International Tables for Crystallography (2006). Vol. C, Section 4.4.2.4.4, pp. 437–438.

Fig. 4.4.2.5 illustrates how variation in the bilayer period can be used to produce a monochromator (the minimum $\Delta\lambda/\lambda$ that can be achieved is of the order of 0.5%), a broad-band device, or a 'supermirror', so called because it is composed of a particular sequence of bilayer thicknesses that in effect extends the region of total mirror reflection beyond the ordinary critical angle (Turchin, 1967; Mezei, 1976; Hayter & Mook, 1989). Supermirrors have been produced that extend the critical angle of nickel by a factor, m, of between three and four with reflectivities better than 90%. Such high reflectivities enable supermirror neutron guides to be constructed with flux gains, compared with nickel guides, close to the theoretical value of m^2.

The choice of the layer pairs depends on the application. For non-polarizing supermirrors and broad-band devices (Høghøj, Anderson, Ebisawa & Takeda, 1996), the Ni/Ti pair is commonly used, either pure or with some additions to relieve strain and stabilize interfaces (Elsenhans *et al.*, 1994) or alter the magnetism (Anderson & Høghøj, 1996), owing to the high contrast in scattering density, while for narrow-band monochromators a low contrast pair such as W/Si is more suitable.

4.4.2.4.4. *Capillary optics*

Capillary neutron optics, in which hollow glass capillaries act as waveguides, are also based on the concept of total external reflection of neutrons from a smooth surface. The advantage of capillaries, compared with neutron guides, is that the channel sizes are of the order of a few tens of micrometres, so that the radius of curvature can be significantly decreased for a given characteristic wavelength [see equation (4.4.2.6)]. Thus, neutrons can be efficiently deflected through large angles, and the device can be more compact.

Two basic types of capillary optics exist, and the choice depends on the beam characteristics required. Polycapillary fibres are manufactured from hollow glass tubes several centimetres in diameter, which are heated, fused and drawn multiple times until bundles of thousands of micrometre-sized channels are formed having an open area of up to 70% of the cross section. Fibre outer diameters range from 300 to 600 μm and contain hundreds or thousands of individual channels with inner diameters between 3 and 50 μm. The channel cross section is usually hexagonal, though square channels have been produced, and the inner channel wall surface roughness is typically less than 10 Å r.m.s., giving rise to very high reflectivities. The principal limitations on transmission efficiency are the open area, the acceptable divergence (note that the critical angle for glass is 1 mrad Å^{-1}) and reflection losses due to absorption and scattering. A typical optical device will comprise hundreds or thousands of fibres threaded through thin screens to produce the required shape.

Fig. 4.4.2.6 shows typical applications of polycapillary devices. In Fig. 4.4.2.6(*a*), a polycapillary lens is used to refocus neutrons collected from a divergent source. The half lens depicted in Fig. 4.4.2.6(*b*) can be used either to produce a nearly parallel (divergence $= 2\gamma_c$) beam from a divergent source or (in the reverse sense) to focus a nearly parallel beam, *e.g.* from a neutron guide. The size of the focal point depends on the channel size, the beam divergence, and the focal length of the lens. For example, a polycapillary lens used in a prompt γ-activation analysis instrument at the National Institute of Standards and Technology to focus a cold neutron beam from a neutron guide results in a current density gain of 80 averaged over the focused beam size of 0.53 mm (Chen *et al.*, 1995).

Fig. 4.4.2.6(*c*) shows another simple application of polycapillaries as a compact beam bender. In this case, such a bender may be more compact than an equivalent multichannel guide bender, although the accepted divergence will be less. Furthermore, as with curved neutron guides, owing to the wavelength dependence of the critical angle the capillary curvature can be used to filter out thermal or high-energy neutrons.

It should be emphasized that the applications depicted in Fig. 4.4.2.6 obey Liouville's theorem, in that the density of neutrons in phase space is not changed, but the shape of the phase-space volume is altered to meet the requirements of the experiment,

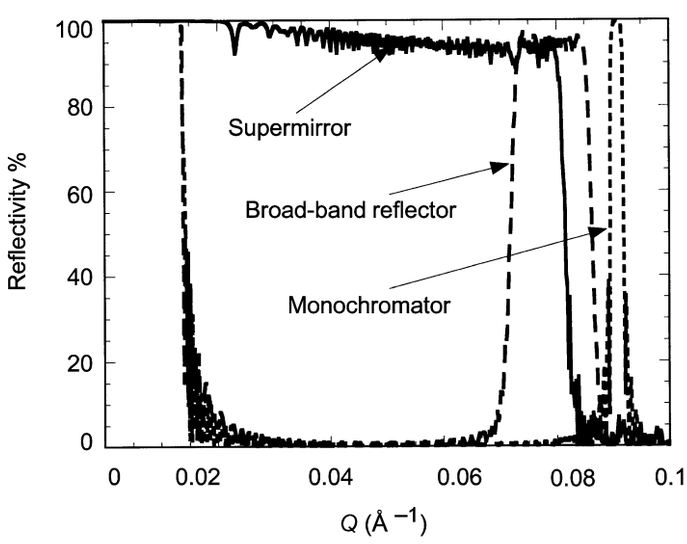

Fig. 4.4.2.5. Illustration of how a variation in the bilayer period can be used to produce a monochromator, a broad-band device, or a supermirror.

