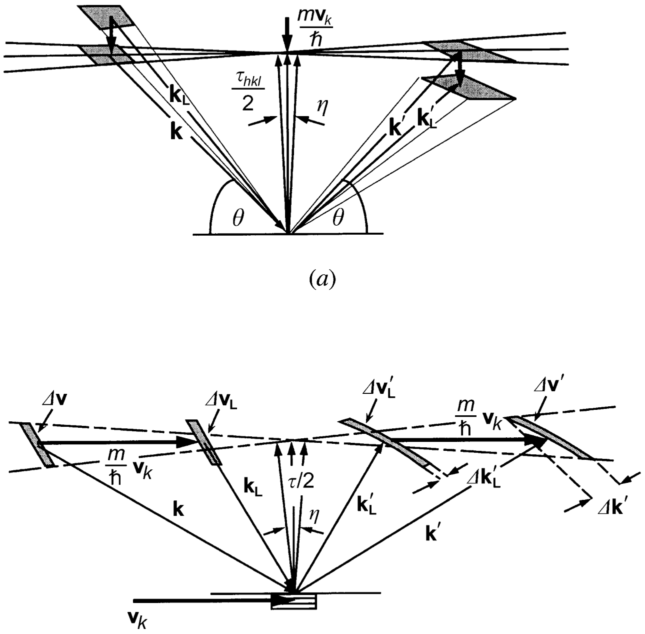
International Tables for Crystallography (2006). Vol. C, Section 4.4.2.4.1, pp. 435–436.

eter, first conceived by Brockhouse (1958). A pulse of monochromatic neutrons is obtained when the reciprocal-lattice vector of a rotating crystal bisects the angle between two collimators. Effectively, the neutron **k** vector is changed in both direction and magnitude, depending on whether the crystal is moving towards or away from the neutron. For the rotating crystal, both of these situations occur simultaneously for different halves of the crystal, so that the net effect over the beam cross section is that a wider energy band is reflected than from the crystal at rest, and that, depending on the sense of rotation, the beam is either focused or defocused in time (Meister & Weckerman, 1972).

The Bragg reflection of neutrons from a crystal moving parallel to its lattice planes is illustrated in Fig. 4.4.2.3(*b*). It can be seen that the moving crystal selects a larger Δk than the crystal at rest, so that the reflected intensity is higher. Furthermore, it is possible under certain conditions to orientate the diffracted phase-space volume orthogonal to the diffraction vector. In this way, a monochromatic divergent beam can be obtained from a collimated beam with a larger energy spread. This provides an elegant means of producing a divergent beam with a sufficiently wide momentum spread to be scanned by the Doppler crystal of a backscattering instrument (Schelten & Alefeld, 1984).

Finally, an alternative method of scanning the energy of a monochromator in backscattering is to apply a steady but uniform temperature variation. The monochromator crystal must have a reasonable thermal expansion coefficient, and care has to be taken to ensure a uniform temperature across the crystal.



(*a*)

(*b*)

Fig. 4.4.2.3. Momentum-space representation of Bragg scattering from a crystal moving (*a*) perpendicular and (*b*) parallel to the diffracting planes with a velocity $\mathbf{v}_k$. The vectors $\mathbf{k}_L$ and $\mathbf{k}_L'$ refer to the incident and reflected wavevectors in the laboratory frame of reference. In (*a*), depending on the direction of $\mathbf{v}_k$, the reflected wavevector is larger or smaller than the incident wavevector, $\mathbf{k}_L$. In (*b*), a larger incident reciprocal-space volume, $\Delta\mathbf{v}_L$, is selected by the moving crystal than would have been selected by the crystal at rest. The reflected reciprocal-space element, $\Delta\mathbf{v}_L'$, has a large divergence, but can be arranged to be normal to $\mathbf{k}_L'$, hence improving the resolution $\Delta\mathbf{k}_L'$.

Table 4.4.2.2. *Neutron scattering-length densities, Nb_{coh}, for some commonly used materials*

Material	Nb (10^{-6} Å^{-2})
^{58}Ni	13.31
Diamond	11.71
Nickel	9.40
Quartz	3.64
Germanium	3.62
Silver	3.50
Aluminium	2.08
Silicon	2.08
Vanadium	−0.27
Titanium	−1.95
Manganese	−2.95

4.4.2.4. *Mirror reflection devices*

The refractive index, n, for neutrons of wavelength λ propagating in a nonmagnetic material of atomic density N is given by the expression

$$n^2 = 1 - \frac{\lambda^2 N b_{\rm coh}}{\pi,} \qquad (4.4.2.4)$$

where $b_{\rm coh}$ is the mean coherent scattering length. Values of the scattering-length density $Nb_{\rm coh}$ for some common materials are listed in Table 4.4.2.2, from which it can be seen that the refractive index for most materials is slightly less than unity, so that total external reflection can take place. Thus, neutrons can be reflected from a smooth surface, but the critical angle of reflection, γ_c, given by

$$\gamma_c = \lambda \sqrt{\frac{N b_{\rm coh}}{\pi}}, \qquad (4.4.2.5)$$

is small, so that reflection can only take place at grazing incidence. The critical angle for nickel, for example, is 0.1° Å^{-1}.

