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1996). Supermirrors consisting of Co and Ti bilayers display high contrast for neutrons with a magnetic moment parallel to the saturation magnetization and very low contrast for the remainder. With suitable modification of the substrate to absorb the antiparallel neutrons, a polarizing supermirror will produce a polarized neutron beam (polarization $> 90\%$) by reflection.

#### 6.2.1.3.4. *Velocity selectors*

The relatively low speed of longer-wavelength neutrons ($\sim 600$ m s$^{-1}$ at 6 Å) enables wavelength selection by mechanical means (Lowde, 1960). In general, there are two classes of mechanical velocity selectors (Clark *et al.*, 1966). Rotating a group of short, parallel, curved collimators about an axis perpendicular to the beam direction will produce a pulsed neutron beam with $\lambda$ and $\Delta\lambda/\lambda$ determined by the speed of rotation. This is a Fermi chopper. An alternate method is to translate short, parallel, curved collimators rapidly across the neutron beam, permitting only neutrons with the correct trajectory to be transmitted. This is achieved in the helical velocity selector, where the neutron wavelength is selected by the speed of rotation and $\Delta\lambda/\lambda$ can be modified by changing the angle between the neutron beam and the axis of rotation (Komura *et al.*, 1983). The neutron beam is essentially continuous, the resolution function is approximately triangular and the overall neutron transmission efficiency exceeds 75% in modern designs (Wagner *et al.*, 1992).

#### 6.2.1.3.5. *Neutron guides*

In order for a collimator to be effective, its walls must absorb all incident neutrons. The angular acceptance is strictly determined by the line-of-sight geometry. Neutron guides can be used to improve this acceptance dramatically and to transport neutrons with a given angular distribution, almost without intensity loss, to regions distant from the source (Maier-Leibnitz & Springer, 1963). The basic principle of a guide is total internal reflection. This occurs for scattering angles less than the critical angle, $\theta_c$, given by

$$\theta_c = 2(1-n)^{1/2},$$

where $n$ is the (neutron) index of refraction related to the coherent scattering length, $b$, of the wall material, *viz*,

$$n = 1 - (\lambda^2 \rho b/2\pi),$$

where $\rho$ is the atom number density (in cm$^{-3}$). Among common materials, Ni with $b = 1.03\times10^{-12}$ cm, in combination with suitable physico-chemical properties, provides the best option, with a critical angle $\theta_c = 0.1\lambda$ (in Å). The dependence of $\theta_c$ on $\lambda$ implies that guides are more effective for long-wavelength neutrons. With the introduction of supermirror guides with up to four times the $\theta_c$ of bulk Ni, both thermal and cold neutron beams are being transported and focused with high efficiency (Böni, 1997).

While a straight guide transports long wavelengths efficiently, it continues to transport all neutrons within the critical angle, including non-thermal neutrons emitted within the solid angle of the guide. This situation may be modified significantly by introducing a curvature to the guide. Since a curved neutron guide provides a form of spectral tailoring (cutoff or bandpass filters), simulation is a distinct advantage in exploring the impact of guide geometry on neutron-beam quality (van Well *et al.*, 1991; Copley & Mildner, 1992; Mildner & Hammouda, 1992).

### 6.2.1.4. *Detectors*

The detection of thermal neutrons is a nuclear event involving one of only a few nuclei with a sufficiently large absorption cross section ($^3$He, $^{10}$B, $^6$Li, Gd and $^{235}$U). The secondary products (fragments, charged particles or photons) from the primary nuclear event are used to determine the location. Depending on the geometry of the instrument, either a spatially integrating or a position-sensitive detector is required (Convert & Forsyth, 1983; Crawford, 1992; Rausch *et al.*, 1992). The relatively weak neutron source is driving instrument design towards maximizing the number of neutrons collected per unit time, and, in many cases, this leads to the use of multiwire or position-sensitive detectors. The main performance characteristics for detector systems are position resolution, number of resolution elements, efficiency, parallax, maximum count rate, dynamic range, sensitivity to $\gamma$ background and long-term stability.

