A conic reflector for increasing of the flux of very cold neutrons.

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Abstract. The work is dedicated to computation of increasing of directed flux of very cold neutrons from moderators of the IBR-2M reactor due to the reflector of nanodispersed diamond powder. Monte Carlo simulation of very cold neutron transport, computation of differential albedo and total albedo were done. Neutron scattering by individual grains with the Born approximation and neutron interaction with hydrogen admixture were accounted for. It was shown that if the ratio of grain size to neutron wavelength is close to unity, then using of the reflector gives two-fold gain in the directed flux.

1. Concept of the conical reflector.

Neutron scattering methods need high fluxes of cold (CN, wavelength from 4Å to ~20Å) and very cold (VCN, wavelength higher than 20Å) neutrons. Such neutrons can be produced by using the cold (cryogenic) moderators [3,6]. Low rate of these neutrons even in Maxwellian spectrum forces us to look for ways of increasing their intensity. Mirror neutron guides with multiple coating are usually used for neutron transport from reactor to samples and cannot be placed close to a reactor core because of radiation damage. We research properties of reflectors contained nanodispersed diamond powder with particle size between 1 and 10 nm. As we know from theoretical and experimental [7,8] investigations, the reflection coefficient of cold and very cold neutrons from nanodispersed material is much higher than from solid material and close to unity. Because of this and because of irradiation stability of the nanodispersed diamond, this material is seems to be much suitable for using in the source of VCN.

Consider a flat source of VCN which is presented by limited surface in the form of the circle with fixed diameter, its plane is orthogonal to axis of neutron beam. Over the source there is a reflector presented by the hollow truncated cone as we see on figure 1. Inner walls of the cone are covered by a layer of the diamond nanopowder; the height of the cone is limited. Thickness of the nanopowder layer should be sufficient for VCN not to penetrate through it, but scattering cross-section of neutrons with small wavelength (thermal and CN) to be low (aluminium, carbon). Then reflector would not reduce fluxes on spectrometers located at the oblique angles.

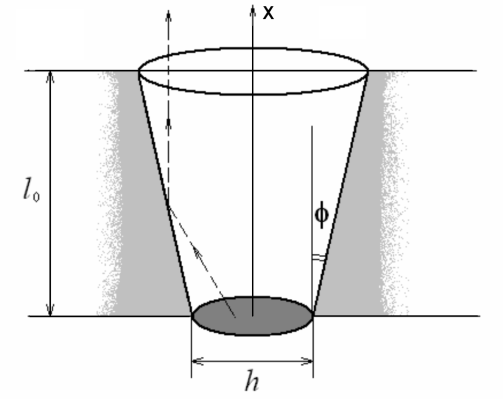

Figure 1. Outline of conic reflector.

Let's define *the directed flux* as the number of neutrons crossing the plane orthogonal to the axis of the beam to the positive direction in a unit of time inside the infinitesimal solid angle and reduced to unity of solid angle. Without reflector, directed flux will be constant along the beam axis. In the presence of the cone reflector, neutrons with direction which is not parallel to the axis, have possibility to get to the wall, reflect and fly out to the right direction. Correspondingly, the directed flux will be increased along the axis right up to the big base of the cone.

Especially high reflection is to be expected for neutrons which get into surface of the cone at the angles close to the angle of small-angle coherent scattering on powder particles. Neutrons fly out the source plane according to the cosine law and this lead to existence of the optimal angle of cone opening. At this angle the directed flux has maximum value (at the fixed cone height).

The main points of our work were:

- computation of the gain in the directed flux as function of parameters of reflector (angle of cone opening, cone length and thickness of nanopowder walls), temperature of the powder, particle radius and neutron wavelength.
- computation of total and differential (angular) albedo as function of hade, particle radius and neutron wavelength in the case of flat surface of nanopowder.

2. Hydrogen cross sections

When modeling the transport of cold neutrons in nanopowder, one should not consider only the interaction between neutrons and diamond nanoparticles. Experiments show that nanopowder contained also atoms and molecules of hydrogen, oxygen and water besides the carbon [4,5]. It is important to taking into account of hydrogen impurities because capture cross section of hydrogen $\sigma_{abs}^{H} = 1,6b$ is much higher than one of carbon. It leads to significant loss of neutrons.

