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Micro-array collimators for X-rays and Neutrons

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ABSTRACT

We describe the fabrication techniques of novel, compact optical elements for collimating and/or focussing beams of X-rays or thermal neutrons. These optical elements are solid composite arrays consisting of regular stacks of alternating micro-foils, analogous in action to Soller slit collimators, but up to three orders of magnitude smaller. The arrays are made of alternating metals with suitable refractive indices for reflection and/or absorption of the specific radiation. In one implementation, the arrays are made of stacked micro-foils of transmissive elements (Al, Cu) coated and/or electroplated with absorbing elements (Gd, Cd), which are repeatedly rolled or drawn and restacked to achieve the required collimation parameters. We present results of these collimators using both X-rays and neutrons. The performance of the collimating element is limited only by the choice of micro-foil materials and the uniformity of their interfaces.

Keywords: Soller collimators, neutron optics, X-ray optics

1. INTRODUCTION

The collimation of beams of X-rays and thermal neutrons is achieved with the aid of Soller slit collimators, arrays of parallel absorbing plates separated by gaps[1]. Currently manufactured neutron collimators have neutrons passing through the air-gaps between parallel stacked arrays of polyethylene films with absorbing coatings[2], generally of Gd or B, stretched over supporting frames. For X-rays, collimation is in the air-gaps between thin foils of Pb or Fe. In order to achieve good collimation and transmission, these sheets are thin and very straight, and hence absorb only a small percentage of the incident radiation. However, in order to achieve a high degree of collimation with such self-supporting devices, the collimator has large dimensions. This precludes their use in all but the largest apparatus. Typical dimensions of these absorbing-film collimators is 300 mm in length, and for a beam cross-section of 50 mm-wide x 100 mm-tall, consist of many tens of these foils with mm separation. Several applications, however, require equivalent collimation but in much more confined spaces.

We have developed collimators small enough for all applications in X-ray and thermal neutron experiments which demand collimation inside the apparatus, for example inside perfect crystal interferometers. To achieve collimation within lengths orders of magnitude smaller than existing devices, the thickness of the individual channels and absorbing layers is proportionally reduced to microscopic size. Consequently, the alternating layers are no longer self-supporting and must form part of a solid composite. The radiation is transmitted by a channel metal layer and absorbed by an adjoining septa layer. We present neutron and X-ray transmission results for the type of micro-collimators shown in Fig.1, that are made of several hundred alternating, flat, micro-foils of (transmitting) Al and (absorbing) Cd.

