintillator would produce the same mean pulse amplitude.

Light collection and scintillator mounting

- Since the light produced travels in all directions, little of the light travels a direct path to collection; many go through two of more reflections.
- The incident angles of the light (reflected or not) is then affected by the surface (of differing optical properties n) and will be governed by Snell’s law (Fig. 8.14).

Light collection and scintillator mounting

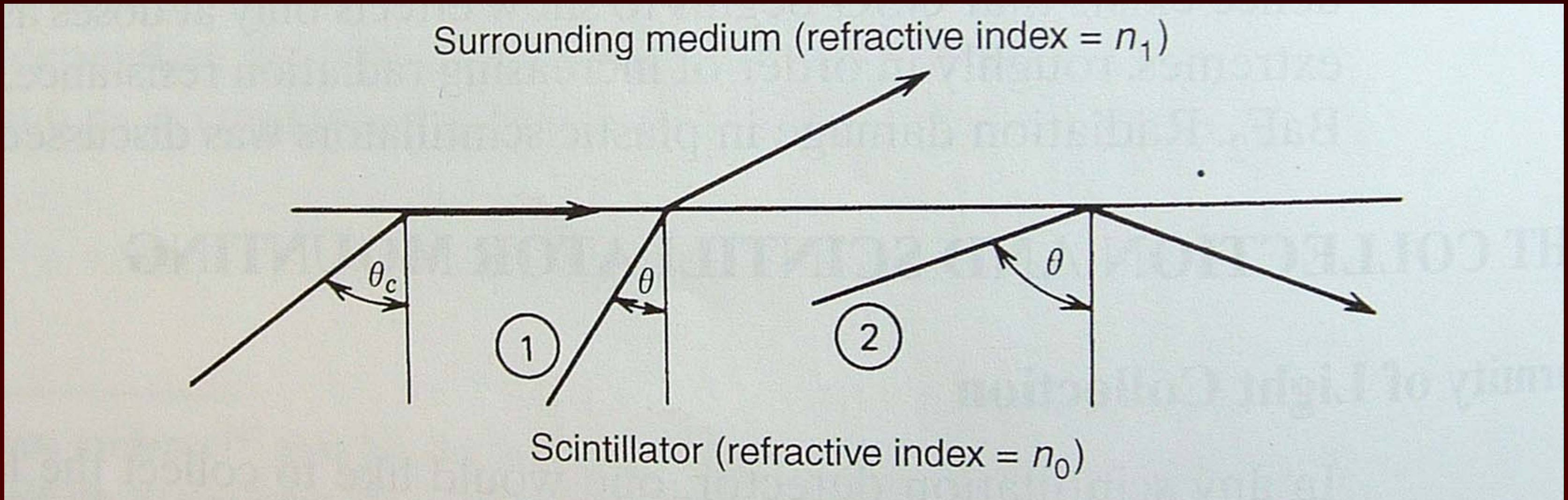


Figure 8.14 Conditions at the interface of dissimilar optical media ($n_0 > n_1$). Ray ① may escape, but ray ② will be internally reflected at the surface.

Light collection and scintillator mounting

- Defining a critical angle θ_c where light incident at θ_c is subject to total internal reflection:

$$\theta_c = \sin^{-1}\left(\frac{n_1}{n_0}\right),$$

  - where *n1* and *no* are the indices of refraction for the surrounding medium and scintillator, respectively.

Light collection and scintillator mounting

- For $\theta < \theta c$, internal reflection (Fresnel reflection) and partial transmission will occur. For $\theta > \theta c$; total internal reflection.
- It is therefore beneficial to minimize reflections by matching the *n*'s of the materials (scintillator to photo-multiplier tube, PMT) with the use of a coupling agent.

Light collection and scintillator mounting

- To reduce efficiency a reflector surrounding the scintillator may also be used, of which there are two types:
  1. Specular: the angle of reflection is equal to the angle of incidence.
  2. Diffuse: angle of reflection is approx. independent of the angle of incidence, and reflection follows Lambert's law:

$$\frac{dI(\Psi)}{dI_o} = \cos \Psi$$

  – Where Ψ is the reflection angle wrt. the perpendicular surface direction.

