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TITLE: COMPARISON OF COLLIMATION SYSTEMS FOR SMALL-ANGLE NEUTRON
SCATTERING

LA-UR--85-2722

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DE85 015732

SUBMITTED TO: INTERNATIONAL CONFERENCE ON NEUTRON SCATTERING, AUG. 19-23,
1985, SANTA FE, NM

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COMPARISON OF COLLIMATION SYSTEMS FOR SMALL-ANGLE NEUTRON SCATTERING

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It is shown by simple first-order geometric arguments that for a given resolution, the flux on sample in a small-angle scattering instrument is independent of the form of the collimator or of the length of the instrument. Count rate may be increased by increasing the sample size, through the use of multi-aperture systems. In second order, it is shown to be advantageous to place the beam defining elements as close as possible to the source and the sample. The multiple-pinhole system gives maximum flux on small samples but has non-uniform illumination so that intensity increases only about half as fast as sample area. Soller slits and continuous tubes from source to sample were also considered, but neutron scattering and reflection from surfaces generate a large halo. Monte-Carlo simulations confirm these results, with the conclusion that the optimum collimator configuration is the multiple-pinhole system.

1. Infinite Moderator

An infinite plane moderator surface produces a neutron phase-space distribution which is independent of position. The 3-D spatial volume element can be represented as $\delta A \delta t$, where δA is a cross-sectional area and δt is a time width, proportional to an effective thickness divided by the neutron velocity. The momentum components can be represented by energy and solid angle, so that the phase-space volume element is

$$\delta V = \delta A \delta t \delta E \delta \Omega .$$

(1)

The elements δt , δE , and $\delta \Omega$ are invariant because the neutrons have no interactions after leaving the moderator, and at any distance from the surface the number which have drifted out of area δA is balanced by those drifting in. Thus every term in eq. (1) is constant, and the neutron flux anywhere outside the moderator is equal to the "surface brightness" given in units of neutrons/cm²/μs/eV/ster.

The purpose of a collimator is to limit the phase space used, particularly δA and $\delta \Omega$. The result is a distribution of particles on the sample or detector with an intense central portion (called the "umbra" by analogy to shadows cast by solid objects shaped like the collimator apertures) and a fringe region ("penumbra"). The collimator is completely characterized by a probability distribution in phase space. It is customary to represent the collimation by the angular width of this distribution and by the penumbra size at the sample. For small-angle scattering, the most significant parameter is the variance of the angular divergence, or $V[\theta]$. To first order, then, we may represent the collimator by $V[\theta]$.

2. Small-Angle Scattering

For small-angle scattering, only a very limited range of $\delta \Omega$ in the vicinity of $\theta = 0$ may be used. As long as θ is small enough that the penumbra at the moderator lies totally within its geometric bounds, then the moderator is "infinite" and the discussions of the preceding section apply. With the nomenclature of fig. 1, there are contributions to $V[\theta]$ due to the variance of the moderator distribution (r_M), due to the distribution at the sample (r_S), and due to the non-negligible binning of the detector (ΔR). Neglecting the detector (which is a separate and independent problem), the variance due to moderator and sample distributions is [1]

$$V[\theta] = \frac{1}{2} \frac{E[r_M^2]}{L_1^2} + \frac{1}{2} \frac{E[r_S^2]}{(L')^2} \quad (2)$$

where $E[r^2]$ is the expectation value of r^2 (or the mean-square radius), and L' is a "reduced length" defined by

$$\frac{1}{L'} = \frac{1}{L_1} + \frac{1}{L_2}, \quad L' = L_1 L_2 / (L_1 + L_2) . \quad (3)$$

Optimization of $V[\theta]$ at fixed intensity requires [1,2] that the two terms of eq. (2) be equal, and hence (to first order, or if the two distributions have the same shape) that

$$\frac{R_M}{L_1} = \frac{R_S}{L'} ; \quad (4)$$

this equation is exact if R_M and R_S are replaced by root-mean-square radii of the distributions. This can also be written

$$\frac{R_M}{R_S} = \frac{L_1 + L_2}{L_2} , \quad (5)$$

which (by similar triangles) shows that any optimized collimator converges to a point umbra at the detector.