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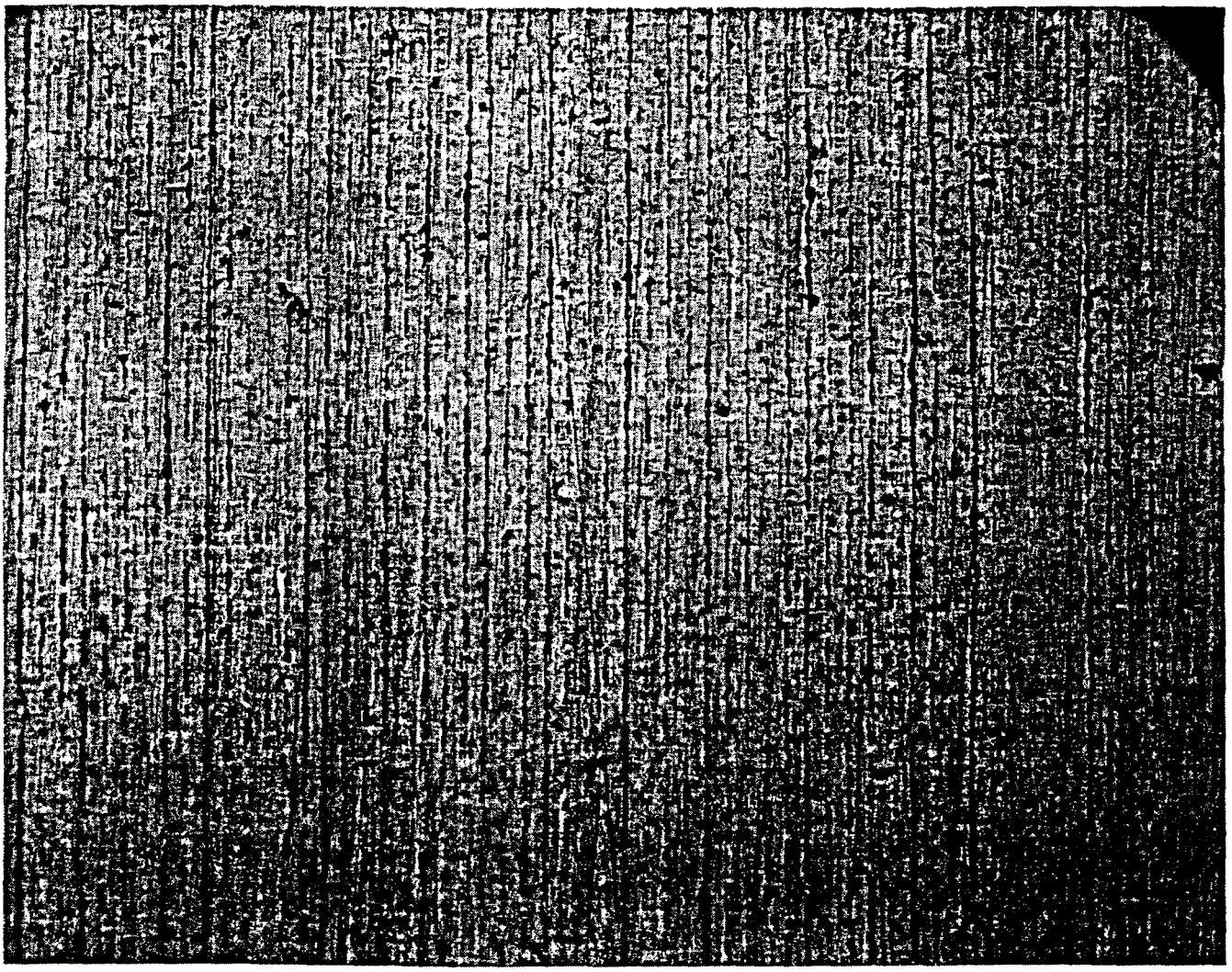

Fig.1. Optical micrograph of the front of a Al-Cd micro-collimator. The Al layers (light bands) are 23μm thick and the Cd layers (dark lines) are 5μm thick. Horizontal lines and discolourations are artifacts of the polishing process.

2. ONE AND TWO-DIMENSIONAL DUCTILE ARRAYS

Our micro-Soller arrays are solid composites and consist of hundreds of alternating, flat micro-foils (Fig.1). Reducing the thickness of the individual layers or channels to microscopic size is achieved by repeated stacking and rolling of an initially thick bi-layer or multi-layer structure of metal composites of high ductility. Radiation propagation is along the layers or channels of a metal selected for negligible absorption and scattering. For thermal neutrons some of the metals with the required properties are Pb, Cu and Al. The absorbing side layers, or septa, are of a different metal chosen to provide optimum conditions for absorption, such as Gd, ^{10}B or Cd. In the case of X-ray collimation, any low atomic number element for the channel versus a high atomic number element for the septum. In the micro-Soller shown in Fig.1, transmission is through 23 μm-thick Al channels (light) sandwiched between absorbing layers of Cd (dark) of average thickness 5 μm. This pairing of metals was used for both the tests with hard X-rays and thermal neutrons.

Finally, our method makes two-dimensional micro-Soller composites practical. In this geometry, rather than a one-dimensional stack of foils, a two-dimensional array of alternating channel and septa square-section wires (again of similar high ductility) are arranged in a square-section checker-board pattern. This composite is then extruded into a smaller square-section wire with 50% open-area. The stacking and extrusion can be repeated as desired. Another possibility is to start with a square section composite wire with a square core channel and uniformly-thick cladding septa. By this method two-dimensional collimators of arbitrary open-area may be made.