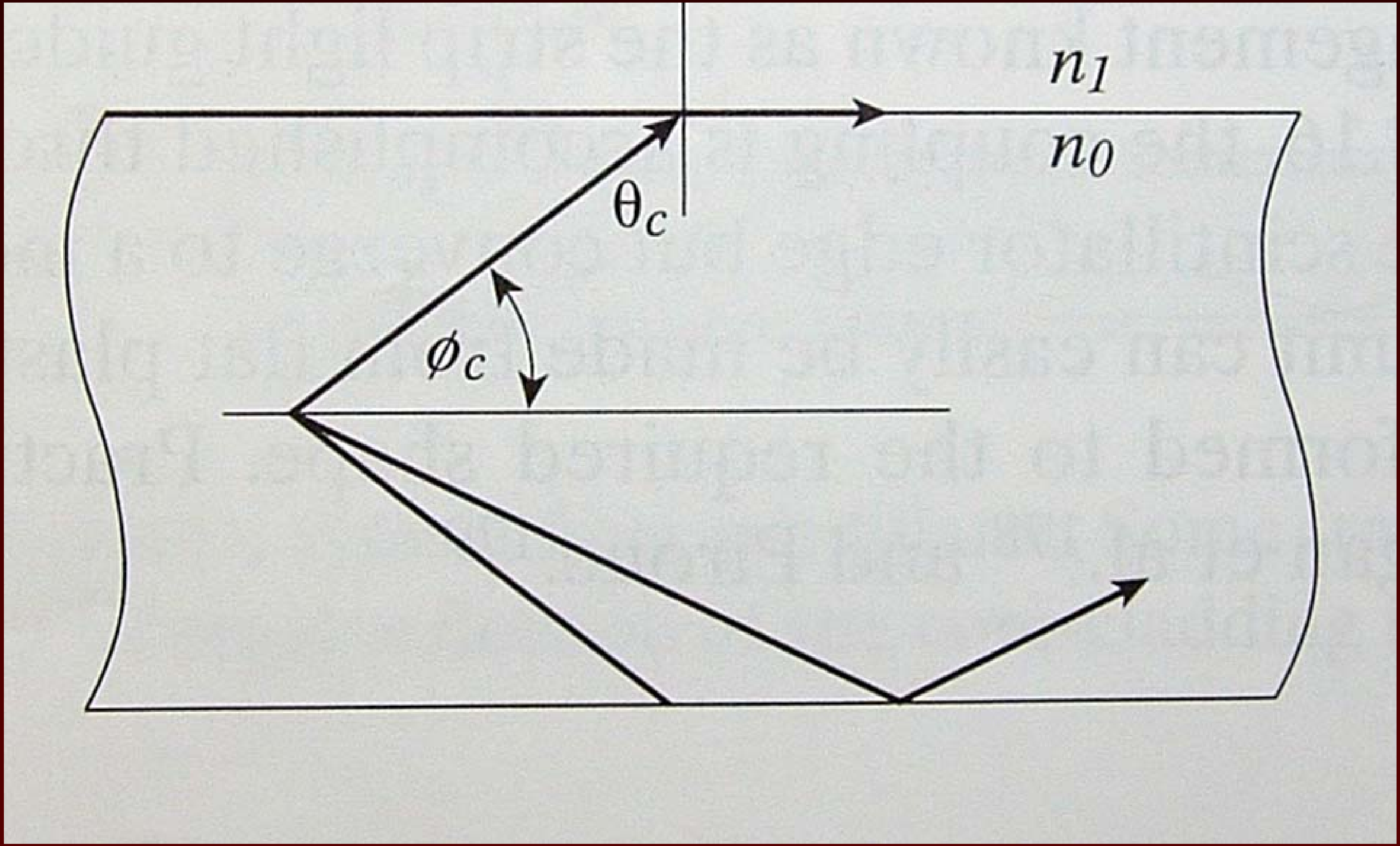
Light collection and scintillator mounting

- Specular reflector: polished metal.
- Diffuse reflector: MgO or Al_2O_3.
- Good light collection also stems from using a single crystal or employing good techniques in cementing several single crystals together.
- Scintillation counters should be shielded from ambient light, i.e. black cover and black tape will usually suffice.
- Large scintillation detectors may enhance light collection by using multiple PMT's

Light pipes

- Since it is impossible or impractical to match a PMT to a scintillator crystal, a light pipe may be employed to increase light collection efficiency.
- A light pipe is a transparent solid physically coupled to the scintillator crystal acting as a guide for the light to the photo-detector.
- Operate on the principal of total internal reflection, seen in the figure at the bottom of page 251.