Secondly, there is elastic and inelastic neutron scattering on hydrogen nuclei.

Elastic scattering (without energy transmission) on hydrogen is isotropic, elastic cross section on hydrogen equals $\sigma_{el}^{H} = 120\,b$.

In collisions neutron can receive additional energy, because hydrogen atoms are in thermal motion. Dependence on temperature is linear:

$$\sigma_{inel}^{H}(T) = \frac{T[K]}{50}[b].$$

3. Calculation of the VCN transport

If reflector is used then straight directed flux sums up from the flux directly from the source (call it as G_s) and reflected flux from the walls of the cone (G_r). Gain factor of the directed flux will be:

$$G = \frac{G_r + G_s}{G_s} = \frac{G_r}{G_s} + 1.$$

Calculating of the very cold neutrons transport was done by Monte Carlo statistical test.

In the nanopowder material, VCN mainly have coherent elastic scattering on particles as a whole. At the scattering on the particle with size close to neutron wavelength, incident wave diffracts on the particle, cross section is proportionate to number of atoms in the particle squared, and angle of scattering is small (small angle scattering). Calculated in perturbation theory with the Born approximation differential section of neutron scattering on spherical particle with radius *a* is given by expression [9]:

$$\frac{d\sigma}{d\Omega}(\Omega) = a^2 \frac{u^2}{q^4}\left(\cos(qa) - \frac{\sin(qa)}{qa}\right)^2.$$

Here are $q = \frac{4\pi}{\lambda}\sin\theta$, θ – angle of deviation, $u = 4\pi N_0 b_C$, $b_C = 0,627 \cdot 10^{-12} cm$ – scattering length (the characteristic of the C^{12} nuclei), $N_0 = 1,76 \cdot 10^{23} cm^{-3}$ – nucleus concentration in solid diamond.

Created program of Monte Carlo method allows calculating the gain factor of directed VCN flux for reflector with conical and parabolic forms and also differential albedo of VCN from the flat wall.

4. The results

4.1. Reflection from the flat wall

Obtained dependences of the total reflectivity of incident flux from the polar and azimuth angles (differential albedo) are listed here (figure 2). Other parameters were: particle radius $R = 2nm$, wavelength $\lambda = 2nm$, thickness of the wall – infinite. One sees that strong dependence of all characteristics from the polar angle is typical for VCN. Angular distribution of reflected neutrons, both for azimuth angle φ and polar angle, is strongly elongated forward at small incident polar angle.

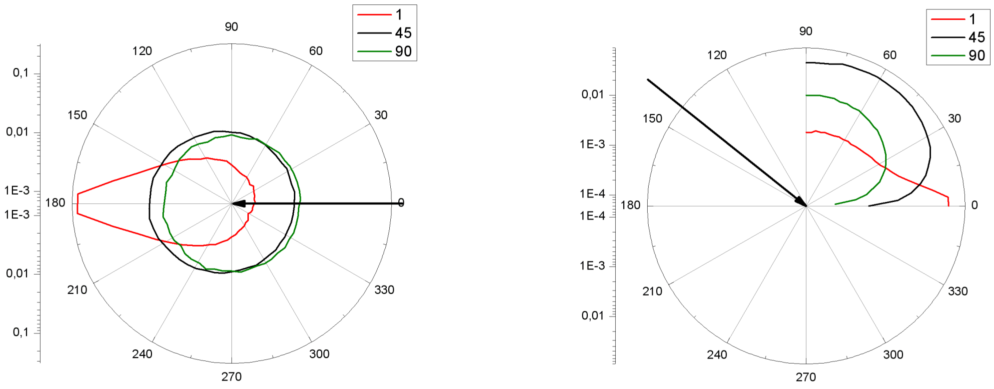

Figure 2. Differential albedo.

On the figure 3 one can see the albedo dependency on particle radius for neutrons with wavelength $\lambda = 2nm$ and three temperatures of nanopowder - 4K (liquid helium), 77K (liquid nitrogen) и 300K (room temperature). Thickness of the wall equals 20cm, which is practically equivalent to infinite thick wall for these neutrons.

