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Channeling of neutrons in polycapillaries. A new way to bend neutrons at large angles

S.B. Dabagov[1,2], A. Marcelli[1], and M.A. Kumakhov[3]
[1)] *INFN, Laboratori Nazionali di Frascati, P.O. Box 13, I-00044 Frascati, Italy*
[2)] *P.N. Lebedev Physical Institute RAS, 117924 Moscow, Russia*
[3)] *Institute for Roentgen Optics, 123098 Moscow, Russia*

Abstract

The possibility to bend intense beams of thermal neutrons by means of polycapillary structures is discussed. Accurate theoretical calculations showed how neutron beams may be bent at large angles, through short distances, using multichannel devices. Experimental results of bending properties of neutrons by a bender device made by many capillaries are also presented and discussed.

Keywords: neutron optics, capillary structures, channeling, neutron bender

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1 Introduction

Non-monochromatic neutron beams are usually deflected by neutron guides that use the total external reflection mechanism to modify the neutron path. A typical guide has a length from a few tens meters up to hundreds meters, while the distance between the reflecting surfaces is in the range of a few centimeters. With these parameters the typical curvature radii obtainable are of the order of thousands meters [1,2]. As a consequence, although the efficiency of the neutron transport is very high, the bending angle of these systems remains small. For example, at the Berlin Neutron Scattering Centre Hann-Meitner Institute (BENSC HMI) the neutron beam produced by the reactor is bent by a conventional neutron guide system by about 7 mrad through the distance of 32 meters. Morever, although the technology associated to the manufacture of these devices is known, it remains complex, and as a consequence, their costs are high.

Recently has been demonstrated that also glass hollow capillaries may be used to guide and deflect neutral particles [3,4]. The possibility to guide both X-rays and neutrons by means of capillary optics was suggested for the first time in the middle of the 80s [5, 6]. The first neutron lens based on capillaries has been designed, manufactured and tested at the laboratory of Institute for Roentgen Optics (IRO) in Moscow in 1991 [7]. After this first succesful experiment, the research in this field received a significant stimulus [8–12]. Nowadays capillary devices permit to focus radiation, to transform divergent rays into quasi-parallel ones, to filter radiation, etc. These results are summarised in reviews [13,14] and, in particular, in several SPIE proceedings [15].

In this paper a summary of new theoretical and experimental results on the bending of thermal neutrons by means of both single polycapillary and system of polycapillaries is presented.

2 The theory

In the optical theory, the critical angle to observe the total external reflection of neutrons by a smooth surface characterized by a reflection coefficient *n*, is defined by the relation [16]

$$\cos \theta_c = n \tag{1}$$

where θ_c is the glancing angle. Because of the glancing angle is very small, $\theta_c \ll 1$, then the relation

$$\theta_c \simeq \sqrt{1 - n^2} \tag{2}$$

holds. Because also the absorption of a neutron (under reflection) is negligible small, the following expression for the critical angle [17] is valid

$$\theta_c = \lambda \sqrt{\frac{N_{at}\, a_{coh}}{\pi}} \ , \tag{3}$$

where λ is a wavelength of neutron, N_{at} is the atomic density of the reflecting surface material, and a_{coh} is the coherent scattering amplitude of the neutrons inside the matter.

When the transport system is an hollow glass capillary, the neutron entering into a capillary at an angle $\theta \leq \theta_c$ respect to the wall surface, is guided by means of multiple successive reflections, i.e., a particle is channeling into the capillary. In the small-angle approximation the transmission coefficient for a neutron beam will be defined both by the coefficient of the single reflection

$$R_0(\theta) \simeq \left(\frac{\sqrt{n^2 - 1} - \theta}{\sqrt{n^2 - 1} + \theta} \right)^{\frac{1}{2}} \tag{4}$$

and by the number *N* of the reflections,

$$R(\theta, \varphi) = [R_0(\theta)]^N \tag{5}$$

The number *N* of reflections is defined both by the parameters of the beam and of the capillary. In the case of a straight capillary ($\varphi = 0$) we have

$$N(\theta, 0) = \frac{L\theta}{d_{in}} \ , \tag{6}$$

where *L* and d_{in} are the length and the inner diameter of the capillary. The glancing angle θ of the neutron beam is determined by the beam divergency $2\Delta\theta : \theta \in (0, \Delta\theta)$, $\Delta\theta \leq \theta_c$. Using a capillary to bend the beam at an angle φ, *N* may be estimated using the approximate relation