3. METHOD OF FABRICATION

Ductile metals (channel and septum) are precision rolled or extruded to reduce their cross-section to an initial, desirable, uniform thickness with very good surface finish. The rolling process was performed with a motorised jewellery mill, the rollers of which are cylindrically ground, nickel plated and optically polished. Alternating layers are superimposed and the composite structure is rolled or extruded. Alternatively, plating a thin layer of the absorbing metal on an initially thick (≈100 μm) channel substrate allows large open-area arrays to be prepared. For example, to achieve the micro-Soller displayed in Fig.1, uniform 100 μm-thick Al foils were plated with approximately 15 μm of Cd. A series of these plated foils are then stacked to form the composite structure. To increase the multiplication of the composite, it can be folded (or cut in half), affecting a doubling of the structure at each fold. The stacking and rolling or extrusion procedure retains the initial uniformity and is repeated until the desired final layer thickness is attained. A schematic of the stacking and rolling procedure is shown in Fig.2. A further final stacking is performed to build the device to a given total cross-section. The composite is thereafter mounted into a metal tube carrier with a low temperature solder. Finally, it is cut to the required length (usually of order 2 mm or less) and the ends polished.

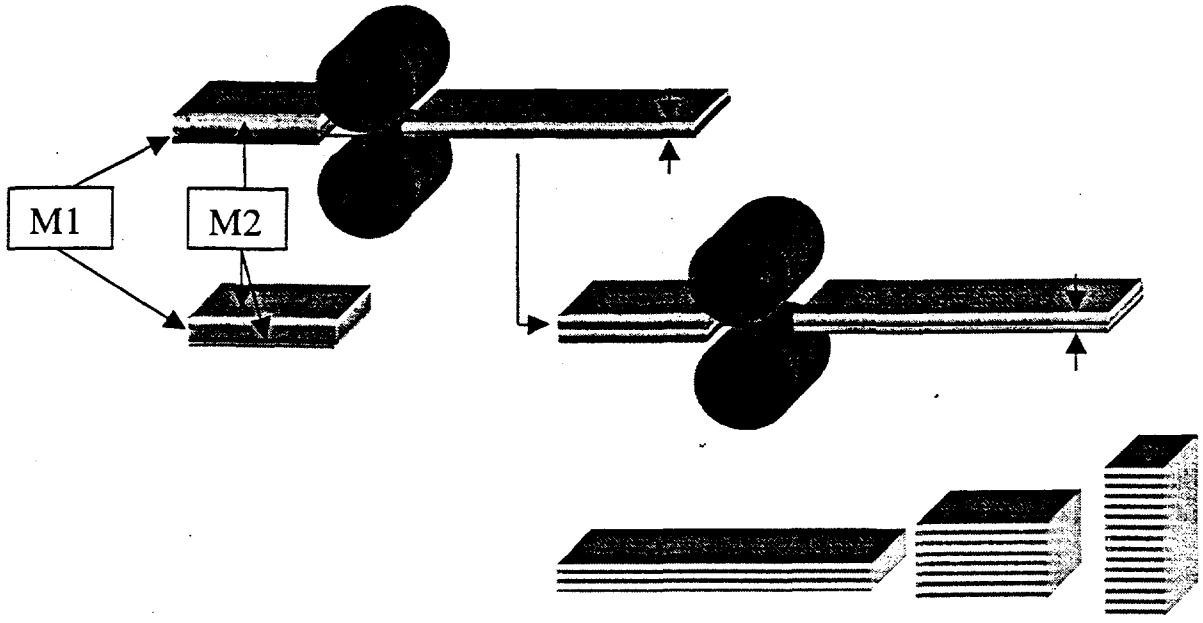

Fig.2. Schematic of the stacking and rolling procedure used to fabricate the arrays. Metals M1 (forming the transmission channels) and M2 (absorber) may have different initial thickness, or M1 may be plated with M2 in order to increase the effective "open area" for transmission.

The final product is a solid block of manageable size, and as can be seen in the micrograph of Fig.1, well-defined geometric parameters. The path length through the "gap" or "channel" material is so reduced (of the order of a few mm or less) as to have minimal effect on the beam flux in terms of both scattering and absorption.