#### 6.2.1.4.1. *Multiwire proportional counters*

The principles of a multiwire proportional counter (MWPC) are well established (Sauli, 1977) and have wide application. For thermal neutron detection (Radeka *et al.*, 1996), the reaction of choice is

$$^3\mathrm{He} + \mathrm{n} \rightarrow {}^3\mathrm{H} + \mathrm{p} + 764\ \mathrm{keV}.$$

The 191 keV triton and the 573 keV proton are emitted in opposite directions and create a charge cloud whose dimensions are determined primarily by the pressure of a stopping gas. Depending on the work function of the gas mixture, approximately $3\times10^4$ electron–ion pairs are created. Low-noise gas amplification of this charge cloud occurs in an intense electric field created in the vicinity of the small diameter (20–30 µm) anode wires (Radeka, 1988). Typical gas gains of $\sim 10$–50 lead to a total charge on the anode of $\sim 50$–100 fC. The efficiency of the detector is determined by the pressure of $^3$He, and the spatial resolution and count-rate capability are determined by the detector geometry and readout system. The event decoding is selected from the time difference (Borkowski & Kopp, 1975), charge division (Alberi *et al.*, 1975), centroid-finding filter (Radeka & Boie, 1980), or wire-by-wire techniques (Jacobé *et al.*, 1983; Knott *et al.*, 1997). Present MWPC technology offers opportunities and challenges to design a detector system that is totally integrated into the instrument design and optimizes data collection rate and accuracy (Schoenborn *et al.*, 1985, 1986; Schoenborn, 1992*b*).

A concept related to the MWPC is the micro-strip gas chamber (MSGC). With the MSGC, the general principles of gas detection and amplification apply; however, the anode is deposited on a suitable substrate (Oed, 1988, 1995; Vellettaz *et al.*, 1997). The MSGC can potentially improve the performance of the MWPC in some applications, particularly with respect to spatial resolution and count-rate capability.

#### 6.2.1.4.2. *Image plates*

The principles underlying the operation of an image plate (IP) are presented in detail in Chapter 7.2. Briefly, the important difference between an IP for X-ray and neutron detection is the presence of a converter (either $Gd_2O_3$ or $^6$Li). The role of the converter is to capture an incoming neutron and create an event within the IP that mimics the detection of an X-ray photon. For example, neutron capture in Gd produces conversion electrons that exit the $Gd_2O_3$ grains, enter neighbouring photostimulated luminescence (PSL) material and create colour centres to form a latent image (Niimura *et al.*, 1994; Takahashi *et al.*, 1996). A neutron IP may have a virtually unlimited area and a shape limited only by the requirement to locate the detection event in a suitable coordinate system. With a neutron-detection efficiency of up to 80% at $\sim 1$–2 Å, a dynamic quantum efficiency of $\sim 25$–30% can be obtained. The dynamic range is intrinsically 1:$10^5$. The spatial resolution is primarily limited by scattering processes of the readout laser beam, and measured line spread functions are typically 150–200 µm. The $\gamma$ sensitivity is high and may restrict the application to instruments with low ambient $\gamma$ background.

Neutron IPs are integrating devices well suited to data-acquisition techniques with long accumulation times, such as Laue diffraction (Niimura *et al.*, 1997) and small-angle scattering. On-line readout is a distinct advantage (Cipriani *et al.*, 1997).

#### 6.2.1.5. *Instrument resolution functions*

For accurate data collection, the instrument smearing contribution to the data must be known with some certainty, particularly when data are collected over an extended range with multiple instrument settings. A balance must be struck between instrument smearing and neutron flux at the sample position; however, careful instrument design can produce: (i) a good signal-to-background ratio, thereby partially offsetting the flux limitation, and (ii) facilities and procedures for determining the instrument resolution function (Johnson, 1986).

As an example, instrumental resolution effects in the small-angle neutron scattering (SANS) technique have been investigated in some detail. A 'typical' SANS instrument is located on a cold neutron source with an extended (and often variable) collimation system. The sample is as large as possible and the detector is large with low spatial resolution. The instrument is best described by pin-hole geometry. Three major contributions to the smearing of an ideal curve are: (i) the finite $\lambda$, (ii) $\Delta\lambda/\lambda$ of the beam and (iii) the finite resolution of the detector. Indirect Fourier transform, Monte Carlo and analytical methods have been developed to analyse experimental data and predict the performance of a given combination of resolution-dependent elements (*e.g.* Wignall *et al.*, 1988; Pedersen *et al.*, 1990; Harris *et al.*, 1995).

### 6.2.2. Spallation neutron sources

Another phenomenon, quite different from the fission process (Section 6.2.1), that will produce neutrons uses high-energy particles to interact with elements of medium to high mass numbers. This process, called spallation, was first demonstrated by Seaborg and Perlman, who showed that the bombardment of nuclei by high-energy particles results in the emission of various nucleons. The nuclear processes involved in spallation (Prael, 1994) are complex and are summarized in Fig. 6.2.2.1. These processes have been investigated in some detail, and excellent background information is available (Hughes, 1988; Carpenter, 1977; Windsor, 1981). Present-day spallation sources typically use high-energy protons from an accelerator to bombard a heavy-metal target, such as W or U, and come in two types, using either a pulsed proton beam (*e.g.* ISIS or LANSCE) or a 'continuous' proton beam (SINQ).