$$N(\theta, \varphi) \simeq \frac{\varphi}{2\theta} \ , \tag{7}$$

Then, the bending efficiency of the beam (and the transmission of the beam) is a function of the bending angle and may be determined by the following formula

$$\eta(\varphi) = \frac{I(\varphi)}{I_0} \ , \tag{8}$$

where I_0 is the intensity of the incident beam, and $I(\varphi)$ is the intensity of the transmitted radiation. This last may be estimated by the integral

$$I(\varphi) \simeq \frac{1}{2\Delta\theta} \int\limits_{-\Delta\theta}^{+\Delta\theta} \theta d\theta \;\; i_0(\theta) R(\theta, \varphi) \;\;, \tag{9}$$

where $i_0(\theta)$ is the angular dependence of the neutron beam intensity at the entrance of the capillary. It is necessary to underline here, that the neutron trajectories into the cylindrical channels are complex paths, that may be approximated to spiral curves made by linear path of length *l* between individual collisions with the channel walls. The effect of a collision is to change the deflection angle of the particle, that determines the increase of the incident angle of the following collision. For neutrons, the channeling regime occurs, when the particle fulfils the condition $\theta \leq \theta_c$ for every collision. As the length l is proportional to the inner channel diameter d_{in}, then if we reduce d_{in}, also the derivative of the deflection angle $(d\theta/dx)$ decreases. In this way, the channeling number of neutrons increases. Hence, we may conclude that the coefficient η increases while d_{in} decreases.

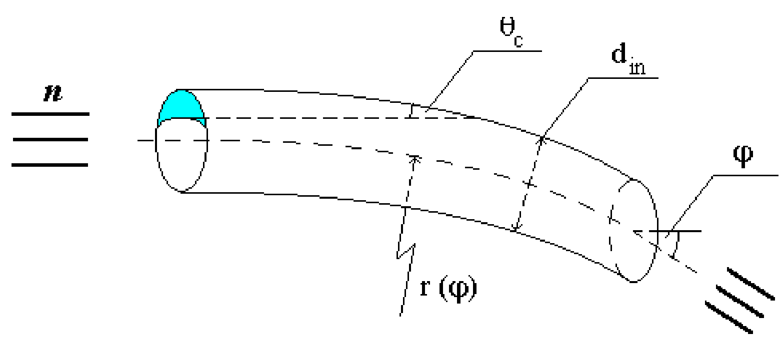

Figure 1: *Scheme of the neutron capture by a capillary channel. θ_c is the critical angle for total external reflection, d_{in} is the inner diameter of capillary (channel), φ and $r(\varphi)$ are the bending angle and the curvature radius of the capillary, respectively.*

Actually, entering into a capillary channel, not all neutrons will be captured into the channeling regime (Fig. 1)). Indeed, only a fraction of the neutron beam fulfils the channeling condition $\theta \leq \theta_c$ (neutrons flying into the channel with dashed area of channel cross-section satisfy the condition (Fig. 1). The fraction of the beam which will be captured in the mode of the effective transport may be estimated by the relation [14]

$$\gamma(\varphi) = \frac{r(\varphi)\theta_c^2}{2d_{in}}, \tag{10}$$

where φ and $r(\varphi)$ are the bending angle and the curvature radius for the capillary, respectively. From Eq.(10) we see that under a fixed curvature radius this parameter is inversely proportional to the inner capillary diameter.

Summarising for a capillary, the efficiency to bend neutron beam may be defined by the coefficient

$$k_{tr}(\varphi) = \gamma(\varphi)\,\eta(\varphi) \tag{11}$$

The transmittance of the polycapillary also depends on the roughness of the inner channel surface. However, for the thermal neutrons the surface roughness scattering factor is negligible small. In addition, as we deal with very small glancing angles, it is necessary to take into account the fact that the incident wave has two components: the transverse wave $\lambda_\perp$, which mainly defines an interaction with the surface, and the longitudinal wave $\lambda_{||}$, which spreads practically without a change. As a consequence, the transverse wave may significantly exceed the incident wave by the value, i.e. $\lambda_\perp \simeq \lambda/\theta \gg \lambda$. This simple estimation shows that the value of the transverse wavelength $\lambda_\perp$ is $2 \div 3$ orders of magnitude higher than the wavelength λ of thermal neutron. Because the roughness of the inner capillary surface is determined by the root-mean-square roughness, that ranges from a few $\AA$ up to tens $\AA$, usually the influence of the roughness may be substantially neglected.