4. MICRO-COLLIMATOR TEST USING HARD X-RAYS AND THERMAL NEUTRONS

Results from previous tests of Cu-Cd and Al-Cd micro-Sollers with thermal neutrons have already been presented[3,4]. This paper presents results of hard X-ray and neutron experiments with an Al-Cd collimator like that shown in Fig.1. The X-ray measurement was performed at the high energy X-ray facility[5] at the Institut Laue-Langevin, Grenoble, France using 60 keV X-rays (Philips X-ray generator) attenuated by 2 mm of Al. A schematic of the experimental set-up is shown in Fig.3. The sample is placed on a rotation stage (with its layers vertical) at the mid-point between source and detector located 7.2 m apart, and covered by a mask to 5 mm-tall x 0.5 mm-wide. A fixed CCD camera (Princeton) took 2 sec exposures of the transmitted beam as the micro-Soller was rotated.

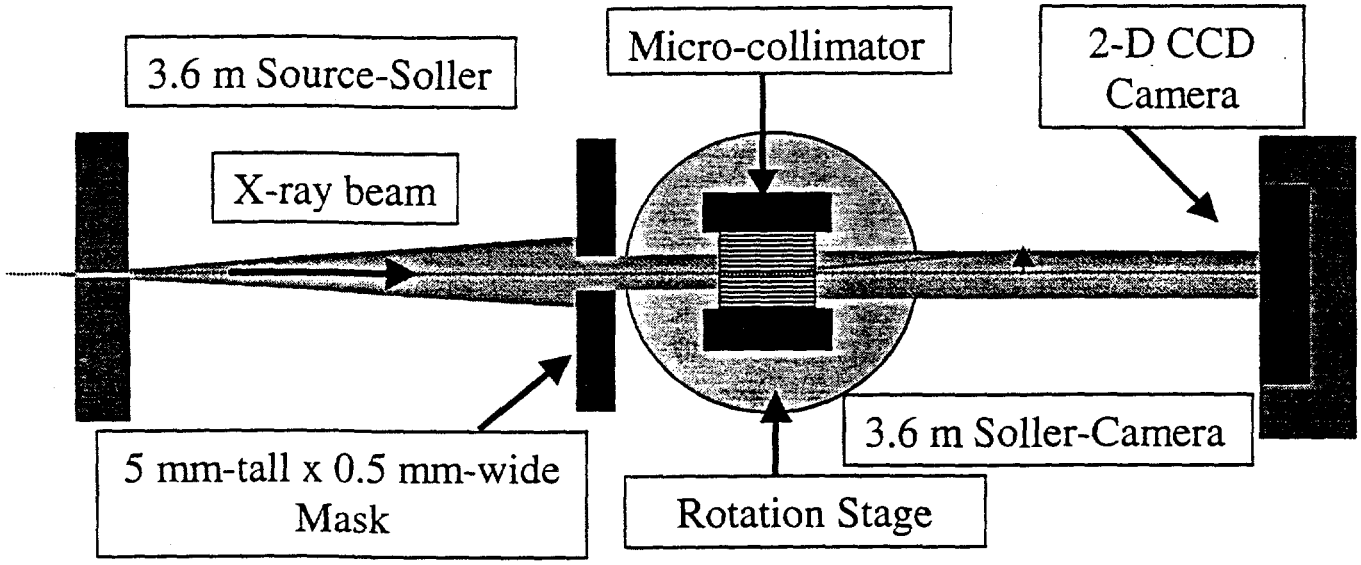

Fig.3 Schematic of the set-up to test the micro-collimators with X-rays.

The neutron measurement was performed at the neutron reflectometer set-up at Oak Ridge National Lab[6]. A schematic of the geometry is given in Fig.4. In this experiment, the sample mounted on the instrument's rotation stage with its layers aligned vertically with the neutron beam. A masking slit limited the illumination and defined the position of a 2.59 Å thermal neutron beam on the sample to about 0.5 mm-wide by 4 mm-high. A fixed Ordela™ 1155N position sensitive detector measures the collimator's throughput.