Light pipes



Light pipes

- For an isotropic source at the central axis of a transparent cylindrical rod:
  - Each ray will pass near the cylinder axis (sometimes called meridional rays).
- Only light emitted in the cone angle ϕ_c(=90°-θ_c) will undergo total internal reflection.

Light pipes

- The fractional solid angle (of light internally reflected) is:

$$F = \frac{\Omega}{4\pi} = \frac{1}{4\pi}\int_{\phi=0}^{\phi=\phi_c} d\Omega = \frac{1}{4\pi}\int_{0}^{\theta_c} 2\pi \sin\theta d\theta$$

$$F = \frac{1}{2}\left(1-\cos\ \phi_c\right) = \frac{1}{2}\left(1-\cos\ \theta_c\right) = \frac{1}{2}\left(1-\frac{n_1}{n_o}\right)$$

Light pipes

- For slab geometry, if considering only the two large surfaces (neglecting the two narrow edges); light with an incident angle greater than θ_c will be internally reflected.

Light pipes

- Any light with an incident angle less than the critical angle will escape or be lost. The total escaping fraction of light is enclosed by the two cones subtending the critical angle:

$$E = \frac{2\Omega}{4\pi} = \frac{1}{2\pi}\int_{\theta=0}^{\theta=\theta_c} d\Omega = \frac{1}{2\pi}\int_0^{\theta_c} 2\pi \sin\theta d\theta$$

$$= 1 - \cos \theta_c = 1 - \sqrt{1 - \left(\frac{n_1}{n_o}\right)^2}$$

Radiological Sciences @ OUHSC

Light pipes

- Thus the fraction of light trapped in the slab is:

$$F = 1 - E = \sqrt{1 - \left(\frac{n_1}{n_o}\right)^2}$$

- Note that for cylindrical geometry the predicted amount of light piped to the edge is 16.7% (33.4% if back cone is reflected forward and transmitted), where for slab geometry this increases to 75% for n=1.5 (Lucite plastic).

Light pipes

- Changing the cladding can also affect pulse height (Fig. 8.15).

- A light pipe is said to be adiabatic if it can transmit all the light that enters within the acceptance angle at the input.

