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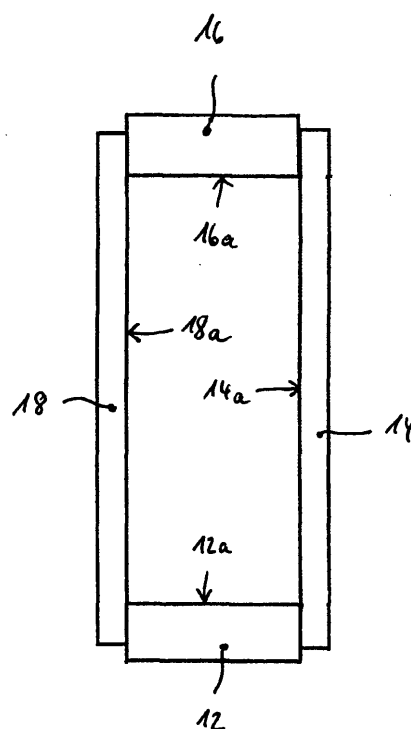
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(54) **Ultracold neutron guide**

(57) Ultracold neutron guide, characterized in that, it is made of polished sapphire. It shows highly specular UCN reflection due to excellent polishing of surfaces, a high mechanical hardness that excludes mechanical deterioration of surfaces during assembling and cleaning, high resistance to radiation, high critical energy, low UCN loss during their storage inside such an ultracold neutron guide.



Figur 4

Description

[0001] The present invention is directed to a ultracold neutron guide.

[0002] Neutron guides are used for transporting neutrons from a neutron source to an experimental installation. Ultracold neutrons (UCN) are intensively used in fundamental physics and probably could be applied to surface and nanoparticles physics. The low density/flux of UCN is an important factor in many experiments such as the search for non-zero electric dipole moment of neutrons, the search for non-zero electric charge of neutrons, and the experiments using quantum states of neutrons in the earth's gravitational field.

[0003] The typical loss of neutron density in a neutron guide between a source and an experimental installation is higher than an order of magnitude. The main reason for UCN loss consists in their diffusive (non-specular) scattering at neutron-guide walls. For pulsed UCN sources this effect is even more important, as the diffusive scattering does not allow so-called time-focusing of a UCN pulsed beam.

[0004] A typical ultracold neutron guide is a pumped out polished-inside tube made of metal or coated with metal with round or rectangular cross-section of 5 - 10 cm size and with the length of 10 - 20 m. The width is usually defined by geometrical constraints in the vicinity of a source, for example an active reactor zone or a spallation target. The length is defined by minimum sufficient distance between the cold neutron source inside a nuclear reactor or a spallation source and an experimental installation. In order to obtain any reasonable UCN density inside solid/liquid converters one has to use maximum available initial neutron density. UCN experiments require low neutron- and gamma-background, therefore the neutron guide length can not be significantly decreased, and the neutron guide width can not be significantly increased. With typical sizes of the neutron guides and correspondingly with $>10^2$ collisions of UCN with neutron-guide walls, the main reason of UCN loss is their diffusive (non-specular) diffusion at the guide walls. The probability of absorption and inelastic scattering is usually much lower, in the range 10^{-4} - 10^{-5} per collision. As known, the probability of diffusive scattering of a wave

at a rough surface is equal approximately to $\sim (\frac{\Delta d}{\lambda})^2$,

where Δd is the average surface roughness and λ is the UCN wavelength of 10 - 20 nm. Thus, high probability of specular reflection (much better than 99 %) is possible if only the wall roughness is smaller than ~ 1 nm. Up to now, this condition has never been satisfied for any existing ultracold neutron guide.

[0005] The roughness of the required size is typical for guides of cold neutrons that has been used for a few decades in many research centers. However, just trans-

ferring the method of extracting from cold neutrons to ultracold neutrons is not sufficient, because glass or silicon walls have too low critical energy. The critical energy should be at least as high as the critical energy of a typical deuterium converter of ~ 100 neV.

[0006] Coating with a substance, for example Ni-metal or other materials as for cold neutron guides, with higher critical energy suffers from low resistance to radiation and worse specular properties of the surface as well as from small wholes in the coatings, which are nevertheless important, because UCN with energy higher than the critical energy of the wall material are lost with high probability through any coating defect.

[0007] Moreover, the coatings and glass do not survive high radiation inside nuclear reactors.

[0008] Therefore, it is the aim of the present invention to provide an ultracold neutron guide with highly specular UCN reflection, high critical energy and high resistance to radiation.

[0009] Said aim is achieved by an ultracold neutron guide, characterized in that it is made of polished sapphire. Said ultracold neutron guide can be used for e. g. UCN production and storage.

[0010] Preferably, its inner surface is polished to an average roughness being equal to or less than about 10 Å. The term "inner surface" as used herein shall mean the surface facing to the neutron beam. Said inner surface can be unitary or made up of several surfaces, for example of four plates.

