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FINAL REPORT

(First year of a 3-year study with two no cost extensions*)

STUDY OF NEUTRON FOCUSING AT THE TEXAS COLD NEUTRON SOURCE

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I. INTRODUCTION

Funds were received for the first year of a three year DOE Nuclear Engineering Research Grant, "Study of Neutron Focusing at the Texas Cold Neutron Source" (DE-FG02-92ER75711). The purpose of this three year study was to develop a neutron focusing system to be used with the Texas Cold Neutron Source (TCNS) to produce an intense beam of neutrons. A prompt gamma activation analysis (PGAA) facility was also to be designed, setup, and tested under the three year project.

During the first year of the DOE grant, a new procedure was developed and used to design a focusing converging guide consisting of truncated rectangular cone sections. Detailed calculations were performed using a 3-D Monte Carlo code which we wrote to trace neutrons through the curved guide of the TCNS into the proposed converging guide. Using realistic reflectivities for Ni-Ti supermirrors, we obtained gains of 3 to 5 for the neutron flux averaged over an area of 1×1 cm.

Two graduate students were supported by the DOE grant. During the time covered by this grant (the first year of a three year project), both students were admitted to candidacy for the doctoral degree at The University of Texas at Austin. Since that time, both students have graduated with Ph.D. degrees.

II. NEUTRON FOCUSING SYSTEM

Because of recent advances in the fabrication of Ni coated silicon wafers and Ni-Ti multilayers for supermirrors, two methods of neutron focusing were considered for use with the TCNS. We had proposed an in-depth study on how to best utilize these new advances for the construction of a neutron focusing system based on one or the other method or possibly both methods in a tandem configuration.

One of the methods for neutron focusing utilizes many thin Ni coated silicon wafers (microguides) stacked together and bent such that each microguide points to the desired point in space [1]. Silicon wafers of a thickness of $10 \mu\text{m}$ were available commercially (Virginia

Semiconductor Inc. 1501 Powhatan St. Fredericksburg, VA 22401). These wafers can be coated with 100 nm of nickel on both sides. Although they are brittle, they show some flexibility for bending.

Stacking many curved microguides on top of one another with their ends slightly overlapping like a shifted stack of playing cards could increase the flux along a line in space. However, we came to the conclusion that the precise arrangement of the microguides would require high precision machining and aligning of hundreds of silicon wafers. After consultation with the NIST group, we abandoned the idea of building a microguide focusing system.

The second method for neutron focusing is based on converging the beam with supermirrors [2-12]. Converging guides using Ni-Ti supermirrors have been applied at ILL, Grenoble, France where a neutron flux amplification of 2.5 was obtained [13]. However, there were reflectivity losses of 38% of the integral number of neutrons per second. With a new technique developed by Ovonics Synthetic Materials Company (1788 Northwood, Troy, MI 48084) multilayers of Ni-Ti of 33 x 10 cm area have been obtained with substantially better reflectivity [14].

In order to achieve an increase in neutron flux, the critical angle for neutron reflection from the surfaces of the TCNS converging guide must be greater than the critical angle for Ni-58 since our curved guide is coated with Ni-58. This dictates coating the converging guide surfaces with Ni-Ti supermirror layers having an effective critical angle of 0.3° for 1-Å neutrons [4]. Recent advances in supermirror technology have produced reflectivities greater than 95% for angles of neutron reflection up to this effective critical angle [14].

We spent considerable time and effort during the last six months of the first year of our study working with Ovonics Synthetic Materials Company on selecting the materials to be used for the converging guide system. They proposed to provide a converging guide made to our design specifications out of glass with the Ni-Ti layers deposited on the glass. However,

this turned out to be considerably more expensive than they first had indicated it would be when we submitted our initial proposal to DOE.

An alternative converging guide material was suggested which would be less expensive. The body of the converging guide would be made of aluminum with thin layers of silicon glued on the aluminum. The multilayer supermirror would be deposited on the silicon. However, this system was also more expensive than the amount we had budgeted for construction of the focusing system.

