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Metal Micro-Arrays for Collimating Neutrons and X-Rays

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Metal Micro-Arrays for Collimating Neutrons and X-rays

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ABSTRACT

We describe the theory, fabrication and experimental results of novel, compact optical elements for collimating and/or focussing beams of X-rays or thermal neutrons. These optical elements are solid composites consisting of regular stacks of alternating micro-foils, analogous in action to Soller slits. They are made out of pairs of metals with suitable refractive indices for reflection and/or absorption of the radiation. The performance of these proof-in-principle collimating elements 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 X-rays and beams of thermal neutrons is achieved with the aid of Soller slit collimators, arrays of absorbing plates separated by gaps[1]. Currently manufactured devices use stacked arrays of stretched polyethylene films with absorbing coatings[2], generally of gadolinium or boron. Under optimum conditions of good collimation and transmission, these sheets are thin and very straight, and hence absorb only a small percentage of those incident neutrons that satisfy the collimator's geometric divergence criteria. 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 with a beam cross-section of 50 mm-wide x 100 mm-tall requires many tens of these foils with mm separations. Many 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. We present neutron transmission results for the type of micro-collimators shown in Fig.1, that are made of several hundred alternating, flat, micro-foils of (transmitting) Cu or Al and (absorbing) Cd.

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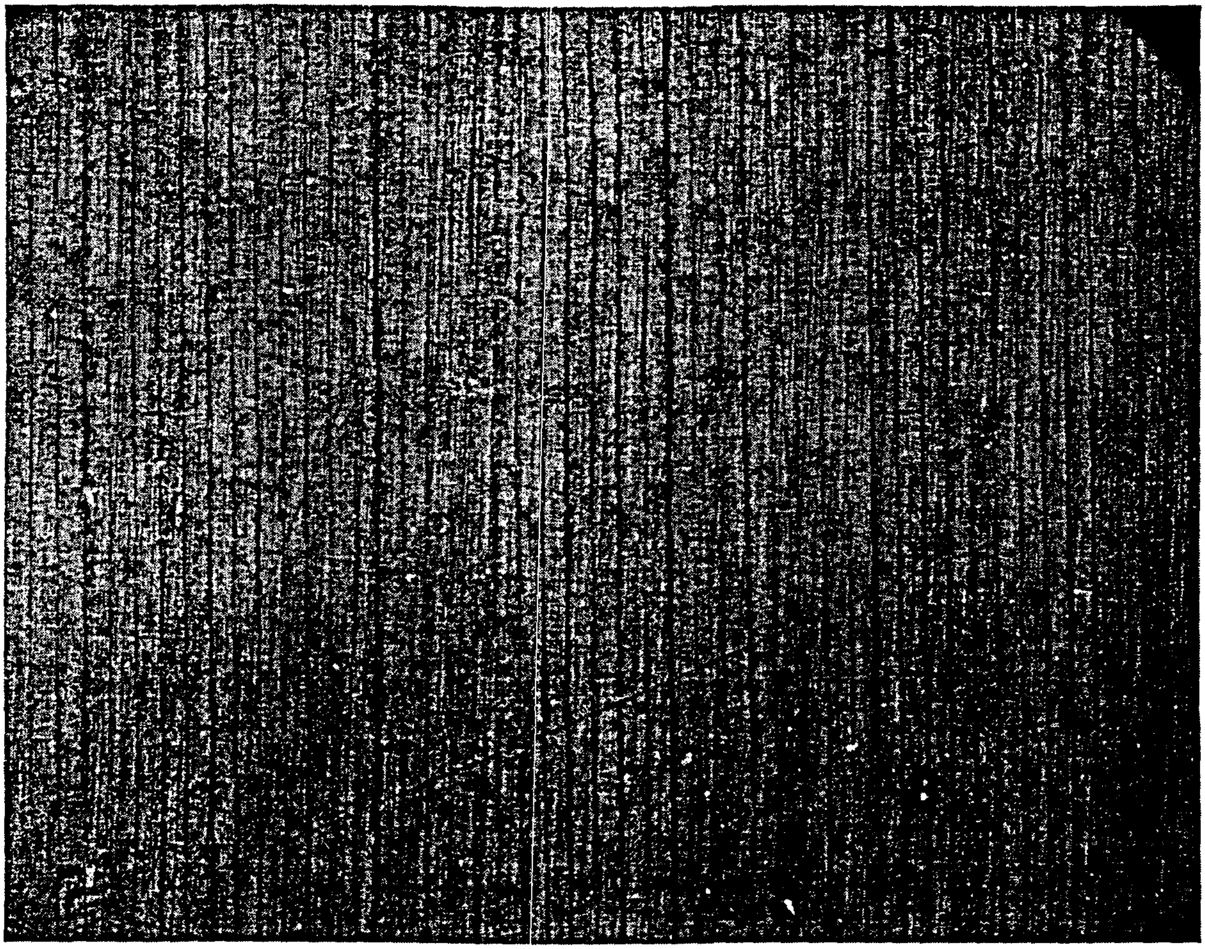


