FLEXIBLE POLYVINYL CHLORIDE TUBES TO TRANSPORT LOW ENERGY NEUTRONS AND SOME OPTIONS FOR THEIR APPLICATION

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Experimental results on transport of very cold neutrons (VCN) through flexible polyvinyl chloride tubes are presented. The coefficient of VCN transmission was investigated as a function of the tube length and curvature. We discuss options for applications of such tubes for construction of portable and tiny sources of ultra cold neutrons (UCN) and gamma rays as well as for tasks of neutron capture therapy.
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An extremely high transmission of ultracold neutrons (UCN) through commercial polyvinyl chloride tubes was discovered in ref. [1]. Polyvinyl chloride is a polymer $(CH_2\text{-}CHCl)_n$ consisting of molecules with very large molecular weight in the range of 30000 – 100000 a.u. The critical velocity of this polymer is not very high and is equal to 2.9 m/s. Nevertheless, a thin layer of fluorine polymer on the internal tube surface converts the tube into a perfect neutron guide for slow neutrons. Such polymer of the type "Fomblin YL VAC 18/8" has critical velocity equal to 4.56 m/s and a very low coefficient of neutron capture $\sim 3\times 10^{-5}$, thus neutrons might be specularly reflected from the tube wall more than 10^4 times before being lost.

Here very cold neutron (VCN) transmission was investigated (Fig. 1). The source of VCN was a Beryllium converter placed nearby the "bottom" of the curved mirror neutron guide with the internal diameter of 8.8 cm just at the boundary of the Beryllium reflector of the reactor core of IR-8 (NRC "Kurchatov Institute"). The internal surface of the guide covered by a layer of the ^{58}Ni-Mo alloy had the critical velocity equal to 7.9 m/s. The longitudinal neutron velocity was in the range of 8-180 m/s with the mean value of about 57 m/s. The investigated tubes with the inner fluorine polymer cover were affixed to the output flange of the guide with the hole with the diameter of 8 mm. At the end of the tube, a ^{3}He filled proportional detector was installed. The transmission coefficient *W(L)* is shown in Fig. 2 as a function of the tube length *L*. The value $W(L) = \frac{I(L)}{I(L=0)}$, where $I(L)$ is the exit neutron flux and $I(L=0)$ is the entrance neutron flux. It is clear from Fig. 2 that at small distances to the tube entrance the neutron flux decreases rapidly as a function of the distance because of the radial velocity components (in the range of 4.6-7.9 m/s) larger than the critical velocity of the fluorine polymer. Such neutrons leave the tube due to their penetration into the tube wall. At large distances, the neutron flux decreases slowly as a function of the distance because the radial velocity components are below 4.6 m/s. When the value of *L* becomes equal to *L* = 138 cm, that corresponds to $\frac{L}{d}$ = 172, the exit flux is equal to 22% of the entrance one.

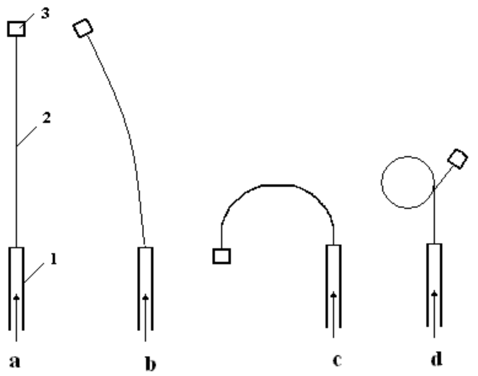

Fig. 1. A scheme of the tube transmission measurements for cold neutrons. 1- output flange of the cold neutron source, 2 - tube, 3 - detector.

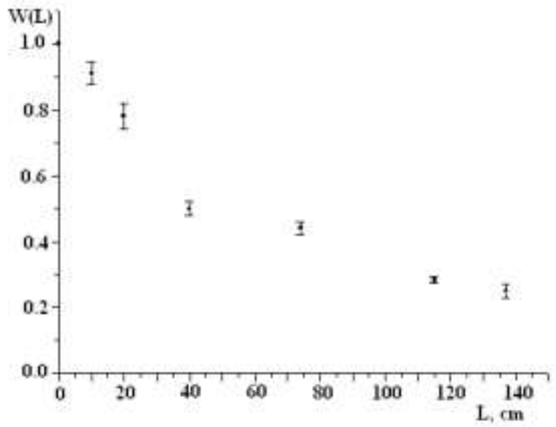

Fig. 2. The transmission coefficient *W(L)* as a function of the tube length *L*.

The tube transmission (L = 138 cm) was also studied as a function of the radius of the tube curvature in the horizontal plane (in the shapes shown in Fig. 1 *b, c, d*). The transmission coefficient $W(R) = \frac{I(R)}{I(\infty)}$ behavior is presented in Fig. 3, where $I(\infty)$ is equal to the flux through a straight tube. The tube curvature decreases the exit neutron flux due to increasing the radial velocity components (> 4.56 m/s). Nevertheless, the transmission coefficient remains larger than 20% if the tube exit is turned by about 360°.

