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Shaping micron-sized cold neutron beams

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ABSTRACT

In the field of neutron scattering, the need for micro-sized (1–50 μm) thermal or cold neutron beams has recently appeared, typically in the field of neutron imaging to probe samples with a high spatial resolution. We discuss various possibilities of producing such micro-sized neutron beams. The advantages and drawbacks of the different techniques are discussed. We show that reflective optics offers the most flexible way of producing tiny neutron beams together with an enhanced signal to background ratio. The use of such micro beams is illustrated by the study of micrometric diameter magnetic wires.

1. Introduction

Neutron beams for condensed matter studies are traditionally used in the form of macroscopic beams on the order of 10×10 mm² or more in size mostly because of the limited neutron flux. However, request for the study of small samples has triggered efforts to produce smaller beams. In the last decade, focusing devices (such as bent crystal monochromators, elliptical guides, capillary lenses, Fresnel lenses) have been developed, which enable focusing neutron beams in one or two dimensions [1]. However, these devices are restricted by their physical properties and manufacturing technologies and cannot produce beam foci of less than 50 μm width. Another drawback of the existing devices is that they often do not produce very "clean" beams. In the case of elliptical guides the beam is strongly structured in space. In the case of capillary lenses a strong background is produced and in the case of Fresnel lenses only a fraction (20–40%) of the beam is focused.

In the following we address the issue of producing sub-100 μm neutron beams with a background contribution as small as possible. We discuss 3 main approaches: (i) collimation slits (Section 2), (ii) reflective optics (Section 3), (iii) neutron wave-guides (Section 3).

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2. Use of collimation slits

The most straightforward way of producing a very small beam consists in using simple slit masks. In order to produce very clean beams, one should consider the use of Gadolinium Gallium Garnet $Gd_3Ga_5O_{12}$ (GGG) single crystals which are readily available commercially. Such crystals have the following advantages. The intrinsic absorption is very high because of the Gd content. Because of the single crystalline nature, no small angle scattering is generated. The material being a ceramic it is also very rigid and does not suffer from plastic deformation which is essential when aiming at μm resolution. One issue in the production of very clean microbeams is connected to the reflection from the slit edges. A first approach is to make the edges rough to limit the reflection. The drawback is that diffuse scattering is likely to appear. Another approach consists in using a knife edge geometry in which the edge of the slit is not rectangular but cone-like (see Fig. 1).

The absorption cross-section of natural Gd is 49,700 barn (at 2200 m/s, $\lambda = 0.1798$ nm, $E = 25.3$ meV). GGG is a cubic crystal with a lattice parameter of 12.38 Å and 24 Gd atoms per cell so that the absorption of GGG can be estimated as 62×10^3 m^{-1} at 1.8 Å and 138×10^3 m^{-1} at 4 Å. In order to define a knife edge, the slits can be tilted at 45° (Fig. 2a) or at a smaller angle (e.g. 80° on Fig. 2b) in order to increase the thickness of GGG seen by the neutrons. Fig. 2 presents the transmission of such GGG tilted slits taking into account the finite thickness of the GGG knife edge. The

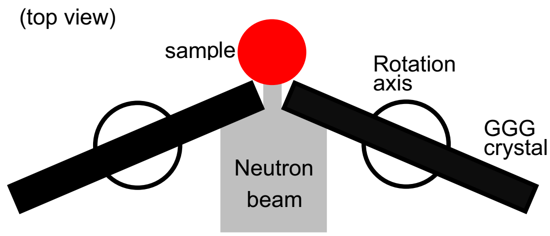

Fig. 1. Use of two GGG crystals mounted on two rotation stages to define a narrow slit. The size of the slit can be adjusted by rotating the crystals.

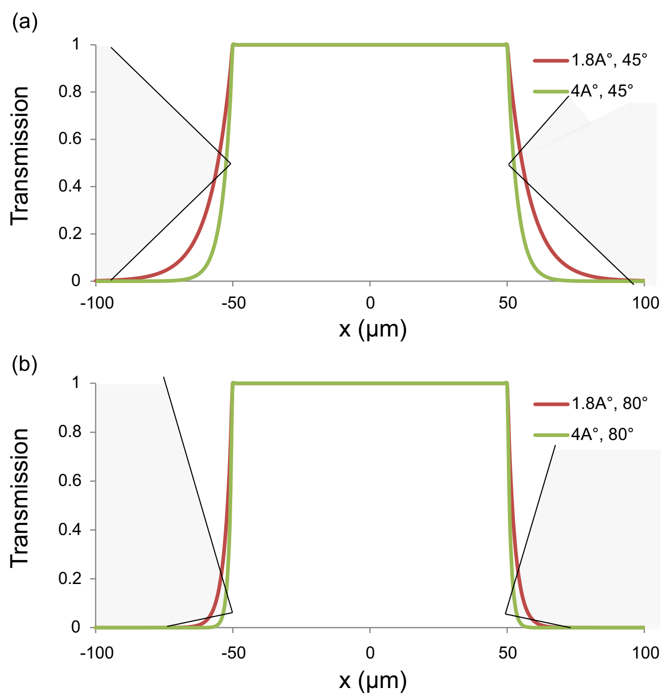

Fig. 2. Transmission of GGG slits tilted (a) at 45° and (b) at 80°. The edges of the transmitted beam are always poorly defined. Even for cold neutrons and a tilt angle of 80°, the edges extend over 10 µm on each side of the main beam. The shaded areas represent the positions of the GGG crystal edges.