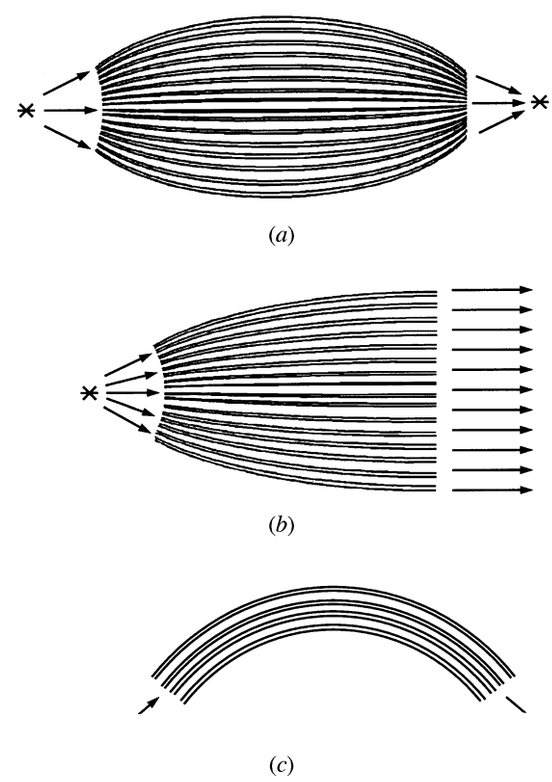

Fig. 4.4.2.6. Typical applications of polycapillary devices: (*a*) lens used to refocus a divergent beam; (*b*) half-lens to produce a nearly parallel beam or to focus a nearly parallel beam; (*c*) a compact bender.

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i.e. there is a simple trade off between beam dimension and divergence.

The second type of capillary optic is a monolithic configuration. The individual capillaries in monolithic optics are tapered and fused together, so that no external frame assembly is necessary (Chen-Mayer *et al.*, 1996). Unlike the multifibre devices, the inner diameters of the channels that make up the monolithic optics vary along the length of the component, resulting in a smaller more compact design.

Further applications of capillary optics include small-angle scattering (Mildner, 1994) and lenses for high-spatial-resolution area detection.

4.4.2.5. *Filters*

Neutron filters are used to remove unwanted radiation from the beam while maintaining as high a transmission as possible for the neutrons of the required energy. Two major applications can be identified: removal of fast neutrons and γ-rays from the primary beam and reduction of higher-order contributions (λ/n) in the secondary beam reflected from crystal monochromators. In this section, we deal with non-polarizing filters, *i.e.* those whose transmission and removal cross sections are independent of the neutron spin. Polarizing filters are discussed in the section concerning polarizers.

Filters rely on a strong variation of the neutron cross section with energy, usually either the wavelength-dependent scattering cross section of polycrystals or a resonant absorption cross section. Following Freund (1983), the total cross section determining the attenuation of neutrons by a crystalline solid can be written as a sum of three terms,

$$\sigma = \sigma_{\rm abs} + \sigma_{\rm tds} + \sigma_{\rm Bragg}. \qquad (4.4.2.7)$$

Here, $\sigma_{\rm abs}$ is the true absorption cross section, which, at low energy, away from resonances, is proportional to $E^{-1/2}$. The temperature-dependent thermal diffuse cross section, $\sigma_{\rm tds}$, describing the attenuation due to inelastic processes, can be split into two parts depending on the neutron energy. At low energy, $E \ll k_b\Theta_D$, where k_b is Boltzmann's constant and Θ_D is the characteristic Debye temperature, single-phonon processes dominate, giving rise to a cross section, $\sigma_{\rm sph}$, which is also proportional to $E^{-1/2}$. The single-phonon cross section is proportional to $T^{7/2}$ at low temperatures and to T at higher temperatures. At higher energies, $E \geq k_b\Theta_D$, multiphonon and multiple-scattering processes come into play, leading to a cross section, $\sigma_{\rm mph}$, that increases with energy and temperature. The third contribution, $\sigma_{\rm Bragg}$, arises due to Bragg scattering in single- or polycrystalline material. At low energies, below the Bragg cut-off ($\lambda > 2d_{\rm max}$), $\sigma_{\rm Bragg}$ is zero. In polycrystalline materials, the cross section rises steeply above the Bragg cut-off and oscillates with increasing energy as more reflections come into play. At still higher energies, $\sigma_{\rm Bragg}$ decreases to zero.