Light pipes

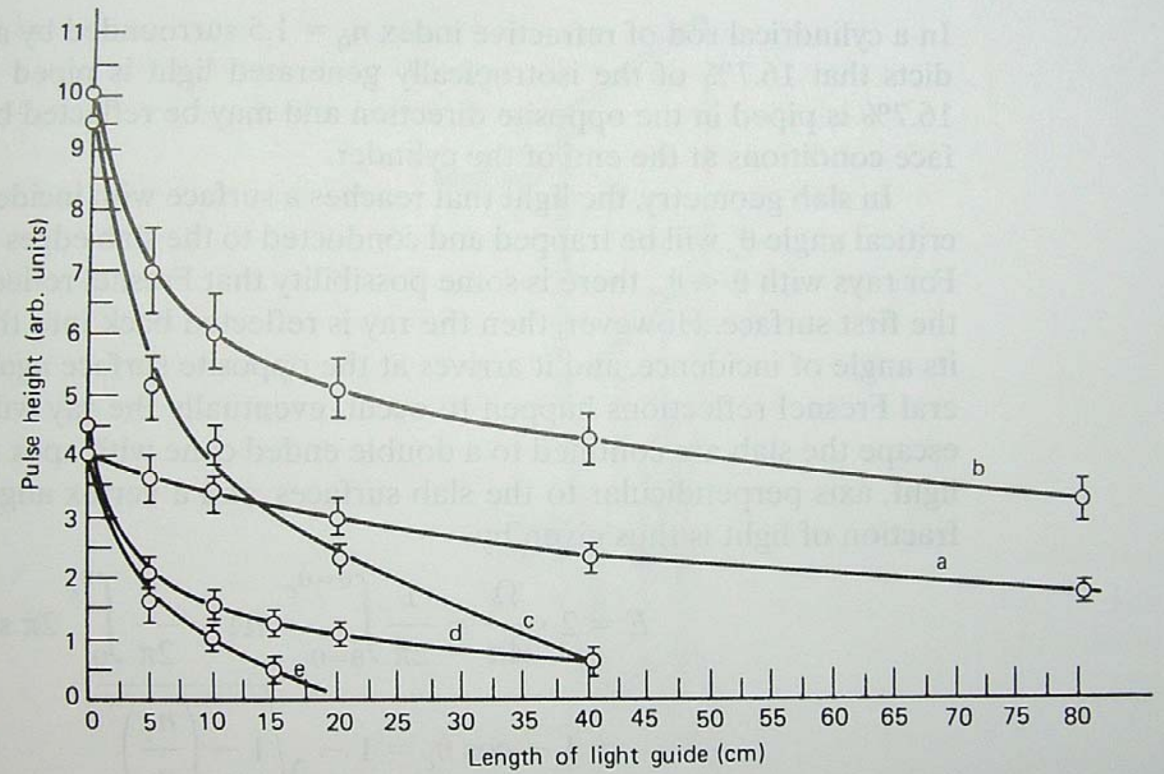


Figure 8.15 Variation of pulse height with length of light guide for various reflective wrappings. (*a*) Total internal reflection only, (*b*) total internal reflection with reflective covering, (*c*) surface of light guide painted with NE 560 reflector paint, (*d*) specular reflector without light guide, (*e*) diffuse reflector without light guide. (From Kilvington et al.[176])

Fiber scintillators

- Fig. 8.17 shows the typical geometry of a fiber scintillator.
- Some fraction of light is trapped by the total internal reflection at the core-cladding interface.
- Both the core and cladding are transparent and the index of refraction of the core is higher than that of the cladding.

Fiber scintillators

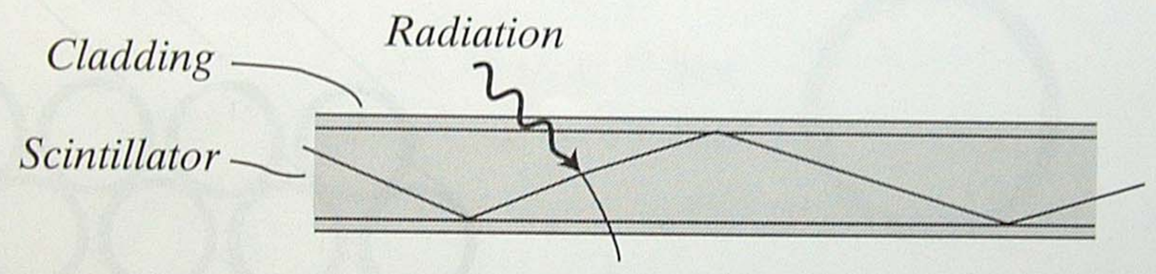


Figure 8.17 Cross section of a typical fiber scintillator. Some fraction of the emitted light is trapped by total internal reflection at the core-cladding interface.

Fiber scintillators

Plastic and Liquid Core Fibers:

- The fiber core generally consists of polystyrene with a few percent of organic fluor, while the cladding is commonly polymethylmethyacrylate or fluorinated polymethacrylate.
- Plastic and easily formable to any cross-section shape.
- Fiber can also be a glass capillary tube filled with a liquid organic scintillator.

Fiber scintillators

Glass Fibers:

- Can be easily drawn into small diameters.
- Typically made of cerium activated glass

Fiber scintillators

- Fraction of light captured by internal reflection:

$$F = \frac{1}{2}\left(1 - \frac{n_1}{n_o}\right),$$

  - *n1* and *no* are the refractive indices for the cladding and core respectively.
- Note the cross section of meridional and skew rays in Fig. 8.20, where skew rays have a higher *F*, but long spiral paths lead to strong attenuation.