transmission is given by $T=e^{-At(x)}$ where $t(x)$ is the thickness of the GGG at the x position. In the case of slits tilted at 45°, one can note that the beam extends over 20 µm beyond the knife edge even at 4 Å. In the case of slits tilted at 80°, the beam still extends up to 10 µm. Thus as soon as one wants to define neutron beams with sizes well below 100 µm, the limitation is given by the neutron absorbing material. To our knowledge, GGG is presently the best suited material since it is a single crystal which can be properly machined. The use of gadolinium oxide powders (Gd_2O_3) paint would be less efficient since the binder would both lead to a reduction of the specific neutron absorption and also to incoherent scattering.

It should be noted that besides being not so well defined, the beam profile depends on the slit tilt angle. For technical reasons, the use of translation stages is risky since any mis-operation of the translation stages may bring the slits against each other and lead to their destruction. The use of rotating stages avoids this problem and allows to safely totally close the slits. The drawback is that the tilt angle varies when the slits are opening, thus changing the actual beam profile.

3. Use of reflected beams

In order to produce "clean" sub-100 µm beams without tails, we propose to use the total reflection of thermal and cold neutrons on a flat surface. In the case of cold or thermal neutrons ($\lambda > 2$Å), it is possible to define the equivalent of an optical index for the neutrons. As in the case of X-rays, this optical index is smaller than 1 and is given by $n=1-\rho b.\lambda^2/2\pi$, where λ is the neutron wavelength, ρ is the atomic density and b is the neutron scattering length. Since the optical index is smaller than 1, by using the Snell's law, it is possible to show that there is an incidence angle $\theta_c=\mathrm{ArcCos}(n)\approx\sqrt{\rho b/\pi}\times\lambda$ below which the neutrons are totally reflected. Above this incidence angle the reflected intensity follows the Fresnel reflectivity and drops very quickly. For $\theta=1.2\times\theta_c$ the reflectivity is only 10%. In the case of nickel, which is one of the most reflecting materials, the critical angle is proportional to the wavelength and is equal to $\theta_c=0.1^\circ\times\ \lambda$ [Å]. In the case of silicon, the critical angle is $\theta_c=0.047^\circ\times\ \lambda$ [Å]. The critical angles are thus very small for cold neutrons with wavelengths in the range $\{\lambda\sim 3\text{–}10$ Å$\}$.

The principle of the setup which creates microbeams by reflection is described on Fig. 3. A silicon wafer with a width w_{Si} of a few mm is cut within a wafer and set at an angle slightly below the critical angle of the peak flux on the neutron beam. For example in the case of a neutron beam with a peak flux at 4 Å, the critical angle is 0.190°. Assuming an incidence angle of 0.15°, the width of the reflected beam is given by $w_r=w_{Si}\ \sin(0.15^\circ)=2.6\times10^{-3}\ w_{Si}$. For a width of the silicon wafer $w_{Si}=8$ mm , the width of the reflected beam is 20 µm. The silicon mirror is mounted on a Cadmium support which absorbs neutrons and absorbs most of the direct beam.

The advantages of such a scheme are that: (i) the microbeam is produced off the direction of the incident direct beam so that the background noise is significantly reduced at the detector position; (ii) the size of the micro-beam can easily be adjusted by simply changing the incidence angle on the Si wafer; (iii) the intensity distribution in the reflected beam is rectangular. It should however be mentioned that the incident beam should be rather well collimated in order to keep a small beam at the sample position. The beam broadening due to the angular divergence $\Delta\theta_i$ is proportional to the (Si-sample) distance $d_{\text{Si-sample}}$ and is given by $\Delta w_r=d_{\text{Si-sample}}\ \sin(\Delta\theta_i)$. Assuming an incidence beam divergence of 0.05° which is routinely used on neutron reflectometers or SANS spectrometers, the extra broadening from the beam divergence is about 1 µm/mm. Thus the sample should to be studied should be set at a typical distance on the order of 10 mm only. This can be relaxed by further increasing the incident beam collimation but at the expense of the neutron flux.

Note that such a setup creates sub-100 µm beams only in 1 direction of space. It is however suitable for scanning measurements of 1 dimensional objects. In order to demonstrate the usability of such narrow neutron beams, we have used this experimental set-up to

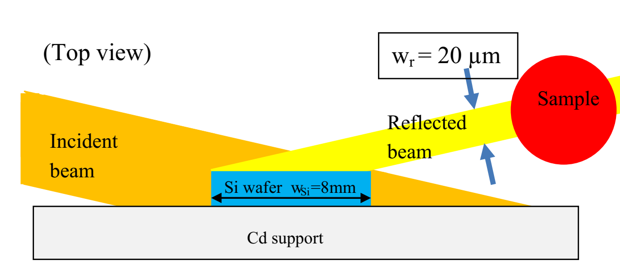

Fig. 3. Scheme (top view) of the production of a sub-100 µm neutron beam using the total reflection on a surface. For a silicon crystal of width 8 mm and an incidence angle of 0.15°, a reflected beam of width 20 µm is obtained.