Fig.1. Optical micrograph of the front of a Al-Cd micro-collimator. The Al layers (light bands) are 36μm thick and the Cd layers (dark lines) are 3μm thick. Horizontal marks and discolouration are artifacts of the polishing process.

2. ONE-DIMENSIONAL DUCTILE ARRAYS

Our micro-Soller arrays consist of hundreds of alternating, flat micro-foils. A micrograph of one example is shown in 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. Neutron 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 micro-Soller shown in Fig.1, transmission is through 36 μm-thick Al channels (light) sandwiched between absorbing layers of Cd (dark) of average thickness 3 μm.

3. METHOD OF FABRICATION

Initially, the 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. 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 10 μm of Cd. A series of these plated foils are then stacked to form the composite structure. 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.

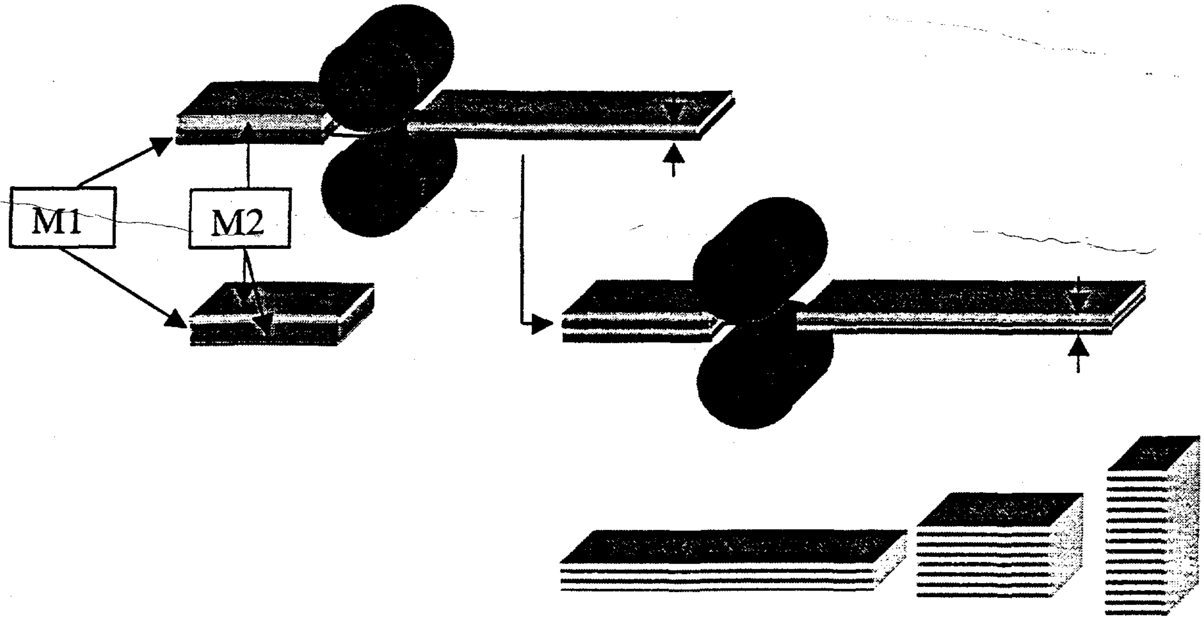


Fig.2. Schematic of the stacking and rolling procedure used to fabricate the arrays. Metals M1 (forming the transmission channels) and M2 (absorber) may have different initial thickness, or M1 may be plated with M2 in order to increase the effective "open area" for transmission. The rollers are precision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