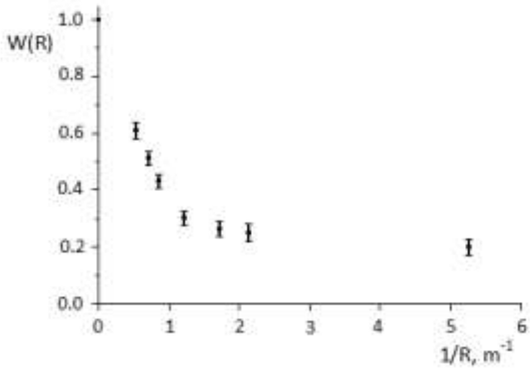

Fig. 3. The transmission of cold neutrons through a PVC tube is shown as a function of its curvature radius.

The efficiency of neutron transmission using flexible tube-guides can turn to be productive for fundamental and applied studies. In particular, such guides can be used in the neutron capture therapy as catheters to deliver neutrons to the cancer tumors. Such flexible guides can penetrate inside body through natural internal body cavities such as esophagus, bronchi, urethra etc. This tube application will be practical keeping in mind future progress in intensity of supper low energy neutron sources [2].

Arrangement of neutron converters of various types at the guide exit enables to produce radioactive sources. For instance, see the following list.

1. Gamma-ray source. A converter made of a material with the neutron capture cross section σ_c that is much larger than the cross section of the neutron inelastic scattering σ_{ie} allows creating a tiny γ-source with a desired characteristic energy spectrum up to 10 MeV while the present radioactive sources provide γ-rays with the energy of up to 1.5 - 2 MeV. The thickness of a converter needed for the total conversion of transmitted neutrons is rather small due to low energy of the neutrons.

2. Fast neutron source. A converter has to be made of fissionable elements that fission by slow neutrons as, for instance, ^{235}U. In this case, one captured neutron provides 2.4 fast neutrons per fission.

3. Thermal neutron source. In this case, a converter has to be made of the material with the neutron capture cross section σ_c much lower than the neutron inelastic scattering cross section σ_{ie}. Cold and ultra cold neutrons have much lower energies than those of atom in thermal motion. Therefore an incident neutron gets promptly an almost thermal energy. A convenient material for the converter is a hydrogenous matter with low or even negative critical energy such as, for instance, polyethylene. For such matter, the reflection of incident neutrons is negligible and they penetrate totally into the converter. The converter thickness is rather small due to low energy of incident neutrons. A polyethylene converter with the thickness of 0.5 mm at the ambient temperature captures totally neutrons as in this case σ_{ie} = 900 barn (per atom) and σ_c = 54 barn for the neutron velocity equal to 9 m/s [3]. 6% of incident neutrons will be converted into γ-rays in the $n(pd)\gamma$ reaction while the 94%-fraction will be inelastically scattered with the energy gain. The energy spectrum of the resulting neutrons is defined by the energy spectrum of the normal thermal oscillation of the Hydrogen atoms inside the converter. The mean energy of the resulting neutrons is equal to 15 meV at the temperature of T = 300° K [4]. In principal, by changing the temperature T one could adjust the mean neutron energy.

A tiny movable source of thermal neutrons was made and used by the authors, see Fig. 4. From the source of HFR at Institute Laue-Langevin, UCN with the velocity in the range of 1.5-5.7 m/s arrive to the flexible PVC tube with the internal diameter of 8 mm; the inner surface of the tube is covered with a Fluorine polymer layer. The exit end of the tube was affixed to the copper cylinder with thin walls. The polyethylene disk-converter with the volume of 0.01 cm^3 was placed inside the cylinder at its bottom. The transmitted UCNs are captured totally in the converter and transformed into thermal neutrons. Thus, this disk-converter represents a source of isotropic thermal neutrons. The monitor detector 3 of thermal neutrons consisted of a set of 6 counters of SNM-18 type placed inside the Cadmium cylinder-shield. The intensity of this source was measured using this detector; the copper cylinder with the converter was placed in the center of the setup; the registration efficiency for thermal neutrons was equal to 25%. Fig. 5 presents the count rate $J(z)$ as a function of the height z of the source relatively to the entrance to the tube. The decrease in the $J(z)$ value from 105 counts per sec to zero if z = 160 cm corresponds to the UCN flux decrease due to the gravity as a neutron with the velocity equal to 5.7 m/s cannot rise higher than 160 cm. The absolute intensity of the thermal neutron source is equal to 420 counts per s for $z = 0$ according to the mentioned above calibration of the detector. The control of the source stability during a three days run showed that it was constant with the precision of 0.5% and changed not more than on (1 – 2)% while horizontal moving in the limits of 20 - 30 cm for z = const.