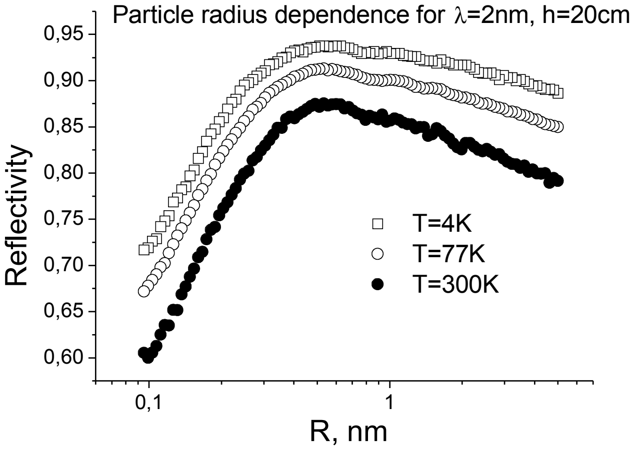

Figure 3. Albedo for $\lambda = 2nm$ as function of particle radius.

All curves have the same form, but differ from each other in constant value. This is effect of loss in channel of inelastic scattering on hydrogen (Σ_{inel}^{H}). Cooling of nanopowder to the temperature of liquid helium increases neutron reflection in 7 percent. Also all curves have maximum at $R = 0{,}54\,nm$, that confirm theoretical prediction [8,9] about best reflectivity at $R \approx 0{,}27\,\lambda$. Such curves for other wavelength look similar, rule $R \approx 0{,}27\,\lambda$ is always confirmed, but the maximum value of albedo is going to unity with increasing of wavelength. One can see that on the next figure 4.

Curves of albedo dependency on wavelength and velocity of neutron are presented on figure 4. In calculations particle radius was 2nm, wall thickness – 20cm, temperature – 4K.

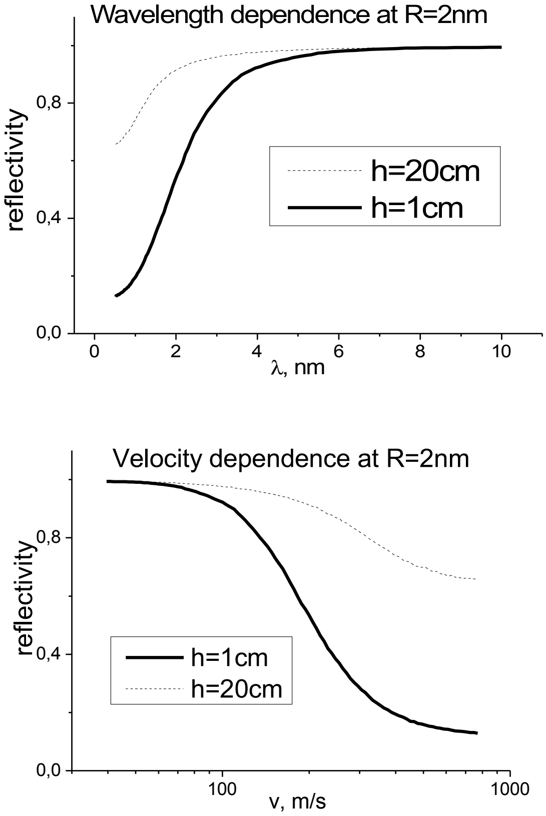

Figure 4. Albedo for $R = 2nm$ as function of wavelength and velocity.

As we see, effective reflection from low thickness of nanopowder (~1cm) is possible for very cold neutrons only (wavelength 4nm and higher). Curves on the figure 4 can be compared with experimental results from the paper [4]. In outline, they coincide in spite of the fact that we consider the one particle radius only ($R = 2\text{нм}$) in calculations.

4.2. Gain factor

In calculating of the gain factor G in the directed flux and of optimal angles φ of the cone opening, we considered diameter of the round source equal to 10cm.