Fiber scintillators

"meridional rays": pass near fiber center axis

"skew rays": originate near outer rim of core. Higher F, but long spiral paths lead to strong attenuation

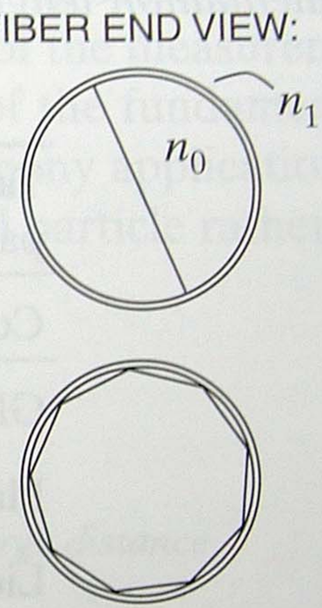


Figure 8.20 Sketch showing the distinction between "meridional rays" that originate near of the fiber, and "skew rays" that represent a much longer transmission path through the f

Fiber scintillators

Light Field and Propagation:

- Figure 8.5 lists the typical light yield for fiber scintillators.

Table 8.5 Typical Light Yield for Fiber Scintillators (for low dE/dx particles, in all directions, will be reduced by light capture fraction)

Core material	photons/keV	λ_{peak} (nm)
Glass scintillator	3–5	400
Plastic scintillator	8–10	420
Liquid scintillator	11–13	420
For comparison:		
NaI(Tl)	38	415

Fiber scintillators

- The intensity of the scintillation light propagated along the length of the fiber is attenuated due to several affects:
  1. Imperfections at the core cladding surface may disturb the total internal reflection.
  2. Re-absorption of the light due to overlap in the emission and absorption bands of the fluorescent species.
  3. Raleigh scattering from small density fluctuations in the core can deflect a ray so it is no longer totally internally reflected.

Fiber scintillators

- The cumulative effect of the processes is often expressed as a quoted "attenuation length" of the fiber.
- If the attenuation probability per path length is constant, the intensity of light (I) at a distance (x) from the original interaction site is given by:

$$\frac{I}{I_o} = e^{-\frac{x}{L}},$$

-Where Io is the intensity near the site and *L* is the attenuation length.

Fiber scintillators

- In general, real fibers do not behave this way since short wavelengths tend to be more readily absorbed than long wavelengths.
- Note the two slopes (components) making up the plot of attenuation vs. distance in Fig. 8.22 for short and long distances indicating the wavelength absorption disparity.

Fiber scintillators

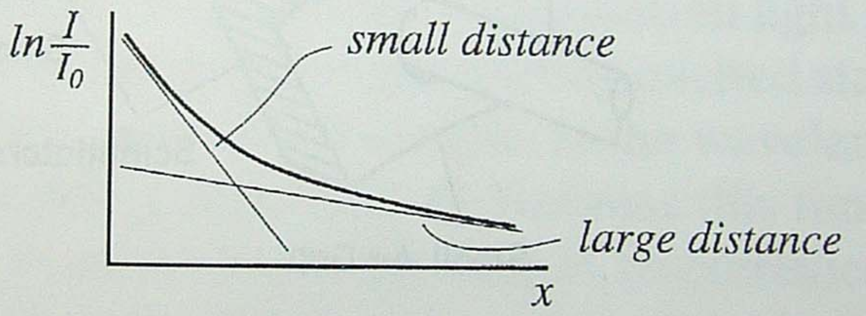


Figure 8.22 The total light transmitted by a fiber as a function of its length. The attenua
length is related to the slope of this plot, and the preferential absorption of the short w
lengths leads to smaller attenuation length for short fibers compared with longer ones.

Wavelength shifters

- Incorporating an organic additive that readily absorbs the primary light and re-radiates the energy at a longer wavelength in a light pipe.
- Doping level adjusts the probability of light absorption in the primary emission.
- The re-radiated light is isotropically produced in the light pipe allowing the light to “turn corners” which might otherwise be impossible.