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Neutron Guide Facility at the ET-RR-1 Reactor

R.M.A. MAAYOUF, *V. TROUNOV, *V. KUDRYASHEV, *A. BULKIN, I.A. ABDEL-LATIF and A.S. El-KADY

Reactor & Neutron Physics Dept., NRC, Atomic Energy Authority, Cairo, Egypt
* *Petersburg Nuclear Physics Institute, St. Petersburg, Russian Federation*

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The present work presents a neutron guide facility, recently installed, at one of the ET-RR-1 reactor horizontal channels. The facility has been designed for delivering neutrons, with wavelengths between 1--4Å, to a Fourier RTOF diffractometer; allowing for neutron diffraction measurements at D values between 0.7 Å and 2.9 Å respectively.

KEYWORDS: neutron guide, neutron reflectivity, neutron wavelength

§.1. Introduction

The most important practical application of total reflection of neutrons from mirrors was found in the construction of neutron guide tubes (NGT)[1-4]; mainly used for the transportation of thermal and subthermal beams.[5,6] Both straight and curved NGT are analyzed in Refs.(5-11). The NGT is analogous to light pipes in ordinary optics; a low energy neutron entering the NGT with an angle of incidince at its mirror walls that is less than the critical angle, for a particular wavelength, will be transported along the tube by multiple total reflections. If a slight curvature is incorporated in the NGT, then only those neutrons with wavelengths greater than some minimum value (typically 1 Å) will be transported down the tube, while fast neutrons, as well as gamma rays in the incident beam, pass through the walls of the NGT where they can be absorbed in a suitable beam stop. In this way a very clean and highly collimated beam of thermal and subthermal neutrons can be transported to a low background location; far from the primary neutron source.

The present work deals with a neutron guide facility, recently installed at one of the ET-RR-1 reactor horizontal channels for delivering neutrons, free from gamma rays and fast neutrons background, to a Fourier chopper; attached to a reverse-time-of flight (RTOF) diffractometer.

§.2. Physical Parameters of the NG Facility

The NGT commonly has a rectangular cross-section, and its walls are made of glass plates with extremely good flatness and low surface roughness. The glass plates are usually coated with natural nickel or with ^{58}Ni. Neutrons with wavelength λ striking the walls of the NGT are totally reflected when the angle of incidence $\theta < \theta_c$, where θ_c is the critical angle for total reflection and is given by:[13]

$$\theta_c = \lambda\sqrt{Nb_c/\pi} \qquad (1)$$

θ_c is rather small and depends on the coherent scattering length b_c. If a thermal or cold neutron beam is guided, out of the direct view to the reactor core, by means of a curved NGT with a radius of curvature R, then the distance of direct view L_d is:

$$L_d = \sqrt{8aR} \qquad (2)$$

The characteristic angle θ^* of a curved NGT is defined as:

$$\theta^* = \sqrt{2a/R} \qquad (3)$$

The wavelength of neutrons with $\theta_c = \theta^*$ is called the characteristic wavelength λ^* of the NGT and is given by:

$$\lambda^* = \sqrt{2a\pi/RNb_c} \qquad (4)$$

Neutrons with $\lambda < \lambda^*$ are transmitted through a curved NGT only according to garland reflection paths, while those with $\lambda > \lambda^*$ follow zig-zag trajectories and have larger reflection angles. It follows from eqs.(2) and (4) that:

$$\lambda^* = 4a\left(\sqrt{\pi/Nb_c}\right)/L_d \qquad (5)$$

Then it follows from eqs.(1) and (5), that the width a of the NGT will be given by:

$$a = L_d\theta\lambda^*/4 = L\theta\lambda^*/4K \qquad (6)$$

where $K = L/L_d$ is the ratio between the actual length of the NGT and the distance of the direct view L_d. In order that the instruments located after the NGT experience low background levels, the value of K should be ~1.1--1.2.