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 THERMAL NEUTRONS

Results from previous tests on Cu-Cd micro-Sollers have already been presented[3]. This paper presents results of experiments from a second series of collimators (Al-Cd and Cu-Cd) performed at the neutron reflectometer set-up at Oak Ridge National Lab[4]. In these experiments, a 2.59 Å thermal neutron beam was collimated by two vertical slits. The first of these is 0.22 mm wide and the second, 950 mm further downstream, is 0.44 mm wide. The sample, 100 mm beyond this second slit, is mounted with its layers aligned vertically with the neutron beam, on the instrument's rotation stage. A further slit limited the illumination and defined the beam position on the sample to about 0.5 mm-wide by 4 mm-high. The sample rotation stage is mounted on a translation stage, so that a series of scans could be performed for a range of positions across the sample. Finally, a fixed Ordela™ 1155N position sensitive detector, a further 3420 mm directly downstream, measures the collimator's throughput. A schematic of the geometry is given in Fig.3.

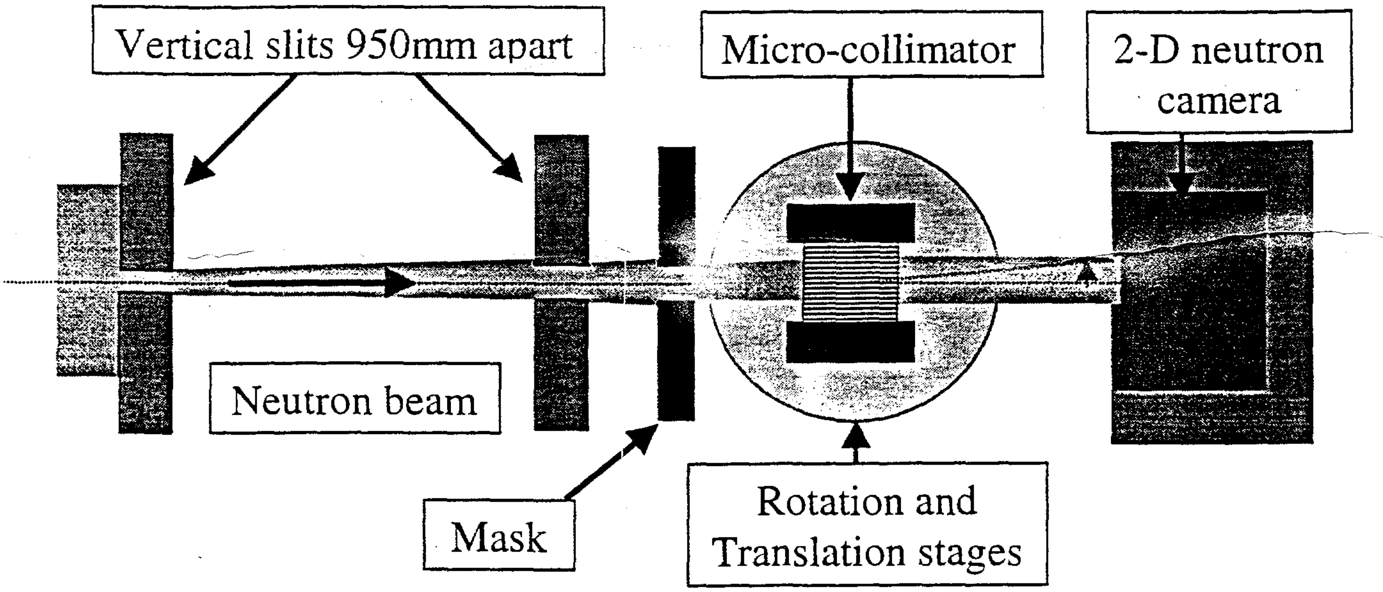


Fig.3. Schematic of the set-up to test the micro-collimators.

