[Characterization Methods]
(Chapter 2.3 in *Elements*)

Methods for characterizing pulsed-source moderators

<u>Spectra</u>

Measuring the energy distribution of the neutrons emerging from pulsed sources is straightforward. The object is to determine the time-integrated number of neutrons per unit energy,

$$I(E) = \int_0^\infty I(E, t)\, dt \ . \tag{1}$$

A detector at a distance L (~ 10 m) from the moderator surface counts neutrons. It is usually placed in the beam emerging perpendicularly from the viewed surface (this is often unimportant because these are usually low-resolution measurements). Ignoring wavelength-dependent emission time and detector response time delays,

$$t = L/v \tag{2}$$

and

$$C(t) = \eta(v) I(E)\ \Delta\Omega\ |dE/dt|. \tag{3}$$

The counting rate at time t is C(t), and η (v) is the detector efficiency for neutrons of speed v (usually a very low-efficiency detector is necessary, for which $\eta(v) = k/v$, where k is a calibration constant). The solid angle subtended by the detector at distance L from the moderator $\Delta\Omega$ is $\Delta\Omega = A_{det}/L^2$. Because $E = (m/2)(L/t)^2$, the Jacobian is $|dE/dt| = 2E/t$. Figure 1 shows a typical arrangement.

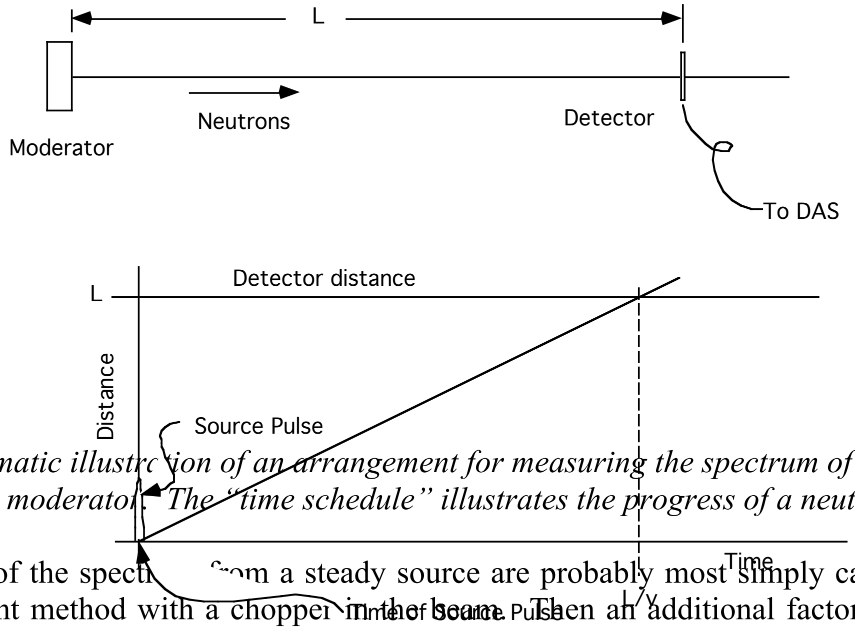

Figure 1. Schematic illustration of an arrangement for measuring the spectrum of neutrons from a pulsed-source moderator. The "time schedule" illustrates the progress of a neutron of speed v.

Measurements of the spectrum from a steady source are probably most simply carried out using the time-of-flight method with a chopper in the beam. Then an additional factor appears in the expression (3) for the counting rate, T(E), the chopper transmission efficiency (see *Elements,* Chapter 7, Devices). The entire detector must view the entire moderator surface through the chopper aperture.

It is important in practice to acknowledge that materials in the beam between the moderator and the detector attenuate neutrons significantly. Almost inescapable are windows for various purposes and air or other gas, and possibly there are filters and choppers. Air attenuates neutrons in a wavelength-dependent way, about 4% per meter under sea-level conditions, the cross section increasing in proportion to the wavelength below about 5 meV energy. Aluminum exhibits numerous Bragg edges (see *Elements,* Chapter 7, Devices)—with significant effects of texture—the longest at a wavelength around 4 Å, with the cross section increasing with wavelength at longer wavelengths. The combined attenuation, represented in a factor $F_{att}(v)$, requires modification of the last result:

$$C(t) \approx \Delta\Omega \int_0^{\infty} F_{att}(v)\eta(v)\, I(E\ , t_e) \left| \frac{dE}{dt} \right| dt_e = \Delta\Omega\ F_{att}(v)\eta(v) I(E) \frac{2E}{t}\ . \tag{4}$$

Pulse shapes

The time distribution of neutrons leaving the moderator is of central importance to the resolution of instruments using neutron beams. Moreover, the shape of the time distribution I(E, t) varies importantly with E. Measuring I(E, t) requires care to preserve time resolution and to define the energy E that corresponds to each time distribution. Figure 2 illustrates one way to accomplish this with good time resolution.