The results presented here are for two micro-Sollers cut from the same composite block and pictured in Fig.1. The details of the pair are given in Table 1. The result of transmission scans for the two are given in Figs.5 and 6. The X-ray data is the horizontal average of the image taken at each angle setting for a 1 mm-tall exposed region. The solid line is a two Gaussian fit to the data, the details of which are given in Table 2. In both cases, the central peak is fitted well by a tall narrow Gaussian determining the divergence of the beam, and a broad diffuse Gaussian is fitted to the remaining background. The fit to the neutron data is quite good, however there do appear to be subsidiary peaks in the X-ray data. For 60 keV X-rays, the absorption of 3.1 mm of Al is 8%, while they are completely absorbed in the same length of Cd. Combined with the open area fraction of the array, the maximum predicted throughput is 75%. In the neutron case, the open-area fraction and absorption of the Al channels gives a maximum predicted throughput of 81%. While performing to about 50% of the geometric throughput

and close to the geometric collimation both samples give an ambient background that diminishes the signal-to-noise. This combination of artifacts will be explained in the next section.

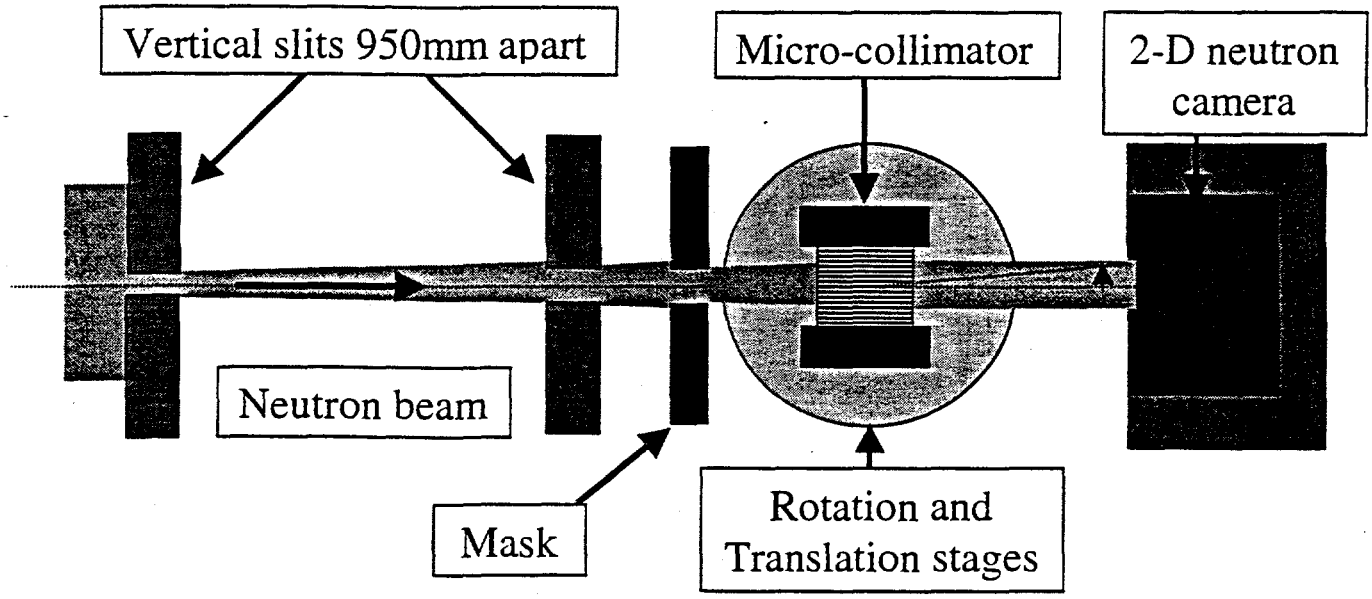

Fig.4. Schematic of the set-up to test the micro-collimators with neutrons.

Experiment	Channel	Width (μm)	Septum	Width (μm)	Length (mm)	Aspect Ratio	Cross-Section (mm^2)	Open Area (%)
X-ray	Al	23	Cd	5	3.1 ± 0.05	135	5 x 7	82
Neutron	Al	23	Cd	5	3.9 ± 0.05	170	5 x 7	82

Table 1. Characteristics of the two micro-Soller collimators used in the experiment.