The results presented here are for two micro-Sollers, the details of which are given in Table 1. The first, is that shown in Fig.1, with 36 µm-thick Al channels and 3 µm-thick Cd septa, and the second is a Cu-Cd composite, having 25 µm Cu channels and 3 µm Cd septa. Fig.4 is a micrograph of the face of the Cu-Cd micro-Soller. Results of five rotation scans taken at 1 mm intervals across the two micro-Sollers are presented in Figs.5 and 6. The solid line is a two Gaussian fit to the sum of these scans (integrated performance) as indicated by the data points. The central region is fitted well by a tall narrow Gaussian determining the divergence of the neutron beam, and a broad diffuse Gaussian is fitted to the remaining background. The results of the double Gaussian fits to the data are given in Table 2. The open-area fraction and absorption of the Al channels gives a maximum predicted throughput of 91%. For the Al-Cd sample, the individual scan's (dotted lines) peaks lie very close to each other and give an integrated performance very close to that of the individual scans. The Cu-Cd Soller shows a monotonic trend in the centres of the individual scans (dotted lines), indicating a fairly uniform tapering of the sample, or put another way the Cd septa converge over the length of the samples. Not surprisingly, the integrated performance of this sample is diminished by the taper. The throughput of a 1.5 mm Cu blank had previously been measured[3] to be 85%. This combined with the open-area fraction results in a theoretical maximum transmission of 75%. While performing to at least 50% of the geometric throughput (individual Cu-Cd Soller scans reached 70%) 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.