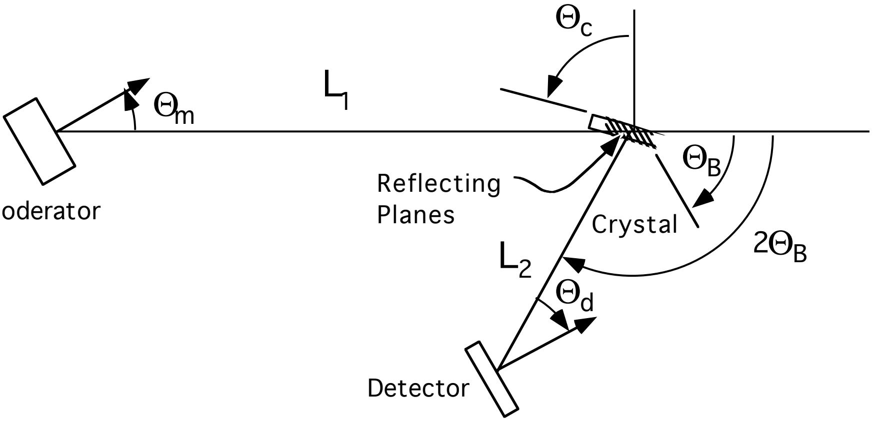

Figure 2. A time-focused crystal analyzer arrangement for measuring emission-time distributions (pulse shapes).

Bragg scattering from a crystal (it can be a mosaic crystal, which provides an intensity advantage with no sacrifice of resolution in a focused configuration) reflects neutrons whose wavelengths satisfy the Bragg condition $n\lambda = 2d\sin\Theta_B$ into the detector. Certain "focusing conditions" relating the flight path lengths, the nominal Bragg angle, and the angles of the moderator, crystal physical plane, and the detector plane allow neutrons that reach the detector to do so without significant broadening in time (Ikeda and Carpenter 1985; Graham and Carpenter 1970). A Bragg angle Θ_B = 60° and a moderator viewing angle Θ_m = 18°, detector angle Θ_D = 73°, with $L_2/L_1 = 0.10$, represents a practical, although not intuitively obvious, setup. Except for a time delay that separates the different orders, the observed time distributions are faithful replicas of the emission time distribution at each wavelength. Under favorable conditions, up to $n \sim 20$ orders of reflection result from a single setting of the crystal analyzer.

A chopper can provide similar results with greater flexibility in the choice of selected wavelengths, but the time resolution is relatively poor.

Figure 3 shows a time distribution measured at IPNS by the crystal analyzer technique (Ikeda and Carpenter 1985). The moderator is poisoned room-temperature polyethylene. The analyzer was Ge(111) cut parallel to the (110) planes, cooled to about 10 K, located 11.7 m from the moderator. The detector was a 3-in.-diam, 1-mm-thick GS-20 scintillator. Many orders of reflection are visible in the figure, in which the detail is greatly compressed. Low-intensity reflections (nnn) for n = 4p-2 systematically missing among those of the perfect diamond lattice show up due to crystal imperfections. (Figure 2.22 in *Elements* shows the (555) reflection in detail.)

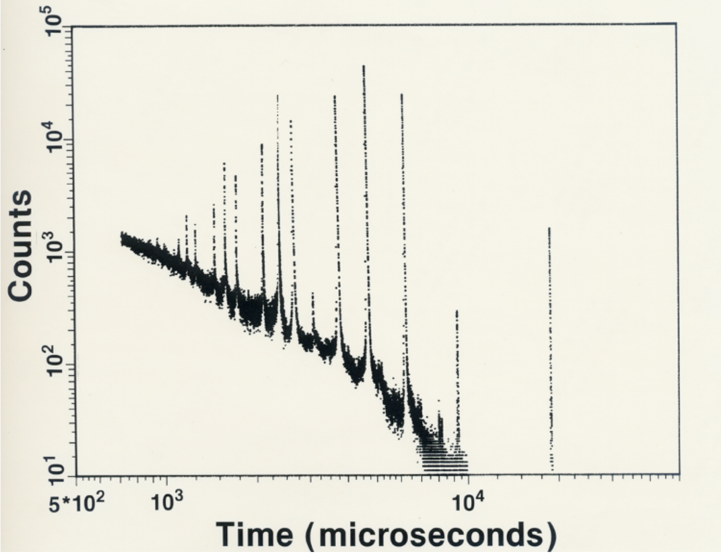

Figure 3. The time distribution of neutrons measured using a time-focused crystal analyzer arrangement (Ikeda and Carpenter 1985).

The time focusing conditions are (Ikeda and Carpenter 1985)

$$\tan \Theta_m = \frac{1}{2}\left(1 + \frac{L_2}{L_1}\right)\cot \Theta_B, \tag{5}$$

$$\tan \Theta_d = \frac{1}{2}\left(1 + \frac{L_1}{L_2}\right)\cot \Theta_B, \tag{6}$$

and

$$\cot \Theta_c = -\frac{\cos\Theta_d \tan \Theta_m + \sin\left(2\Theta_B + \Theta_d\right)}{2\sin \Theta_B \sin\left(\Theta_B + \Theta_d\right)}. \tag{7}$$

The angles are measured in the same sense as the Bragg angle. Note the implication of an "off-cut" crystal: unless $L_1 = L_2$, the physical crystal face is in general not parallel to the reflecting planes. In the instance previously shown, the (111) were the reflecting planes, while the cut face was the (110), differing by $\Theta_c = 35.3° = \cos^{-1}(2/\sqrt{6})$.

Scientists in the various neutron scattering facilities have either developed their own methods for characterizing their sources or have adopted the methods outlined here, which have been successful in IPNS and SNS.