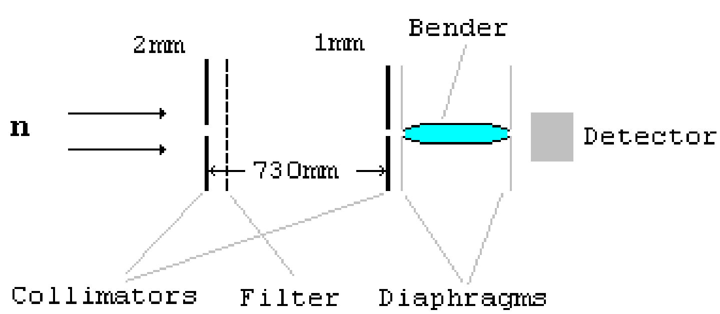

Figure 2: *Layout of the experimental set-up assembled to investigate the complex path of a neutron beam through a polycapillary structure.*

3 Experimental results

To test the bending characteristics of a polycapillary system, a set of experiments was carried out at the BENSC facility using a neutron beam of wavelength about $5\,\AA$, collimated up to 3 mrad. Such divergence was necessary because of the capillary angular acceptance is defined by the critical angle of the total external reflection. The systems of polycapillaries were bent by our special device.

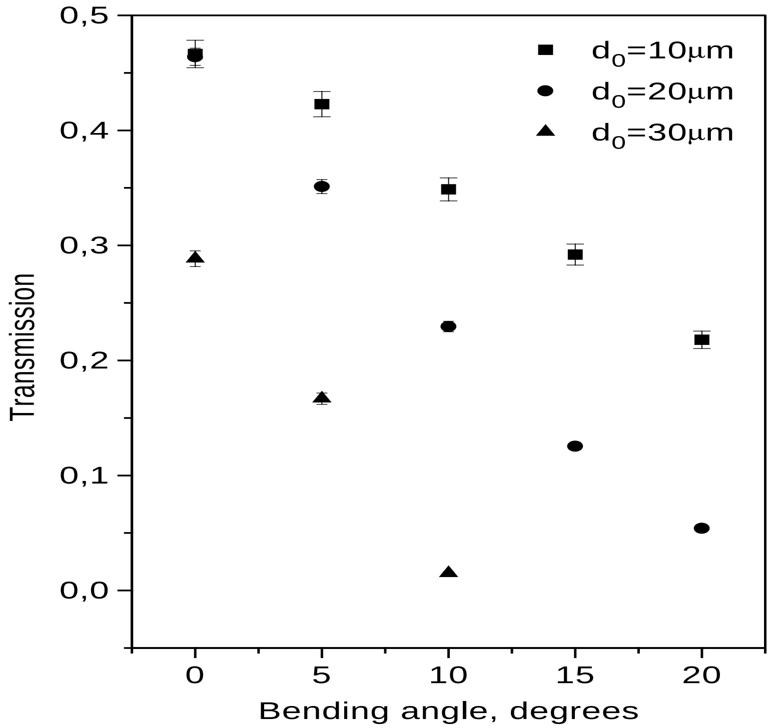

Figure 3: *Transmission coefficient vs bending angle for a single polycapillary of different inner diameters.*

This device realise the bending with four bearing points; the last three (along the neutron beam) allow to change the curvature radius. To prevent parasite transmission, diaphragms of corresponding diameters were set at the ends of the capillary. The layout of the experiments is presented in Fig. 2.

Polycapillary systems consisting of hollow glass channels were also tested. These devices are of two types: one are monocapillary systems manufactured from single hollow capillaries, the others - polycapillary systems - are realised with monocapillaries [4]. The used technological methods allow to significantly reduce the channel size for the polycapillary systems, so that typical diameters of the channels of these systems range from 10 to 30 μm. The results of the experiments, averaged on the tested capillaries, are shown in Fig. 3.