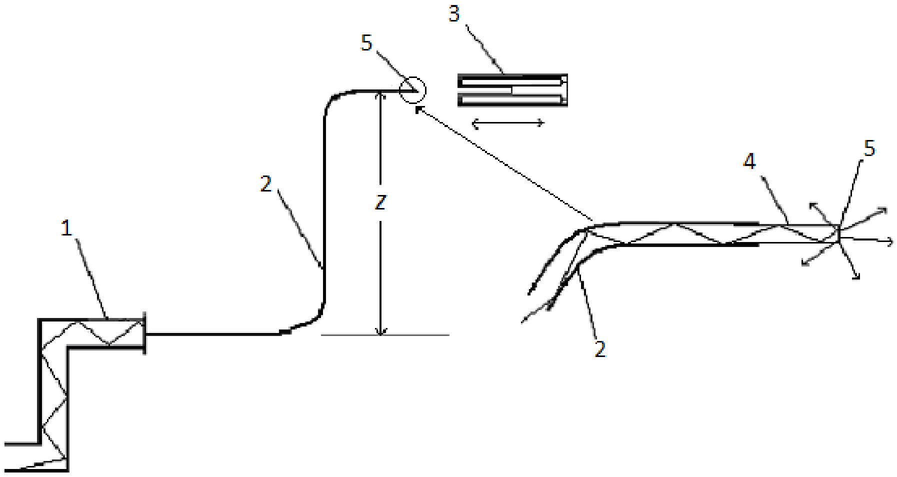

Fig. 4. A scheme of the tiny movable source of thermal neutrons. 1- output flange of the UCN guide, 2 - flexible PVC tube, 3 - monitor detector of thermal neutrons, 4 - copper cylinder, 5 - polyethylene disk-converter.

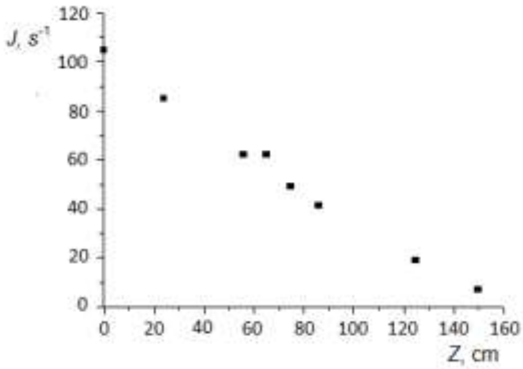

Fig. 5. The count rate *J(z)* of thermal neutrons from the tiny movable source as a function of the height *z*.

The tiny movable sources of thermal neutrons are useful for a rank of tasks in various branches of applied physics and medicine. For example, for calibration of the thermal neutron detectors, for local studies of shields, for the diffusion length measurements, for the analysis of local element content in large samples using the neutron activation method, for the radioactive therapy of a cancer diseases. Currently available movable sources of thermal neutrons are based on deceleration of fast neutrons emitted in various nuclear reactions due to surrounding the reaction space with a moderator matter. The most effective moderators, such as water or polyethylene, need rather a thick layer (of 10 - 20 cm) to decelerate a neutron into the thermal energy. In this case, thermal neutron source is not point-like but bulky and has a noticeable admixture of fast neutrons. A tiny source of thermal neutrons described above is compatible in intensity to usual ones but it has no fast neutron admixture.

This tiny thermal neutron source has been used successfully in the experiment on the neutron lifetime measurement using the method of UCN storage with simultaneous detection (in an external thermal neutron detector) neutrons escaping the storage vessel due to their inelastic scattering at reflection from the vessel wall [5]. The surface distribution of the detection efficiency for the external thermal neutron detector was investigated by placing the tiny source to different points on the internal surface of the storage vessel. Results of these measurements allowed to decrease the methodical uncertainty in the neutron lifetime experiment and to get the final uncertainty of the neutron lifetime measurement equal to 1 sec.

It should be noted that the assembly shown in Fig. 4 includes a tube, a polyethylene converter and a monitor detector and represents a Gravity barrier spectrometer for the UCNs [6]; it could be applied to a rank of installation with UCN.

Possible applications of the efficient transmission of UCNs through flexible neutron guides are discussed in [2, 7] for the tasks of the neutron capture therapy. In particular, in analogy to the method avoiding affection of healthy biological tissues because of direct neutron delivery to the cancerous tumors, it uses natural internal body cavities as esophagus, bronchi, urethra etc. It looks effective to use the flexible neutron guides in surgery techniques; after introducing ^{10}B-containing drugs into a tumor and its surgery the neutron source could be applied directly to the tumor. Compared to the traditional neutron capture therapy, the flexible neutron guides with UCN provide thermal neutron sources with no admixture of fast neutrons and γ-rays. Moreover, the technology of the suggested method to transport UCNs using flexible tubes is rather simple and is not expensive.

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