The width a of the NGT, that might be used for guiding neutrons from the ET-RR-1 reactor was calculated in Ref. 13 for several NGT lengths. Similar calculations,[13] were carried out according to the values (calculated for mirrors coated with ^{58}Ni): 1.15, 1.377 Å and 2.05 × 10^{-3} Sr respectively for K, λ^* and θ. The value 1.377 Å of the NGT characteristic wavelength was chosen considering that the maximum of the distribution of thermal neutrons emitted from the ET-RR-1 reactor is at ~1.2 Å.[14] The calculations yielded the value a = 13.5 *mm* for a NG length 22*m*; adequate for use at the ET-RR-1 reactor.

The output neutron flux expected for that case when ^{58}Ni is used as a coating of the NGT mirror walls was calculated according to the formulae given in Ref.(15); and found to be 1.4 times more than that resulting when using natural Ni.

The dependency between the neutron guide length and the neutron flux emitted from the reactor beam channel was calculated following the same procedure given in Ref.(13).

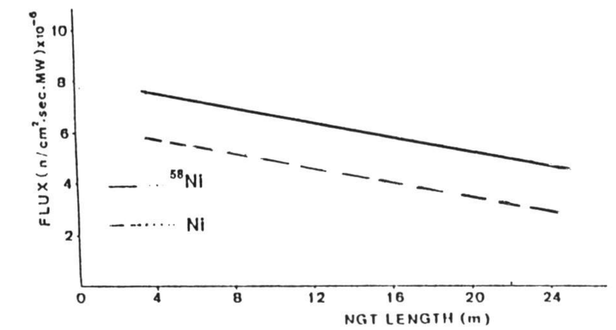

Fig.1. The correlation between the neutron flux and NGT length.

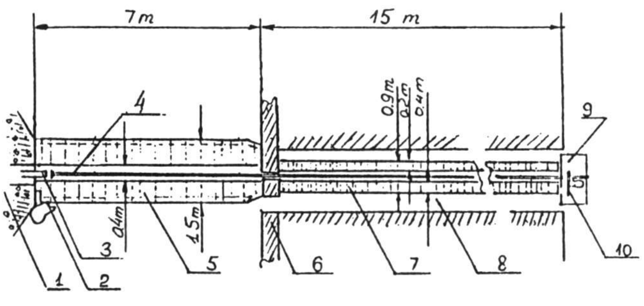

Fig.2. A schematic of the NG Facility.

1:	ET-RR-1 Reactor	2, 5, 7:	Heavy Concrete Shield
3:	Inpile Collimator	4:	Curved Neutron Guide
6:	Reactor Hall's Wall	8:	Corridor
9:	Fourier Chopper Table	10:	Fourier Chopper

The calculated dependency is represented in Fig.1; both for natural Ni and ^{58}Ni.

The effective luminosity, which should result at different lenths of the NGT, was calculated according to the correllation dependency of Fig.1. The effective luminosity is given by:[13)]

$$Lum = k_0 \cdot O_s \cdot W_d \cdot V_s \qquad (7)$$

where:

k_0 = is a factor accounts for the decrease in neutron flux due to absorption by the chopper's material, as well as for neutron losses due to scattering and absorption by the flight path air and sample.

O_s = is the neutron flux at the sample position

W_d= is the solid angle of the detector

V_s = $a \cdot h \cdot d$: is the volume of a sample of a height h and thickness d

Thus the effective luminosities which should result when using the NGT, were calculated for different values of a, and at the values 0.7, 0.1Sr, 10*cm* and 1*cm* respectively for k_0, W_d, h and d.

The luminosities resulting, when considering that the Fourier chopper is set at the exit of the NGT are given in table 1. It is noticeable that the best effective luminosity is achieved with the NGT length 22*m* and whose width is 13.5*mm*; with curvature radius R = 3885.5*m*.