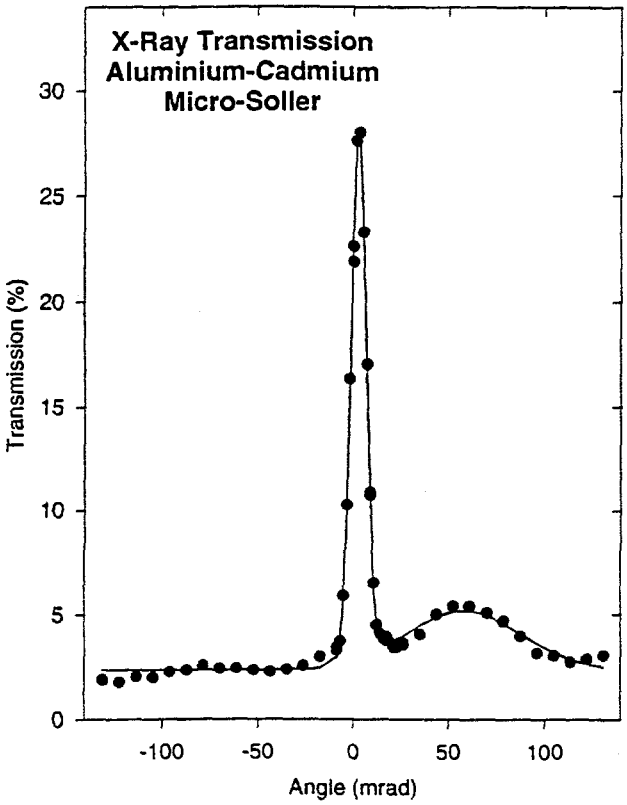

Fig.5 Plot of the X-ray throughput for the Al-Cd micro-Soller as described in the text. The solid line is a two Gaussian fit to the data.

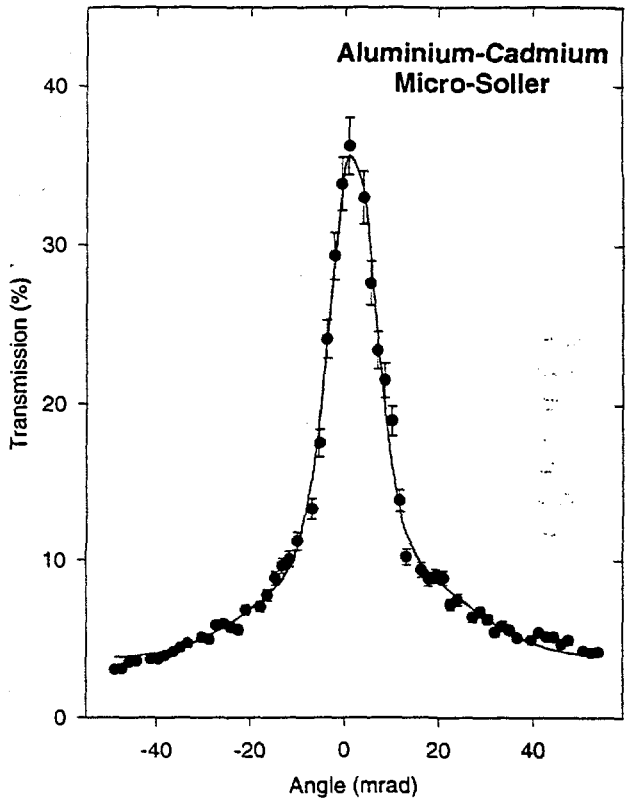

Fig.6. Plot of the neutron throughput for the Al-Cd micro-Soller as described in the text. The solid line is a two Gaussian fit to the data.

Sample: Al-Cd (60 keV X-rays)	Transmission	FWHM	Background Transmission	Background FWHM
Theory	75%	6 mrad	0%	-
Experiment	28%	9 mrad	5%	71 mrad
Sample: Al-Cd (thermal neutrons)				
Theory	81%	8 mrad	0%	-
Experiment	36%	11 mrad	4%	42 mrad

Table 2. Transmission and collimation for the two micro-Soller collimators.

5. ANALYSIS

The micrograph of the micro-Sollers in Fig.1 shows that the end face of the individual layers are neither perfectly straight nor of uniform thickness. If this is the case through the entire length, it will reduce the ultimate performance of the collimator, as indicated by Carlile[2]. Thus instead of sharp edges between the layers, a smoothing will occur between the "opaque" Cd layer and the "transparent" channel layer. It may also be envisioned that even with the high neutron and X-ray absorption cross-section of the Cd, and the length of the samples being many times greater than the extinction length, the septa may not be thick enough to entirely absorb the radiation, especially at increased angular divergence. Consequently, an ambient transmitted background exists.