Have to be found:

- Gain factor $G(\varphi)$ for three fixed values of cone length L = 20, 30 and 40cm as function of angle φ of the cone opening.
- Gain factor $G(\varphi)$ for different values R and λ. Cone length L equals 30cm in this case.
- Influence of wall thickness.
- Influence of wall temperature.
- Maximum gain factor for parabolic reflector (figure 5) with height $l_0 = L\cos\varphi_{\max}$, where $\varphi_{\max}$ is angle of the cone opening at maximum $G(\varphi)$.

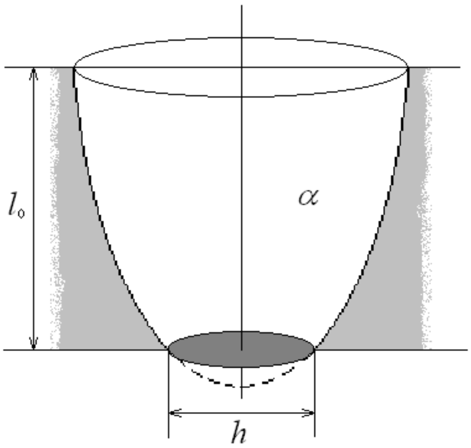

Figure 5. Outline of parabolic reflector.

It should be noted that the form of such parabolic reflector is determined completely by one parameter α from the equation of paraboloid generatrix.

Curves $G(\varphi)$ for three fixed values of cone length are presented on figure 6. Other parameters were fixed: $R = \lambda = 2nm$, $T = 4K$. Wall thickness d is considered high enough for good reflection of such neutrons.

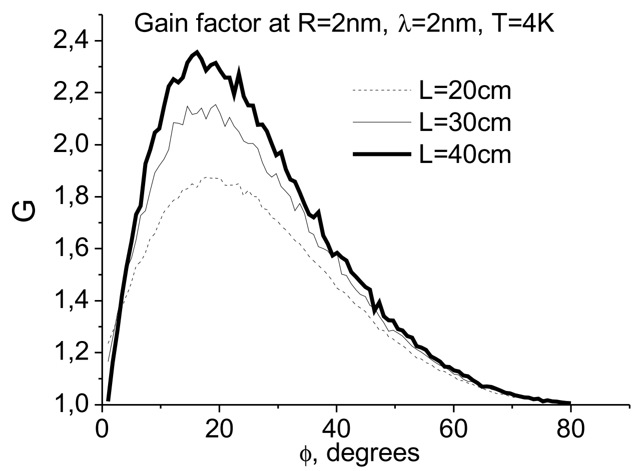

Figure 6. Gain factor at three values of L.

All three curves look similar, $G(\varphi)$ grows fast at low φ, then reaches maximum near 20° and decreases slowly to unity. Maximum value of gain factor depends on cone length, because increasing L means increasing of reflecting surface. Thus, at $L = 20cm$ directed flux increases in 1,85 times, at $L = 30cm$ - in 2,15 times, at $L = 40cm$ - in 2,3 times.

Further, curves $G(\varphi)$ for different combinations of R and λ are presented on figure 7. Cone length L was 30cm.

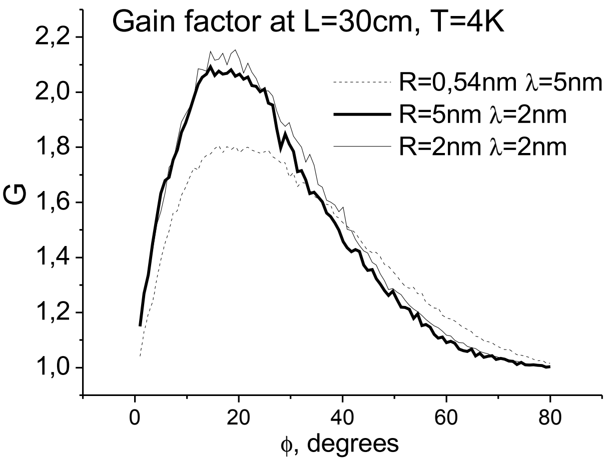

Figure 7. Gain factor at three cases of R and λ.