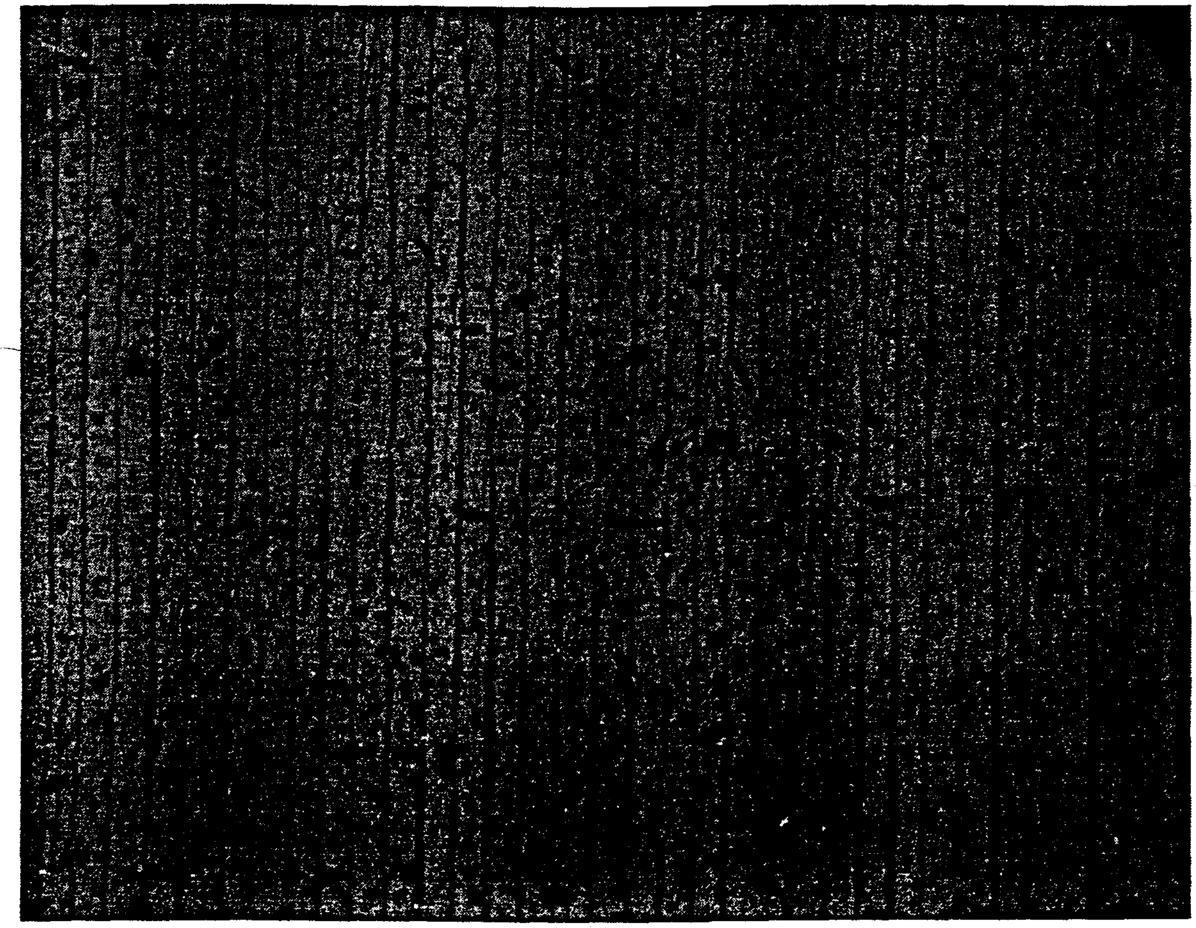


Fig.4. Optical micrograph of the front of a Cu-Cd micro-collimator. The Cu layers (light bands) are 25μm thick and the Cd layers (dark lines) are 3μm thick. The spots and discolouration are artifacts of the polishing process.

Sample	Channel	Width (μm)	Septum	Width (μm)	Length (mm)	Aspect Ratio	Cross-Section (mm^2)	Open Area (%)
Al-Cd	Al	36	Cd	3	5.35 ± 0.05	150	7 x 7	92
Cu-Cd	Cu	25	Cd	3	1.50 ± 0.05	60	9 x 10	90

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

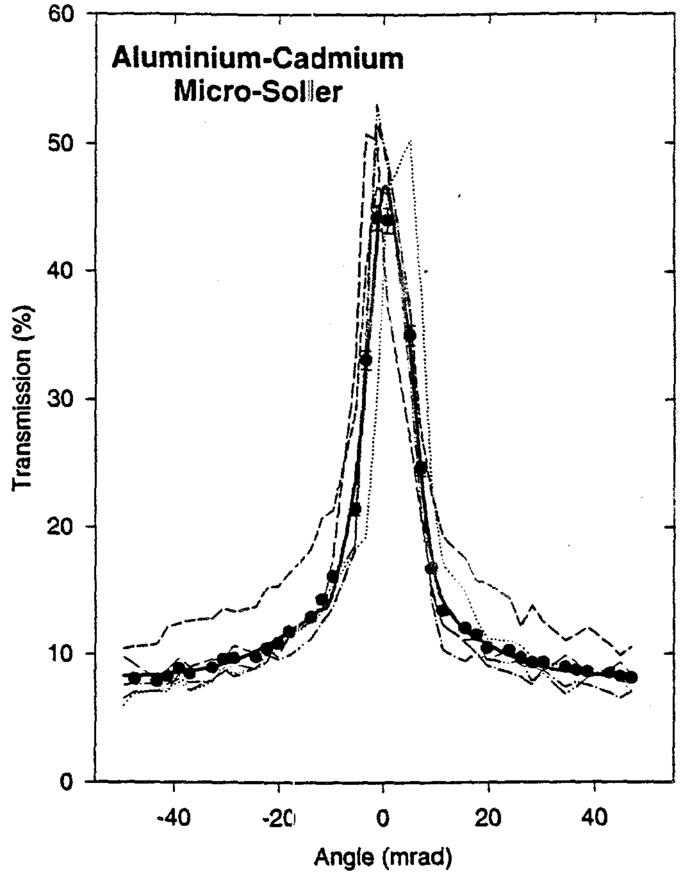


Fig.5. Series of plots for five individual throughput scans (dotted lines) taken at 1 mm intervals across the Al-Cd micro-Soller as described in the text. The points represent the integrated performance (average of these five scans) and the solid line is a two Gaussian fit to this.