Neglecting experimental errors the transmission coefficient for a direct polycapillary is proportional to the polycapillary openness, defined as the ratio of the area of hol-

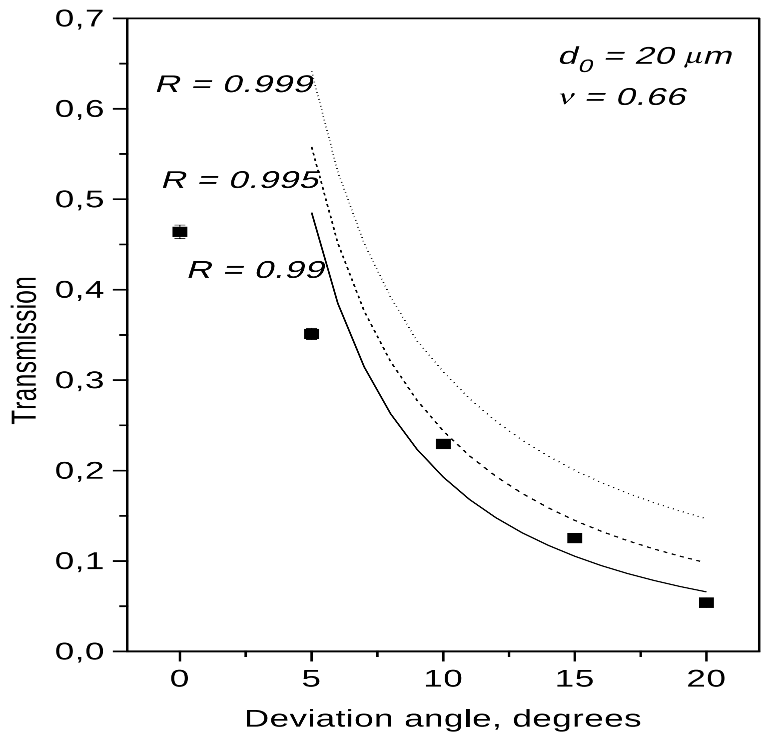

Figure 4: *Comparison of theoretical curves (obtained for different values of single reflection coefficient R_0) and experimental results (squares) of thermal neutrons travelling into single polycapillaries.*

low channels to the total transverse cross-section of the polycapillary. As it was expected from the above considerations the efficiency of a capillary as a neutron guide, may be significantly improved by decreasing the inner diameter or, at the same time, increasing the openness of the polycapillary structures. One may also demonstrate that for microcapillaries of $d_{in} = 10\,\mu m$ a rather high transmission may be achieved, i.e., about 35% and 22% for deflection at 10 and 20 degrees, respectively. These results are also in good agreement with theoretical predictions.

A more delicate question is the determination of the coefficient of a single reflection from the channel walls. Comparison between transmission measurements from polycapillaries with $d_{in} = 20\,\mu m$ and theoretical evaluations for different values of the coefficient of the single reflection R_0 are presented in Fig. 4. From these results we may evaluate that the reflection coefficient of the polycapillaries has a very high reflecting value $R_0 \approx 0.99$.

The additional experiments performed with new polycapillaries ($d_{in} = 10\,\mu m$) were also carried out in the same scheme. The results of the experiments on neutron beam bending ($\lambda_1 = 2.5$ Å and $\lambda_2 = 5$ Å) by means of single polycapillaries, presented in Fig. 5, are

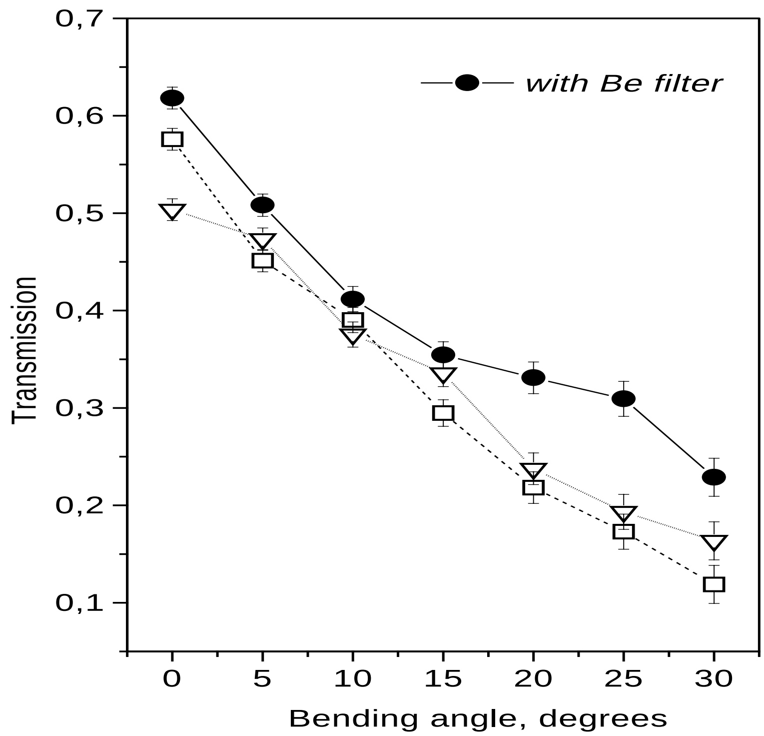

Figure 5: *Transmission coefficients of single polycapillaries with* $d_{in} = 10\,\mu m$ *vs bending angle (circles - with Be filter; squares and triangles - without filter).*