[0011] Even more preferable, its inner surface is polished to an average roughness in the range of 5 - 7 Å.

[0012] Advantagely, its inner surface is polished to a flatness being equal to or less than about 10^{-3} rad.

[0013] According to one preferred embodiment, the ultracold neutron guide is in the shape of a tube.

[0014] In particular, said tube may have a rectangular or quadratic cross-section.

[0015] Alternatively, said tube can have a circular cross-section.

[0016] Also, said sapphire can be artificial single-crystal sapphire.

[0017] Finally, preferably said ultracold neutron guide is a specular ultracold neutron guide.

[0018] The ultracold neutron guide according to the present invention shows highly specular UCN reflection due to excellent polishing of surfaces, a high mechanical hardness that excludes mechanical deterioration of surfaces during assembling and cleaning, high resistance to radiation, high critical energy, low UCN loss during their storage inside such an ultracold neutron guide.

[0019] Sapphire, in particular artificial single-crystal sapphire, can be sufficiently polished and flat, is hard, in particular it is not broken at sharp edges, wherein a broken edge would produce diffusive scattering, survives radiation, its critical energy of ~ 150 neV is sufficiently high to use it without any coating.

[0020] The resistance of any coating to radiation used in prior art neutron guides is a weak point and is never

guaranteed.

[0021] The principle constitution of the ultracold neutron guide according to the invention is considered to be efficient under the condition that the probability of non-specular reflection multiplied by the average number of collisions with walls of the guide is significantly smaller than 1.

[0022] These and other features and advantages of the invention will be apparent from the description and drawings and from the claims.

Figure 1 shows a principle scheme of a gravitational UCN spectrometer;

Figure 2 shows a scheme of the measurement of UCN transmission through a narrow long slit between two parallel vertical sapphire plates;

Figure 3 shows the total UCN flux between two vertical sapphire plates; and

Figure 4 shows a cross-section of specular ultracold neutron guide according to an embodiment of the present invention.

[0023] In order to determine the quality of specular reflections, we used rectangular plates of artificial single-crystal sapphire with size 50 x 50 x 5 mm³. Their surfaces were polished to ~7 Å average roughness, measured using X-ray scattering, and to a flatness of <1 μm.

[0024] The measurement was carried out using the installation used for the investigation of quantum states of neutrons in the earth's gravitational field: a gravitational UCN spectrometer of high resolution [V.V.Nesvizhevsky et al, Nature 415 (2002) 297, V.V.Nesvizhevsky et al, NIM 440A (2000) 754] (see Fig. 1).

[0025] Figure 1 shows a principle scheme of the gravitational UCN spectrometer. From the left to the right: the vertical bold lines indicate the upper and lower plates of an input collimator (1); the solid arrows correspond to classical neutron trajectories (2) between the input collimator and the entrance slit between a mirror (3, the empty rectangle below) and a scatterer (4, the black rectangle above). The dotted horizontal arrows illustrate the quantum motion of neutrons above a mirror (5), and the black box presents a neutron detector (6). The size of the slit between a mirror and a scatterer is equal to 250 μm, which corresponds to the spread of vertical velocity components of ±0.07 m/s.

[0026] The UCN beam produced in the gravitational spectrometer has small spread of the vertical velocity components of ±0.07 m/s. That corresponds to the slit size between the bottom mirror and the absorber of ~250 μm. It was transmitted through a narrow long slit between two vertical parallel identical sapphire plates. A scheme of the corresponding measurement is shown in Fig. 2.

[0027] Figure 2 shows the scheme of the measure-

ment of UCN transmission through a narrow long slit between two parallel vertical sapphire plates: a) view from above, b) side view. Arrows show the UCN beam. The two sapphire mirrors (1), the bottom glass mirror (2), the absorber (3) and the detector (4) are indicated in the figure.

[0028] The average spread of the horizontal velocity components at the entrance to the experimental setup was ±3°, the angle between the plates and the initial neutron beam axis was 30°. The average velocity along the beam axis was ~7 m/s. Defects at the edges of the plates were significantly smaller than the slit size. The UCN beam size at the entrance to the slit was much larger in the horizontal plane than the slit size. During the travel of UCN between the sapphire plates, the gravitational field shifted them down by ~100 μm. The detector was installed in such a way that its horizontal collimation slit with the height/width of -5 mm was placed at the "center of mass" of the UCN beam.

[0029] The result of the total UCN flux through the vertical slit between two polished sapphire plates measured as a function of the slit size is shown in Fig. 3.

[0030] Figure 3 shows the total UCN flux (indicated by circles) between two vertical sapphire plates as a function of the slit size. The solid curve corresponds to theoretical expectation, in which the probability of diffusive reflection is a free parameter.