The final design used 20-cm-long thick single crystals of silicon for the body of the converging guide. These plates (a total of 16) were glued together to form the converging guide. All reflecting surfaces were coated with NiC-Ti supermirror layers. Two no cost extensions were given by DOE under the first year grant to carry equipment money over to cover a portion of the cost of the focusing system. The focusing system has been delivered, but has not been tested.

III. DESIGN OF FOCUSING CONVERGING GUIDE

The goal of a neutron focusing apparatus for absorption experiments is to increase the flux at the expense of angular divergence. Several geometries and shapes have been suggested to obtain neutron focusing with minimal reflectivity losses, a logarithmic spiral [15], a conical mirror which may be square or circular in cross section, etc. During the grant period of FY 1992, we developed a procedure to design a converging guide consisting of truncated rectangular cone sections. See Fig. 1. The converging guide would be located at the far end of the existing curved guide. This arrangement is shown schematically in Fig. 2.

The procedure which was developed to design the converging guide maximized the neutron flux over an area 1 x 1 cm at the focal point of the converging guide by varying the two slant angles, α_1 and α_2 (Fig. 1), for each truncated rectangular cone section as the sections were added one at a time. This was done by using our 3-D Monte Carlo simulation that traced neutrons through both the curved guide and the converging guide. The resulting

Fig. 1. Truncated rectangular cone section. The converging guide consists of several truncated rectangular cone sections each with different slant angles, α_1 and α_2 .

Fig. 2. Top cross sectional view of the Texas Cold Neutron Source in the piercing beam port showing the 2-m section of the curved neutron guide inside the beam port, the 4-m section of the curved neutron guide outside the beam port, and the converging neutron guide.

set of slant angles was a good approximation to the set that would be obtained using a global optimization since only a small fraction of the neutrons suffer more than one reflection in the converging guide.

Several analytical calculations on the performance of neutron guides were found in the literature [16-19], but these calculations were carried out in two dimensions with a uniform "isotropic-in-2D" neutron source. These 2-D treatments could not be used for designing a converging guide because neutron reflections from all four walls (top, bottom, and 2 sides) are important. Also, the spatial distribution of neutrons entering the converging guide is not uniform and the angular distribution is not "isotropic in 2D." By "isotropic in 2D" we mean $dn/d\phi$ is constant where ϕ is the polar angle in 2 dimensions. An isotropic 3-D source would have $dn/d\Omega$ constant where Ω is the solid angle in 3 dimensions.

Thus, we wrote our own 3-D Monte Carlo code to trace neutrons through neutron guides. To have the correct spatial and angular distributions for neutrons which enter the converging guide, neutrons were first transported through the curved guide and then through the converging guide for all calculations. Two different neutron sources were used. One was assumed to be a uniform isotropic-in-3D source of 4-Å neutrons located at the entrance of the curved guide. The other source had the energy dependence calculated for neutrons leaving the moderator chamber in the general direction of the guide and was biased by calculated angular and spatial neutron distributions.

In order to verify that the results of our 3-D Monte Carlo code were correct, we did benchmark calculations. Neutron transport through one channel of our curved guide was selected as the benchmark. The spatial and angular distributions for neutrons exiting the curved guide were calculated using the following methods:

- a) 2-D analytical calculation with a spatially uniform "isotropic-in-2D" source,
- b) 2-D analytical calculation with a spatially uniform "equivalent-3D" source, and
- c) 3-D Monte Carlo with a spatially uniform isotropic-in-3D source.

By comparing the results for the three calculations, we concluded that our 3-D Monte Carlo code gave correct results.

During the first year of the three-year research project, two different converging guide systems were designed, using the 4-Å neutron source: one with four 20-cm long sections and one with eight 20-cm long sections. As previously explained, our design procedure involved varying the two slant angles for each truncated rectangular cone section to give maximum flux over a 1 cm² area at the focal point as the sections are added one at a time. The slant angles and corresponding dimensions for the 80-cm and 160-cm long converging guides are given in Table I.