The high-energy neutrons produced by spallation are moderated in a reflector region to intermediate energies and then reduced to thermal energies in a hydrogenous medium called the moderator (Russell *et al.*, 1996). These thermal neutrons are then extracted *via* beam pipes. A typical layout of a target system with reflectors and moderators is shown in Fig. 6.2.2.2.

The neutrons produced by the proton pulse travel along beam pipes as a function of their velocity, proportional to their energy. At a given distance from the target, neutrons of different energies are observed to arrive as a function of time, with the short-wavelength neutrons arriving first, followed by the longer-wavelength neutrons. Diffraction experiments are therefore carried out with pulsed 'polychromatic' neutron beams as a function of time; a time-resolved Laue pattern results. Clearly, the energy resolution of these beams depends on the volume of the neutron source. To achieve high energy resolution, the volume from which thermal neutrons are extracted is limited to the moderator by suitable use of liners and poisons (Fig. 6.2.2.2) that prevent thermal neutrons produced in the reflector from streaming into the beam pipe (decoupled moderators). The use of liners and poisons achieves high energy resolution, but at the expense of flux. The omission or reconfiguration of liners and poisons allows higher flux, but results in lower energy (wavelength) resolution (see Section 6.2.2.2).

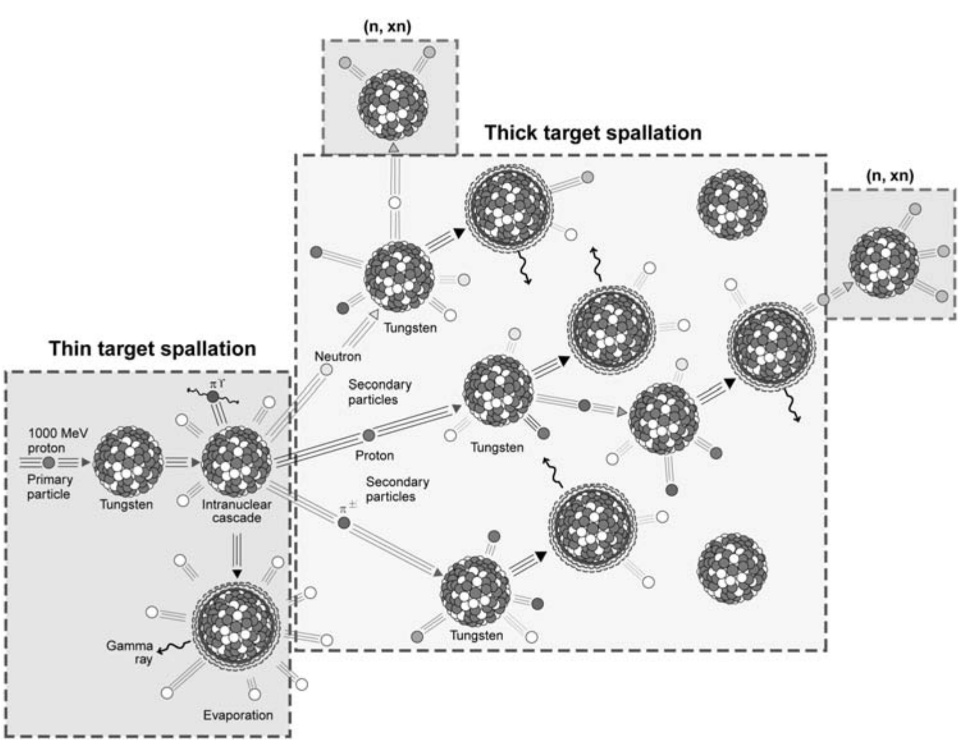


Fig. 6.2.2.1. Schematic presentation of the various nuclear processes encountered in spallation. The numerical analysis of these processes is carried out by two Monte Carlo-based codes – the *LAHET* code models the higher-energy nuclear interactions, while the *HMCNP* code models the thermal interactions and the transport of neutrons to the sample.

#### 6.2.2.1. *Spallation neutron production*

Pulsed spallation neutrons are produced by protons generated by a particle accelerator (linac) with a frequency typically in the range 10 to 120 Hz. The proton pulses are often shaped in compressor rings to shorten the pulses from the millisecond range to less than a microsecond in duration, with currents reaching the sub-milliampere range at energies of 800 MeV or higher. The planned new spallation source at the Oak Ridge National Laboratory will have a proton energy of 1.2 GeV with a power of 1 MW and a repetition frequency of 60 Hz. The high-energy



references