For a given $V[\theta]$, all terms scale with the total instrument length, and all angles are preserved. Flux at sample is constant because the change in area viewed on the moderator is exactly compensated by change in the solid angle of an element of the sample as seen from the moderator. For a simple collimator such as the pair of pinholes in fig. 1, sample area and total count rate increase as L^2 , but for multiple-aperture systems such as Soller slits the sample size may be independent of R_S and the count rate is thus also independent of L . The absolute maximum sample size is determined by the requirement that the penumbra of the source distribution be within the moderator size: so long as this criterion is met, the count rate is independent of the form of the collimator or of the length of the instrument.

Note that the angular resolution of a multiple-aperture collimator is determined by the dimensions of any one aperture if all converge to the same point on the detector as required by eq. (5). Any point on the sample

is in the umbra of only one aperture, though it may see penumbrae from several.

3. Higher-Order Terms

To compare different forms of collimators we must consider the moderator and/or sample distributions in addition to $V[\theta]$. The maximum possible intensity for given $V[\theta]$ and surface brightness occurs for a square distribution as shown in fig. 2a. This corresponds to $\lambda_1 = 0$ in fig. 1. At the other extreme, as λ_1 becomes large compared to the length of the actual collimator section, the distribution on the moderator becomes triangular, as in fig. 2b, and the intensity for the same $V[\theta]$ is reduced to half. Because of the symmetry of eq. (2) and the equality of its terms when optimized, the same argument applies if λ_2 is long. Thus a short collimator placed in a long flight path has only half the flux at the same resolution as simple pinholes placed close to the source and sample. This is a problem with Soller collimators. The sample area can be made larger to increase intensity, but the large penumbra on the moderator severely limits the available gain.

To increase sample size in a pinhole system, multiple apertures can also be used, as illustrated by the seven converging pinhole sets in fig. 3. Intermediate baffles prevent crosstalk between neighboring cones. Although the flux in any one imaginary tube has the maximum possible value, the sample is not uniformly illuminated, as shown in the Monte-Carlo calculation in fig. 4. Count rate for large samples is thus essentially equal to the Soller collimator, but is twice as high for samples smaller than one pinhole.

Another parameter which is very significant for design of a small-angle instrument is the minimum angle which can be measured outside the penumbra radius at the detector (R_p in fig. 1). This is clearly optimized by maximizing the length λ of the collimator section.

4. Monte-Carlo Simulations

The use of Monte-Carlo to analyze the resolution function is given in ref. [3], and is shown to give results consistent with simple geometric arguments. Using the dimensions shown in fig. 3, and requiring $V(\theta) = (1.5 \text{ mrad})^2$, the resulting aperture diameters are 16.7 mm (entrance) and 9.4 mm (exit).

A Soller-slit package 1 m long giving the same R_p provides only % of the peak flux and only allows % of the sample area compared to the pinhole system; total count rate is %.

A 19-hole collimator with ℓ_1 increased to 4.5 m has also been considered [4]; the advantage of this system is that the entire collimator is located outside the biological shield of the source for versatility. The aperture diameters became 12.0 mm and 6.0 mm. Peak flux for small samples is %, and maximum sample area is % of the case with $\ell_1 = 1 \text{ m}$. This is quite similar to the Soller collimator, but avoids the problems of surface reflections.

The conclusion of the study is that the optimum collimator system is multiple pinholes, with the apertures close to the source and to the sample.

Acknowledgment

This work was performed under the auspices of the U.S. Department of Energy, Office of Basic Energy Sciences.

References

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Fig. 1.

Fig. 2.

Fig. 3.

Metallurgical Position
Sample

Detector

10 mm

Fig.4.

(Figure Captions)

Fig. 1. Geometry and nomenclature of small-angle scattering.

Fig. 2. Comparison of square and triangular distributions. For the same $V(\theta)$, the square distribution has twice the intensity.

Fig. 3. Multiple-aperture collimator. Seven converging beams are defined by entrance and exit aperture pairs. Intermediate baffles prevent crosstalk between imaginary "tubes."

Fig. 4. Monte-Carlo simulation of neutrons at the sample location and at the detector. The sample illumination is non-uniform, but all beams converge to the same pattern at the detector.