We define gain as the mean current density over a 1 x 1 cm area at the focal point of the converging guide divided by the mean entrance current density over the 15.5 x 50 mm area at the entrance to the converging guide. The gains for our two designs are 4.2 and 5.2 for the 80-cm and 160-cm guides, respectively. The calculated spatial distributions for 4-Å neutrons entering the converging guides from the curved guide and exiting the converging guide at the focal point are shown in Fig. 3 for the 160-cm long converging guide. The final design results are given in a Nuclear Instruments and Methods paper attached.

IV. STUDENT INVOLVEMENT AND RELATED DEVELOPMENTS FOR TCNS

Mr. Jong-Youl Kim, supported by the DOE grant, was admitted to candidacy for the doctoral degree at The University of Texas at Austin during the first-year reporting period. The subject of his dissertation was the design and analysis of a focusing converging guide to be used with the TCNS. Dr. Greg Downing, a scientist at the National Institute of Standards and Technology, was a member of Mr. Kim's Ph.D. committee.

Plans for the Prompt Gamma Activation Analysis facility to be used with the focusing converging guide and TCNS were finalized during the first-year reporting period. Mr. Carlos Rios-Martinez, supported by the DOE grant, was also admitted to candidacy for the doctoral degree; the subject of his dissertation was the design, construction, and use of a PGAA facility

Table I.

Design of 4-element converging guide

Length of each element: 20 cm

Focal point: 24 cm from the exit of focusing system

Focal area: 1 x 1 cm

Reflectivity: Measured data from Ovonic

Histories: 3,000,000

Neutron wavelength: 4 Å

Element	Entrance Height (mm)	Entrance Width (mm)	Slope (H)	Slope (W)
1	50.0	15.5	2.45 / 200	0.70 / 200
2	45.1	14.1	2.95 / 200	0.90 / 200
3	39.2	12.3	3.25 / 200	1.25 / 200
4	32.7	9.8	3.60 / 200	1.50 / 200
	25.5*	6.8*		

* Exit of element 4

Design of 8-element converging guide

Length of each element: 20 cm

Focal point: 24 cm from the exit of focusing system

Focal area: 1 x 1 cm

Reflectivity: Measured data from Ovonic

Histories: 30,000,000

Neutron wavelength: 4 Å

Element	Entrance Height (mm)	Entrance Width (mm)	Slope (H)	Slope (W)
1	50.0	15.5	1.10 / 200	0.00 / 200
2	47.8	15.5	1.30 / 200	0.00 / 200
3	45.2	15.5	1.50 / 200	0.10 / 200
4	42.2	15.3	1.70 / 200	0.20 / 200
5	38.8	14.9	1.90 / 200	0.40 / 200
6	35.0	14.1	2.20 / 200	0.70 / 200
7	30.6	12.7	2.50 / 200	1.20 / 200
8	25.6	10.3	2.50 / 200	1.70 / 200
	20.6*	6.9*		

* Exit of element 8

(A) Neutrons entering converging guide

(B) Neutrons exiting at focal point

Fig. 3. Spatial distributions calculated for 4-Å neutrons entering the converging guide (A) and exiting the converging guide at the focal point (B). The z-axis is number of neutrons per mm^2 .

using focused cold neutrons. Dr. Richard Lindstrom, a scientist at the National Institute of Standards and Technology, was a member of Mr. Rios-Martinez's Ph.D. committee. Our plans for a PGAA facility were reported in a talk given by Mr. Rios-Martinez at Tercer Congreso Anual, Instituto de Investigaciones Eléctricas Cuernavaca, Mor., November 22, 1992 [20].

The construction of the Texas Cold Neutron Source (TCNS) was completed early in the DOE-grant reporting period utilizing funds provided by the State of Texas. The results of this work were reported in 2 transactions [21,22] given at the 1992 ANS Annual Meeting at Boston. The thermal performance of the TCNS was then determined by a series of measurements, the initial thermal tests being reported in a transaction [23] given at the 1992 ANS Winter Meeting at Chicago. The final thermal tests were done with nuclear heating of the mesitylene [24].

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