The losses of the neutron flux inside the neutron guide, mainly, due to the length and junctions of the optical sections, were estimated following the procedure of Ref.(16). Accordingly, the deviation of the actual mirror channel of a straight neutron guide, whose optical sections are each of a length l_s, from a curved one is called poligonality. The poligonality is characterized by the value of the deviation angle $\gamma = l_s / R$, where R is the curvature radius. The poligonality results with the loss of 20% of the neutron flux when l_s =0.5 *m*. Besides, the junction of the optical sections with respect to the loss of the neutron flux is characterized by the step value Δ_{st}, the gap value Δ_{sl} and by the number of joints (n-1), where n is a number of joining sections. Due to the application of a spherical fixer at the joints, the step value Δ_{st} could be decreased to 0.02*mm* while the gap value Δ_{sl} remains invariant. Taking into account the increasing number of the optical sections and the application of the spherical fixer the calculated loss value caused by the junctions of the optical sections does not exceed 20% in the case of Δ_{sl}=0.5 *m*. However, according to Ref.(16), the neutron flux losses inside the NGT could amount to 60%.

Table 1. The values of the neutron flux expected for different NGT widths and luminosities

Length of NGT	the calculated value of a	expected flux ($n/cm^2 \cdot sec$)	effective luminosity
4.1m	2.5mm	1.5×10^7	6.0×10^5
7.4m	4.5mm	1.41×10^7	1.0×10^6
22m	13.5mm	10.6×10^6	2.5×10^6

§.3. Measurements with the NG Facility

The neutron guide facility, recently installed at the ET-RR-1 reactor, is schematically presented in Fig.2. It is intended to deliver thermal neutrons to a Fourier RTOF diffractometer arrangement described in details elsewhere.[19,20)] It includes an inpile steel cone collimator and a curved neutron guide tube 22m long. The inpile collimator is intended for the preliminary formation of the neutron beam at the input of the NGT; it is tapered in such a way so that the whole area of the reactor channel's bottom is seen from any point of the NGT input cross-section. The NGT mirror channel is of rectangular cross-section (13.5*mm* width, 90*mm* height). The mirror channel walls are made of boron loaded optical glass (2*cm* thick) coated with a film (2200 Å thick) of ^{58}Ni. The efficiency of boron loaded glass has been confirmed,[10)] as it reduces the gamma-radiation dose by a factor of 10.

The neutron reflectivity of a sample of the NGT mirror walls was measured at St. Petersburg Nuclear Physics Institute (Russia) with both a time of flight (TOF), at glancing angle θ= 13.3', and with a monoenergetic (λ= 3.0 Å) neutron beam reflectometers. The measured reflectivity behaviours are presented in Fig.3 as a function of θ/λ. It is noticeable that both behaviours are consistent. Besides, the glancing angle of 13.3' and the neutron coherent scattering length given in Ref. 17 lead to a critical wavelength of 1.91 Å which is consistent with the value 2.02 deduced from the present measurements. The neutron reflectivity is ~99.9% for values of θ/λ < 17.5 × 10^{-4} rad/ Å; a behaviour consistent with that reported for ^{58}Ni mirrors.[12,18)]

The biological shielding around the NGT is constructed mainly from borated polyethelene, lead and a wall of heavy concrete. The thickness of the NGT shield is ~0.55*m* for that part (7*m* in length) situated in the reactor hall (see Fig.2); the shield of the rest of the NGT (15*m* long) is of thickness 0.2 and 0.4*m* (see Fig.2). The biological shielding has proved to be efficient in cutting down the gamma ray background to values between 1 mR/h and 3 mR/h respectively for the reactor hall and corridor (see Fig.2) ; providing the safety of the working personnel.

The integral neutron flux, at the exit of the NGT, was measured by a BF3 detector and found to be 6.3×10^6 n/cm^2·sec. This value is consistent with the value 6.36×10^6n/cm^2·sec deduced from the expected one (Table 1) after accounting for losses due to poligonality and junction effects of the NGT optical sections.