Sample: Al-Cd	Transmission	FWHM	Background Transmission	Background FWHM
Theory	91%	7 mrad	0%	-
Experiment:				
Integrated Performance	47%	10 mrad	8%	36 mrad
Individual Scan	50%	8 mrad	8%	39 mrad
Sample: Cu-Cd				
Theory	75%	17 mrad	0%	-
Experiment:				
Integrated Performance	44%	22 mrad	18%	43 mrad
Individual Scan	55%	19 mrad	18%	96 mrad

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

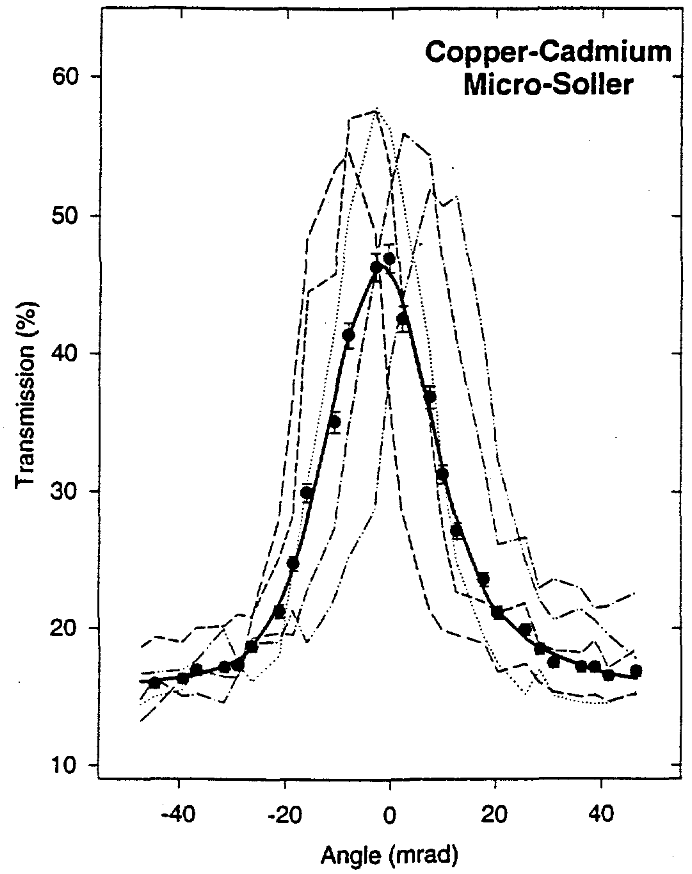


Fig.6. Series of plots for five individual throughput scans (dotted lines) taken at 1 mm intervals across the Cu-Cd micro-Soller as described in the text. The points represent the integrated performance (average of these five scans) and the solid line is a two Gaussian fit to this.

5. ANALYSIS

Carlile's article[2] lists four factors effecting Soller slit collimator efficiency: i) the uniformity of the spacing throughout the collimator length, ii) the neutron capture cross-section of the septum material, iii) the thickness of the septa and iv) the straightness of the septa edges at the entrance and exit to the collimator. The micrographs of the micro-Sollers in Figs.1 and 4 show that the end face of the individual layers are neither perfectly straight nor of uniform thickness. This, we may assume, is the case through the entire length of the collimator and hence will reduce its ultimate performance, as indicated by i), iii) and iv) above. Thus instead of sharp edges between the layers, a smoothing will occur between the "opaque" Cd layer and the "transparent" channel layer, to the degree that the Cd layer may no longer even be entirely absorbing (condition ii) above), especially at increased angular divergence where the path length through the Cd is reduced. Consequently, even though the length of the samples are many times greater than the extinction length of thermal neutrons in Cd, at large angles to the array an ambient transmitted background exists.