Because of the shallowness of the critical angle, reflective optics are traditionally bulky, and focusing devices tend to have long focal lengths. In some cases, however, depending on the beam divergence, a long mirror can be replaced by an equivalent stack of shorter mirrors.

4.4.2.4.1. *Neutron guides*

The principle of mirror reflection is the basis of neutron guides, which are used to transmit neutron beams to instruments that may be situated up to 100 m away from the source (Christ & Springer, 1962; Maier-Leibnitz & Springer, 1963). A standard neutron guide is constructed from boron glass plates assembled to form a rectangular tube, the dimensions of which may be up to 200 mm high by 50 mm wide. The inner surface of the guide is coated with approximately 1200 Å of either nickel, ^{58}Ni ($\gamma_c = 0.12°$ Å^{-1}), or a 'supermirror' (described below). The guide is usually evacuated to reduce losses due to absorption and scattering of neutrons in air.

Theoretically, a neutron guide that is fully illuminated by the source will transmit a beam with a square divergence of full width $2\gamma_c$ in both the horizontal and vertical directions, so that the transmitted solid angle is proportional to λ^2. In practice, owing to imperfections in the assembly of the guide system, the divergence profile is closer to Gaussian than square at the end of a long guide. Since the neutrons may undergo a large number of reflections in the guide, it is important to achieve a high reflectivity. The specular reflectivity is determined by the surface roughness, and typically values in the range 98.5 to 99% are 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.

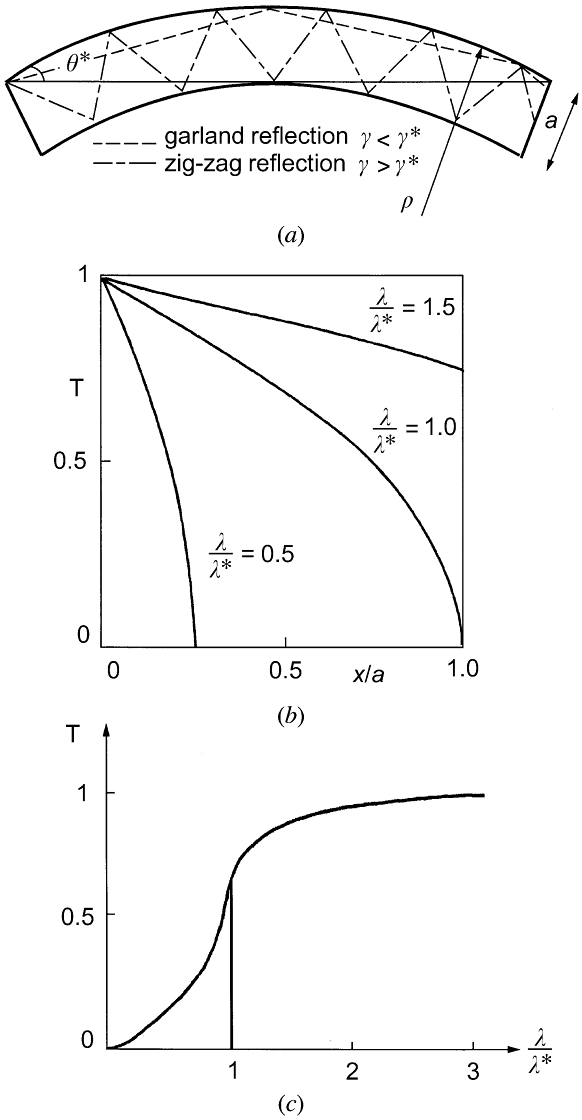


Fig. 4.4.2.4. In a curved neutron guide, the transmission becomes λ dependent: (*a*) the possible types of reflection (garland and zig-zag), the direct line-of-sight length, the critical angle θ^*, which is related to the characteristic wavelength $\lambda^* = \theta^* \sqrt{\pi/Nb_{\rm coh}}$; (*b*)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

references