The neutron spectrum emitted from the NGT; transmitted through the Fourier chopper and another straight NGT (3*m* long) of the same ^{58}Ni walls and cross-section (13.5 × 90mm^2), was measured with a disk chopper of the Fermi Type; described in details elsewhere.[19,20] The detector used for spectrum measurements was a neutron sensitive Li-6 glass scintillator (NE-912 type) with efficiency for neutron detection varying from 86% ~ 98% respectively for neutron wavelengths between 1 Å ~ 2 Å. It was set at a flight distance (from the Fermi chopper) L = (3448+5) *mm*. The detector was combined with a multichannel time analyzer whose channel width was set at 4μsec. The measured neutron spectrum is given in Fig.4 along with that measured one after transmission through 12*cm* of Be (Fig.4b); using the same detector. The well known Be Bragg cut-off at 3.952 Å was observed at channel number 845.46. Accordingly, the thermal neutron spectrum peak was found to be at wavelength λ = 1.374 Å; very close to the value 1.377 Å of the ^{58}Ni coating characteristic wavelength. The spectrum also covers the wavelength range from 1 Å ~ 4 Å.

It is concluded that the present NGT facility is able to provide the Fourier RTOF diffractometer with an integral neutron flux 6.3×10^6n/cm^2·sec at a wavelength range from 1 Å ~ 4 Å; quite adequate for neutron diffraction measurements at D values between 0.7 Å and 2.9 Å respectively[20]; offering 0.5% resolution at scattering angle 2θ= 90°.

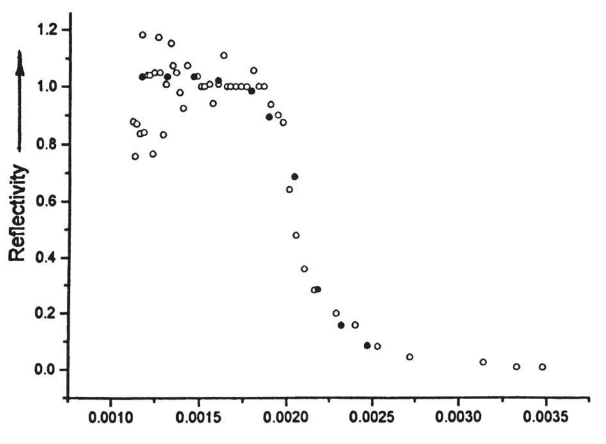

Fig.3. The neutron reflectivity of the NG sample mirror:
○ with a TOF reflectometer ; • with a constant λ reflectometer

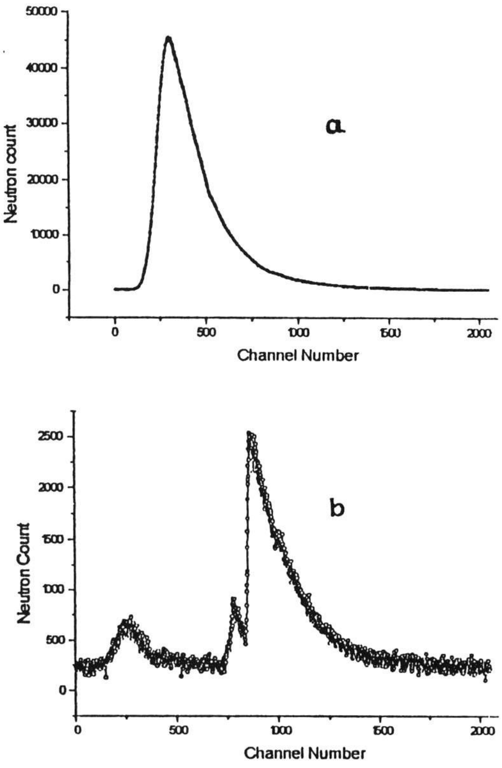

Fig.4. Neutron spectra measured at the NGT output
a: spectrum measured at 3448mm; *b*: Be filtered spectrum.

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