A simple theoretical modelling of the Al-Cd micro-Soller has been performed[4]. The transmission for a model based on a Gaussian absorption profile of the Cd layer due to the microscopic interdiffusion of the Al and Cd layers, and an ambient absorption in the Al channel-layer is shown in Fig.7. The model represents the optimised fit to the neutron data, with a well defined central maximum and a number of subsidiary peaks. The subsidiary peaks represent the neutron beam crossing successive neighbouring Cd layers at ever-increasing angular divergence. A further smoothing takes into account the macroscopic waviness of the Al-Cd interfacial region across a number of channels and any mis-alignment of the Cd layers internal to the micro-Soller (which is not visibly obvious at the polished ends), and gives the result (solid line) indicated in Figs.8 and 9. This model fits the neutron data well, but the optimised X-ray model gives a much broader peak than the data.

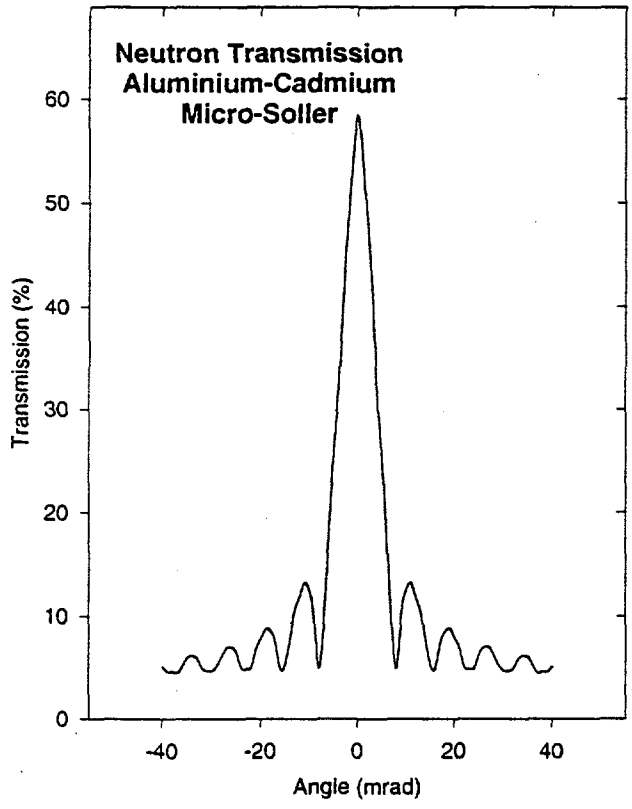

Fig.7. Plot of modelled transmission function vs beam divergence angle, showing the central transmission peak and diffuse background distribution.

6. COMPARISON WITH NEUTRON RESULTS

The broad diffuse background which appears in these and previous neutron results[4] may be due to small angle neutron scattering of the transmitted beam while passing through the collimator's channel material. Neutrons are scattered by microscopic cracks, defects, oxide surfaces etc. For a 42 mrad FWHM background (Al-Cd sample), this means a scattering angle of 17 mrad and imperfections of rms size 150 Å.