A simple theoretical modelling of the Al-Cd micro-Soller has been performed. The absorption of the individual channels of the micro-Soller in units of extinction lengths in Cd (about 600 μm) is shown in Fig.7. The model is that of the optimised fit to the data. It is based on a Gaussian absorption profile to the Cd layer due to the microscopic interdiffusion of the Al and Cd layers, and an ambient absorption of about 10% in the Al channel-layer. The resultant transmission for this model is shown in

Fig.8. Two features stand out: i) the two sections to the throughput, a well defined central maximum intensity and a broad diffuse background, and ii) the subsidiary peaks, a consequence of the neutron beam crossing successive neighbouring Cd layers at ever-increasing angular divergence. The model is then convoluted by the 0.7 mrad divergence of the incident beam. A further smoothing takes into account the macroscopic waviness of the Al-Cd interfacial region across a number of channels and any non-parallelness to 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 Fig.9. This model fits the integrated data well. However, instead of achieving some equilibrium throughput at greater angles the data continues to decrease. That is, the background distribution is broader than we have been able to model.

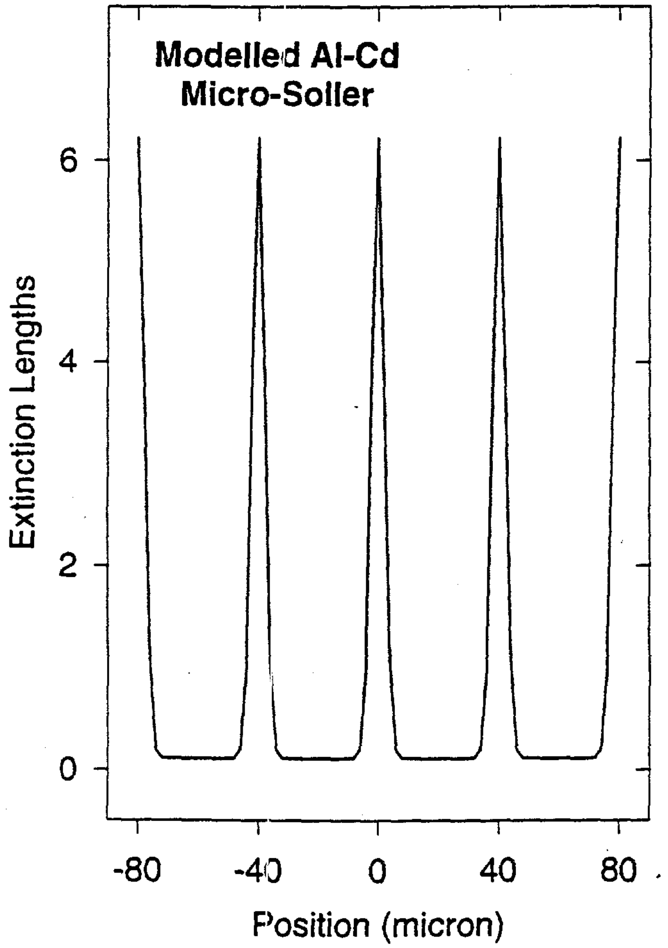
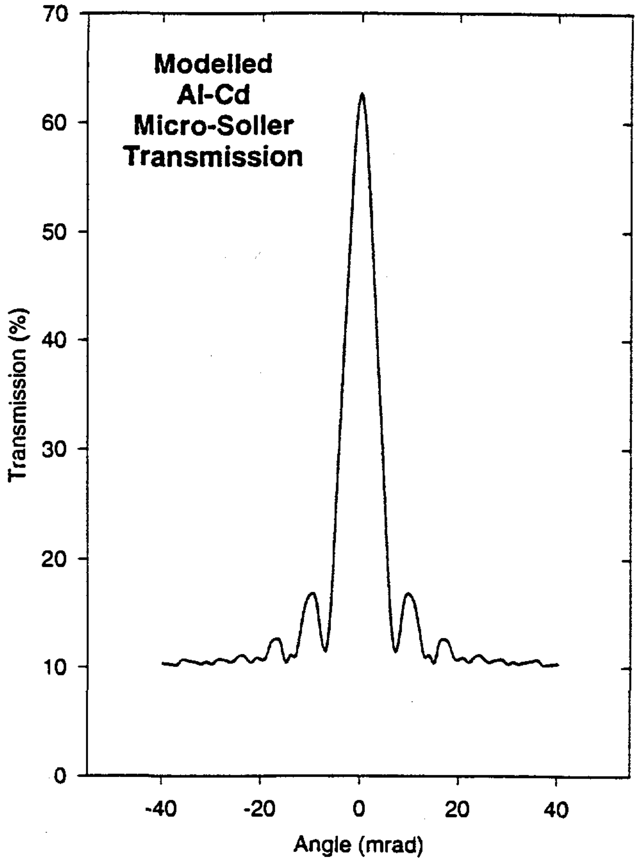


Fig.7. Model of the Al-Cd Soller, plotted in units of extinction length, used to generate the fit to the data.