On figure 7 we can see $G(\varphi)$ for three cases: $R < \lambda$, $R > \lambda$ and $R = \lambda$. In two last cases (solid lines) curves almost coincide, that is particles with radii from $R = \lambda$ to $R = 2{,}5\lambda$ "work" in reflector equally. This occurs in spite of the fact that differential and total cross sections for $R = \lambda$ and $R = 2{,}5\lambda$ differ from each other very much. Other curve $G(\varphi)$ (dash line) has more gentle maximum and low value of maximum $G(\varphi)$.

For indication of influence of wall thickness functions $G(\varphi)$ were calculated for different value of thickness d (infinite, 1cm and 0,1cm). Other parameters were fixed: $L = 30cm$, $R = \lambda = 2nm$, $T = 4K$. Obtained results are listed on figure 8.

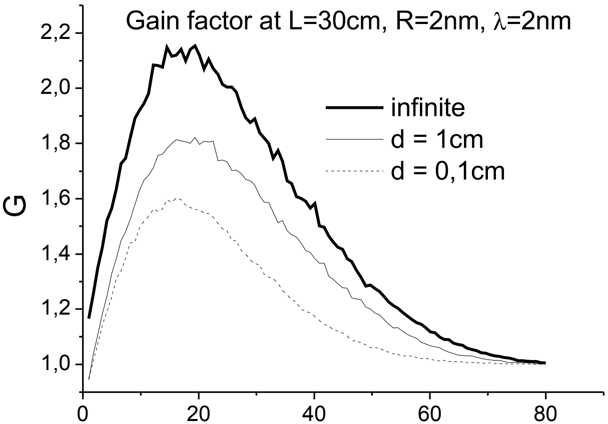

Figure 8. Gain factor at three values of thickness *d*.

One can see that for neutrons with wavelength 2nm (and lower) double gain of directed flux can be achieved with thick walls only (several centimeters of nanopowder). For real walls with thickness about 1cm gain factor will be about 1,8.

For indication of influence of wall's temperature three curves $G(\varphi)$ were calculated for different temperature of nanopowder: 4K, 77K and 300K. They are listed on figure 9. Other parameters were fixed: $L = 30cm$, $R = \lambda = 2nm$.

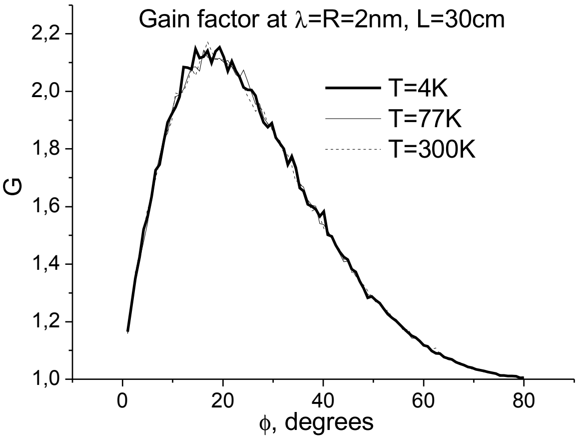

Figure 9. Gain factor at three temperatures of nanopowder.

We see that all three curves almost coincide, that is temperature of the walls doesn't affect the directed flux of cold neutrons. Obviously, this occurs because every neutron spends low time inside the nanopowder in several, it reflects in a few acts of scattering. Since inelastic cross section is lower than elastic one then at short contact with material directed neutron flux has no time to "get warm".

So, the reflector work good both at room and at cryogenic temperatures. This is advantage of such type of reflectors.

The parabolic reflector was also investigated and its gain factor didn't differ from gain factor of the conic reflector.

5. Conclusion

As was found from the Monte Carlo computation of the VCN transport, addition of the conical reflector to the cold moderator raises forward directed VCN flux about twice. This is consequence of high reflectivity of nanopowder. But thickness of the walls should be more than 1cm.

Maximum gain factor of the flux is obtained at angles of cone opening about 15-30 degrees, this confirm initial supposition. Obviously, because of the anisotropy of differential albedo value of optimal angle must depend on distribution of the neutrons flying out from the source.

Because of the scale invariance of neutron transport inside the reflector, this estimation of directed flux gain factor can be used for reflector and moderator of any size.

Also, reflector work equally both at cryogenic and at room temperatures.

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