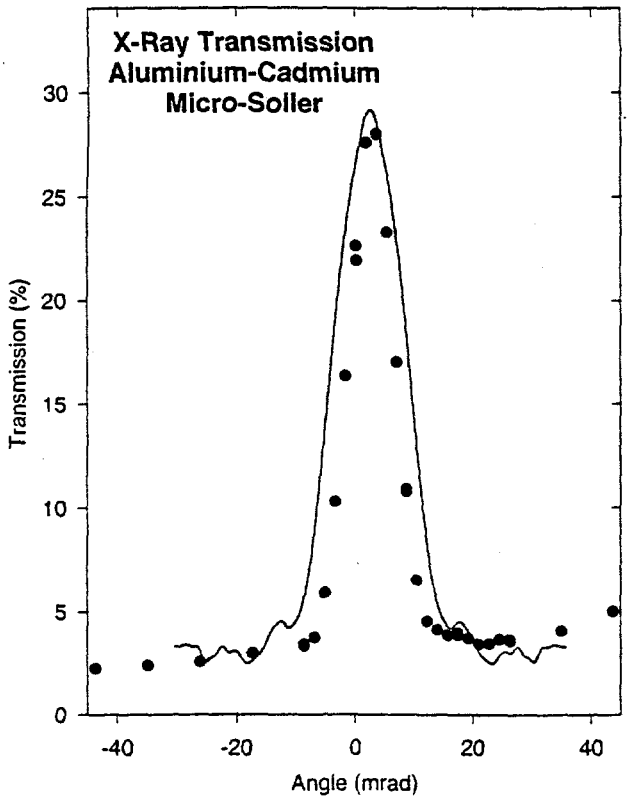

Fig.8. Fit of the smoothed model to the X-ray data.

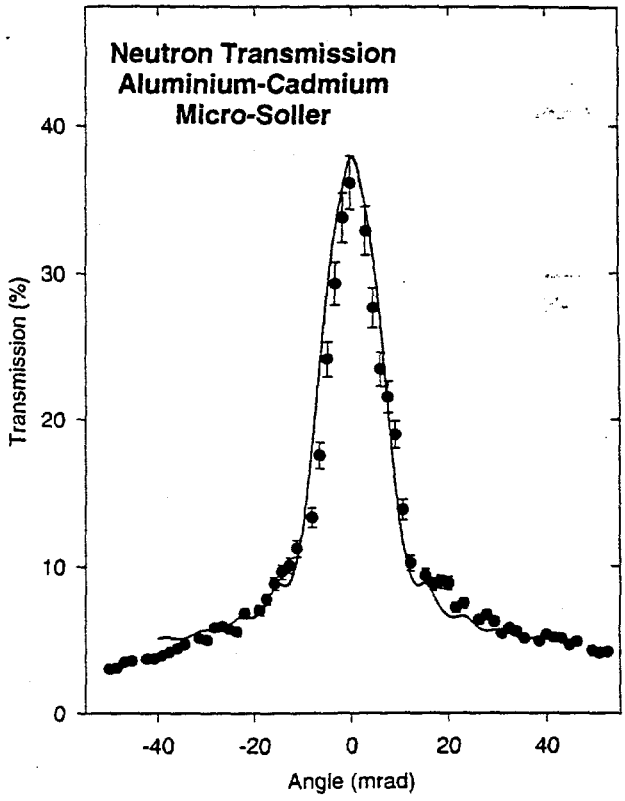

Fig.9. Fit of the smoothed model to the neutron data.

7. DISCUSSION

The results indicate that several of the four collimation efficiency conditions of Carlile are not optimised in our micro-Soller devices. The non-sharp boundary of the interface region between the bilayer metals has a major influence on the smoothing of the throughput intensity profile from theoretical. The microscopic features of the metal foils are a mirror image of the surface of the rollers, that is imprinted on the metal during the rolling stage of the fabrication. The macroscopic waviness of the bilayers is a function of foil non-uniformity and of variations in roller speed and separation. Future improved collimators will therefore require more uniformly spaced rollers with mirror surfaces, as well as more accurate speed control.

Finally, good mirror interfaces between appropriately selected metal layers will make possible reflective and focussing elements for neutrons based on channel array optics[7]. Further processing, like bending through an arc or pressing into a

suitable shape, would result in optical devices optimised for guiding and imaging applications. Finally, with the selection of appropriate metals, cognate devices for conditioning X-ray and neutron beams over the entire spectrum of energies can be envisioned.

8. CONCLUSION

We have presented proof-in-principle results of the fabrication and testing of solid-composite, micro-Soller arrays for the collimation of thermal neutron and hard X-ray beams. The advantages of such compact arrays are: i) very simple and economical tools and materials can be used for the manufacture of accurate and reproducible devices and ii) the optical elements can be made small enough to be placed directly at the beam delivery point. These devices can be built to process beams of any cross-section, achieving the desired collimation (and ideally, deflection or focussing), within lengths orders of magnitude smaller than existing devices.

9. ACKNOWLEDGEMENTS

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