Another possible explanation for the broad diffuse background is small angle neutron scattering of the transmitted beam while passing through the collimator's channel material. The neutron is scattered by microscopic cracks, defects, oxide surfaces etc., and deviated from the geometric collimation. For a 36 mrad FWHM background (Al-Cd sample), this means a scattering angle of 15 mrad and imperfections of rms size 170 Å. All quite likely given the manufacturing process. Not surprisingly, a different set of numbers is achieved for the Cu-Cd sample. This postulate could be tested by manufacturing a sample minus the septa. Further modelling of the sample is required.



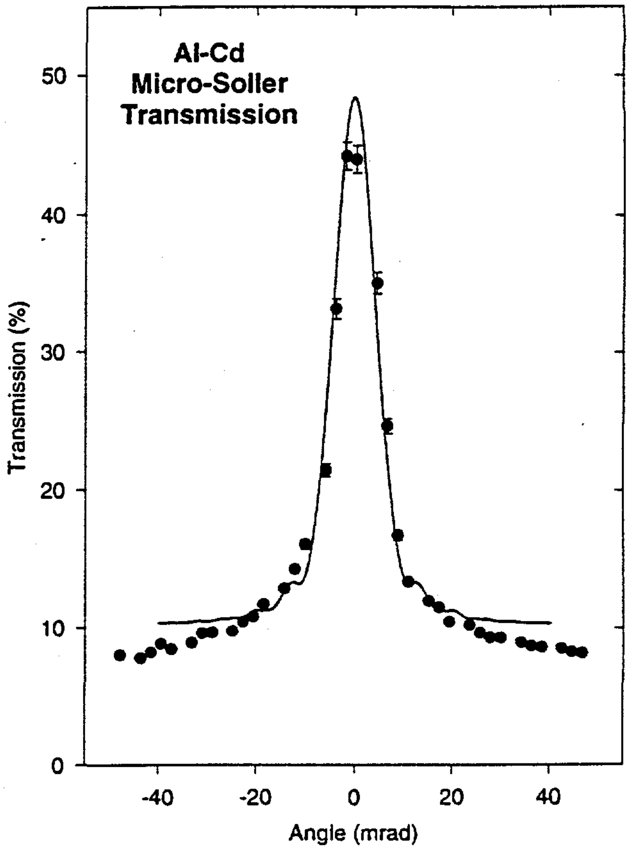


Fig.8. Plot of modelled transmission function vs beam divergence angle, showing the central transmission intensity peak and diffuse background intensity.

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

6. 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 intensity throughput 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.

The ambient loss due to the scattering in Cu channels is also undesirable. In this second round of experiments we have used Al, which is both ductile and considerably more transparent to thermal neutrons, even though the quality of the Cu-Cd individual scans was much closer to the theoretical limit.

Finally, good mirror interfaces between appropriately selected metal layers will make possible reflective and focussing elements for neutrons based on channel array optics[5]. 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 hard X-ray beams can be envisioned.

7. 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 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.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. W. Soller, *Phys. Rev.* **24**, 158 (1924).
2. C.J. Carlile, P.D. Hey and B. Mack, *J. Phys. E Sci. Instr.* **10**, 543 (1977).
3. B.E. Allman, A. Cimmino, A.G. Klein and S.A. Werner, *Neutron News* (submitted Feb. 1998).
4. W.A. Hamilton, J.B Hayter and G.S. Smith, *J.Neut.Res.* **2**, 1 (1994).
5. H.N. Chapman, K.A. Nugent and S.W. Wilkins, *Rev. Sci. Instrum.* **62**, 1542 (1991).