International Tables for Crystallography (2006). Vol. C, Figure 4.4.2.4, p. 436.

achieved. Further transmission losses occur due to imperfections in the alignment of the sections that make up the guide.

The great advantage of neutron guides, in addition to the transport of neutrons to areas of low background, is that they can be multiplexed, *i.e.* one guide can serve many instruments. This is achieved either by deflecting only a part of the total cross section to a given instrument or by selecting a small wavelength range from the guide spectrum. In the latter case, the selection device (usually a crystal monochromator) must have a high transmission at other wavelengths.

If the neutron guide is curved, the transmission becomes wavelength dependent, as illustrated in Fig. 4.4.2.4. In this case, one can define a characteristic wavelength, λ^*, given by the relation $\theta^* = \sqrt{2a/\rho}$, so that

$$\lambda^* = \sqrt{\frac{\pi}{Nb_{\rm coh}}}\sqrt{\frac{2a}{\rho}} \qquad (4.4.2.6)$$

(where a is the guide width and ρ the radius of curvature), for which the theoretical transmission drops to 67%. For wavelengths less than λ^*, neutrons can only be transmitted by 'garland' reflections along the concave wall of the curved guide. Thus, the guide acts as a low-pass energy filter as long as its length is longer than the direct line-of-sight length $L_1 = \sqrt{8a\rho}$. For example, a 3 cm wide nickel-coated guide whose characteristic wavelength is 4 Å (radius of curvature 1300 m) must be at least 18 m long to act as a filter. The line-of-sight length can be reduced by subdividing the guide into a number of narrower channels, each of which acts as a miniguide. The resulting device, often referred to as a neutron bender, since deviation of the beam is achieved more rapidly, is used in beam deviators (Alefeld *et al.*, 1988) or polarizers (Hayter, Penfold & Williams, 1978). A microbender was devised by Marx (1971) in which the channels were made by evaporating alternate layers of aluminium (transmission layer) and nickel (mirror layer) onto a flexible smooth substrate.

Tapered guides can be used to reduce the beam size in one or two dimensions (Rossbach *et al.*, 1988), although, since mirror reflection obeys Liouville's theorem, focusing in real space is achieved at the expense of an increase in divergence. This fact can be used to calculate analytically the expected gain in neutron flux at the end of a tapered guide (Anderson, 1988). Alternatively, focusing can be achieved in one dimension using a bender in which the individual channel lengths are adjusted to create a focus (Freund & Forsyth, 1979).

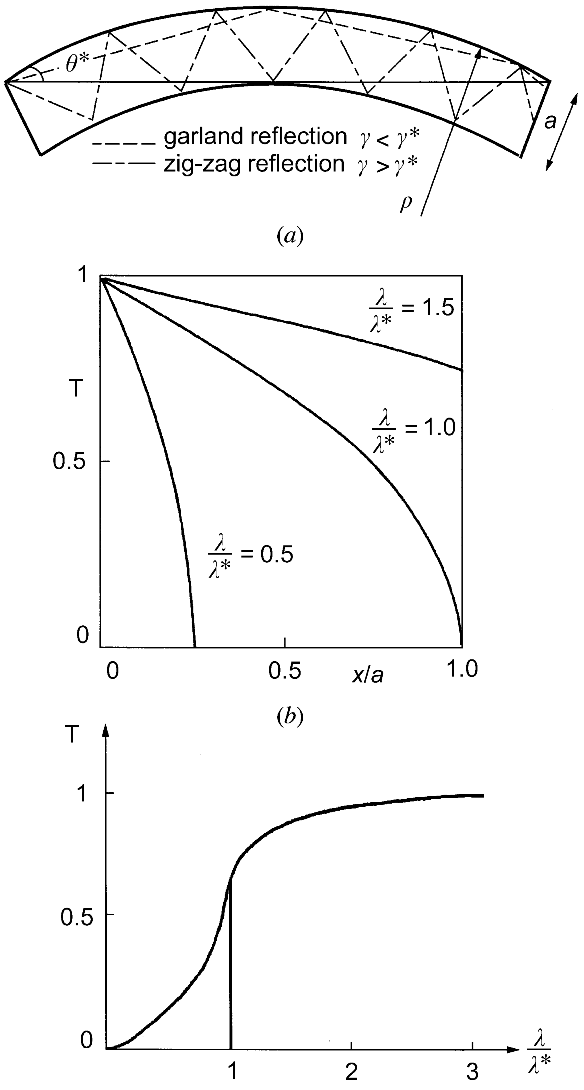
4.4.2.4.2. *Focusing mirrors*

Optical imaging of neutrons can be achieved using ellipsoidal or torroidal mirrors, but, owing to the small critical angle of reflection, the dimensions of the mirrors themselves and the radii of curvature must be large. For example, a 4 m long toroidal mirror has been installed at the IN15 neutron spin echo spectrometer at the Institut Laue–Langevin, Grenoble (Hayes *et al.*, 1996), to focus neutrons with wavelengths greater than 15Å. The mirror has an in-plane radius of curvature of 408.75 m, and the sagittal radius is 280 mm. A coating of ^{65}Cu is used to obtain a high critical angle of reflection while maintaining a low surface roughness. Slope errors of less than 2.5×10^{-5} rad (r.m.s.) combined with a surface roughness of less than 3Å allow a minimum resolvable scattering vector of about 5×10^{-4} Å^{-1} to be reached.

For best results, the slope errors and the surface roughness must be low, in particular in small-angle scattering applications, since diffuse scattering from surface roughness gives rise to a halo around the image point. Owing to its low thermal expansion coefficient, highly polished Zerodur is often chosen as substrate.

4.4.2.4.3. *Multilayers*

Schoenborn, Caspar & Kammerer (1974) first pointed out that multibilayers, comprising alternating thin films of different scattering-length densities ($Nb_{\rm coh}$) act like two-dimensional crystals with a d spacing given by the bilayer period. With modern deposition techniques (usually sputtering), uniform films of thickness ranging from about twenty to a few hundred ångströms can be deposited over large surface areas of the order of 1 m^2. Owing to the rather large d spacings involved, the Bragg reflection from multilayers is generally at grazing incidence, so that long devices are required to cover a typical beam width, or a stacked device must be used. However, with judicious choice of the scattering-length contrast, the surface and interface roughness, and the number of layers, reflectivities close to 100% can be reached.



(*a*)

(*b*)

(*c*)

Fig. 4.4.2.4. In a curved neutron guide, the transmission becomes λ dependent: (*a*) the possible types of reflection (garland and zig-zag), the direct line-of-sight length, the critical angle θ^*, which is related to the characteristic wavelength $\lambda^* = \theta^*\sqrt{\pi/Nb_{\rm coh}}$; (*b*) transmission across the exit of the guide for different wavelengths, normalized to unity at the outside edge; (*c*) total transmission of the guide as a function of λ.