in good agreement with previous data. For these wavelengths, because of the direct dependence between the total reflection angle and the wave length of the neutrons ($\theta_c \propto \lambda$), the most energetic fraction of the beam is filtered out travelling inside the polycapillary channels. As a consequence, polycapillaries can be also considered as efficient filters.

4 Neutron capillary bender

To complete the research program we manufactured and tested also a bender that allows a continuous change of the bending angle. This bender allows also to bend a system of polycapillaries to a definite curve.

The selection of the capillaries necessary to manufacture this special bender was the result of the analysis of a great number of single polycapillaries. The total number of the polycapillaries used was 60 (although two polycapillaries were probably closed by the diaphragms during the experiments), each one with a length of about 16 cm. The experimental results on the deflecting of the neutron beam without filter ($\lambda_1 = 2.5\,\AA$) and with a Be filter ($\lambda_2 = 5\,\AA$) are shown in Fig. 6 .

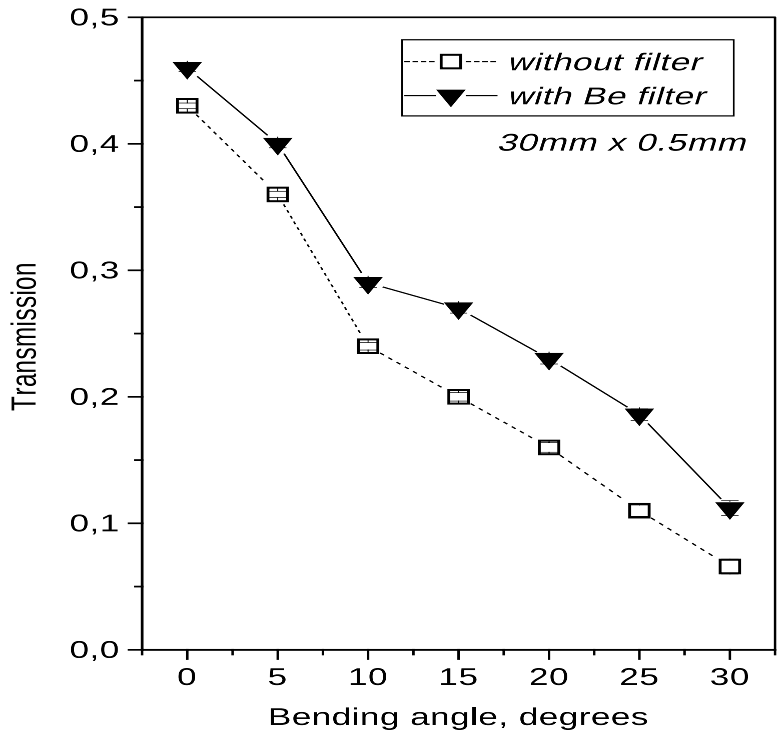

Figure 6: *Transmission of the bender vs the bending angle (triangles and squares - with and without filter, respectively).*

The comparison between the bending efficiency of this device and that of a single polycapillary shows that the bending characteristics of the last one are superior. Although the technology to pack capillaries have still to be improved, the efficiency of a neutron beam bending device based on a capillary system is much better than any existing neutron guide.

5 Conclusion

The results of the bending performances of thermal neutrons by means of capillary structures demonstrate that glass capillary structures with an inner channel diameter of $10\,\mu m$ allow to bend the neutron beam at angles up to 30 degrees in relatively small distance (15÷19 cm) along the beam direction. For example, at bending angles of 10, 20 and 30 degrees the measured efficiencies are about $24\%\,(30\%), 17\%\,(23\%)$ and $7\%\,(12\%)$, respectively, at $\lambda_1 = 2.5\,\AA\,(\lambda_2 = 5\,\AA)$. It is important to underline also that a significant reduction of the most energetic (hard) part of the beam is observed with the use of a bending device.

The bender discussed in the manuscript is an effective device not only for an intense thermal neutron beam but, as already demonstrated [15], also for an intense and brilliant synchrotron radiation source both in the soft and hard x-ray regions.

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