In single-crystalline material above the Bragg cut-off, $\sigma_{\rm Bragg}$ is characterized by a discrete spectrum of peaks whose heights and widths depend on the beam collimation, energy resolution, and the perfection and orientation of the crystal. Hence a monocrystalline filter has to be tuned by careful orientation.

The resulting attenuation cross section for beryllium is shown in Fig. 4.4.2.7. Cooled polycrystalline beryllium is frequently used as a filter for neutrons with energies less than 5 meV, since there is an increase of nearly two orders of magnitude in the attenuation cross section for higher energies. BeO, with a Bragg cut-off at approximately 4 meV, is also commonly used.

Pyrolytic graphite, being a layered material with good crystalline properties along the c direction but random orientation perpendicular to it, lies somewhere between a polycrystal and a single crystal as far as its attenuation cross section is concerned. The energy-dependent cross section for a neutron beam incident along the c axis of a pyrolytic graphite filter is shown in Fig. 4.4.2.8, where the attenuation peaks due to the 00ξ reflections can be seen. Pyrolytic graphite serves as an efficient second- or third-order filter (Shapiro & Chesser, 1972) and can be 'tuned' by slight misorientation away from the c axis.

Further examples of typical filter materials (*e.g.* silicon, lead, bismuth, sapphire) can be found in the paper by Freund (1983).

Resonant absorption filters show a large increase in their attenuation cross sections at the resonant energy and are therefore used as selective filters for that energy. A list of typical filter materials and their resonance energies is given in Table 4.4.2.3.

4.4.2.6. *Polarizers*

Methods used to polarize a neutron beam are many and varied, and the choice of the best technique depends on the instrument and the experiment to be performed. The main parameter that has to be considered when describing the effectiveness of a given polarizer is the polarizing efficiency, defined as

$$P = (N_+ - N_-)/(N_+ + N_-), \qquad (4.4.2.8)$$

where N_+ and N_- are the numbers of neutrons with spin parallel (+) or antiparallel (−) to the guide field in the outgoing beam. The second important factor, the transmission of the wanted spin state, depends on various factors, such as acceptance angles, reflection, and absorption.

4.4.2.6.1. *Single-crystal polarizers*

The principle by which ferromagnetic single crystals are used to polarize and monochromate a neutron beam simultaneously is shown in Fig. 4.4.2.9. A field $\mathbf{B}$, applied perpendicular to the scattering vector $\boldsymbol{\kappa}$, saturates the atomic moments $\mathbf{M}_\nu$ along the field direction. The cross section for Bragg reflection in this geometry is

$$(\mathrm{d}\sigma/\mathrm{d}\Omega) = F_N(\boldsymbol{\kappa})^2 + 2F_N(\boldsymbol{\kappa})F_M(\boldsymbol{\kappa})(\mathbf{P}\cdot\boldsymbol{\mu}) + F_M(\boldsymbol{\kappa})^2, \qquad (4.4.2.9)$$

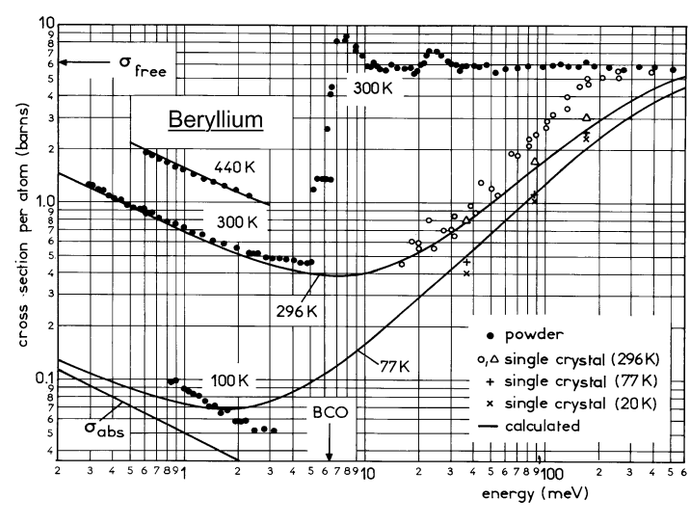

Fig. 4.4.2.7. Total cross section for beryllium in the energy range where it can be used as a filter for neutrons with energy below 5 meV (Freund, 1983).

references