[0031] As one can directly see from Fig. 3, the total loss of UCN at their reflection from sapphire surface is extremely small. These losses are due to absorption, inelastic scattering of neutrons and diffusive scattering; the first two loss channels are expected to be negligible at the level discussed in the present article. The total losses were measured to be equal to (0.4±0.9)·10³ per collision. The theoretical dependence could be described by

$$F(\Delta x) = \alpha \cdot \Delta x \cdot (1 - \mu)^{\frac{L \cdot g(\varphi)}{\Delta x}}, \quad \text{with } F(\Delta x) - \text{the}$$

UCN flux in function of the slit size Δx, μ - is the total loss probability per collision, φ - the angle between the initial beam direction and the sapphire plates plane, and α - the normalization coefficient.

[0032] One should note that the condition "specular reflection" is defined in this experiment in a very strict and conservative way: UCN are reflected in specular direction only if the resulting deviation (after many consequent, up to 10³, reflections) in vertical plane does not exceed -0.04 rad. This angle corresponds to the position and size of the narrow horizontal collimation slit at the entrance to the detector. The average incident angle in this experiment corresponds to the typical values for transmission of UCN through neutron guides, the UCN velocity corresponds to the typical values as well (when UCN are transmitted through a horizontal guide, their velocity is even smaller, therefore the wavelength is even longer, therefore the requirements for specular reflections are even less severe). There was no additional treatment of surfaces of the sapphire plates besides their

polishing and standard cleaning. The accuracy in the slit size and in parallelism was as high as a few micrometers. The measurements of the neutron flux were repeated many times for every slit size in order to check for systematic errors in the adjustment procedure.

[0033] The presented measurement allows us to conclude clearly that UCN reflection at sapphire surface polished to ~ 7 Å average roughness is highly specular, as expected, at least with a probability 99.8 % per collision under realistic experimental conditions. This value allows the transport of UCN through a neutron guide with a typical cross section of 5-10 cm up to distances of 25-100 m, without high loss in intensity. Such UCN transport at specular trajectories provides a qualitatively new experimental situation: 1) Ultracold neutrons can be transported from the neutron source to an experimental installation without significant losses. This would improve the quality of almost any existing or planned UCN source; 2) We have a principle possibility to transport neutrons out of the reactor, or a spallation source, to a specially constructed UCN hall, with low background conditions, specialized equipment and no spatial constraints (could be important, for instance, for [U.Trinks et al, NIM 440A (2000) 666]); 3) The specular sapphire guides are an elegant solution for UCN extraction from pulsed UCN sources [B.V.Bagrjanov et al, Phys. At. Nucl. 62 (1999) 844, Yu.N.Pokotilovki, NIM 356A (1995) 412, A.I.Frank et al, Phys. At. Nucl. 63 (2000) 545].

[0034] Figure 4 shows a cross-section of a specular ultracold neutron guide according to an embodiment of the present invention. Said ultracold neutron guide 10 has a rectangular cross-section of 3,0 mm x 7,5 mm and is made of four plates 12, 14, 16, 18 made of a commercially available artificial single crystal-sapphire. Their inner surfaces 12a, 14a, 16a and 18a are polished to an average roughness of 7 Å, measured using X-ray scattering, and to the flatness < 1 µm. The length of the ultracold neutron guide could be the range of for example 25 - 100 m. The probability of specular UCN reflection at sapphire surface in the typical experimental conditions was measured to be at least > 99.8 %, so that it could provide nearly loss free transport of UCN between a source and an experimental installation at a distance of a few tens meters.

[0035] The ultracold neutron guide as set fourth above allows to extract by far more UCN than possible before and if a small volume of solid D2 could be added - one might even expect additional gain.

[0036] The features disclosed in the foregoing description, in the claims and/or in the accompanying drawings may, both separately and in any combination thereof, be material for realising the invention in diverse forms thereof.

characterized in that,
it is made of polished sapphire.

2. Ultracold neutron guide (10) according to claim 1, **characterized in that** its inner surface (12a, 14a, 16a, 18a) is polished to an average roughness being equal to or less than about 10 Å.
3. Ultracold neutron guide (10) according to claim 2, **characterized in that** its inner surface (12a, 14a, 16a, 18a) is polished to an average roughness in the range of 5 to 7 Å.
4. Ultracold neutron guide (10) according to any one of the preceding claims, **characterized in that** its inner surface (12a, 14a, 16a, 18a) is polished to a flatness being equal to or less than about 10^{-3} rad.
5. Ultracold neutron guide (10) according to any one of the preceding claims, **characterized in that** it is in the shape of a tube.
6. Ultracold neutron guide (10) according to claim 5, **characterized in that** said tube has a rectangular or quadratic cross-section.
7. Ultracold neutron guide (10) according to claim 5, **characterized in that** said tube has a circular cross-section.
8. Ultracold neutron guide (10) according to any one of the preceding claims, **characterized in that** said sapphire is artificial single-crystal sapphire.
9. Ultracold neutron guide (10) according to any one of the preceding claims, **characterized in that** it is a specular ultracold neutron guide.

Claims

1. Ultracold neutron guide (10),

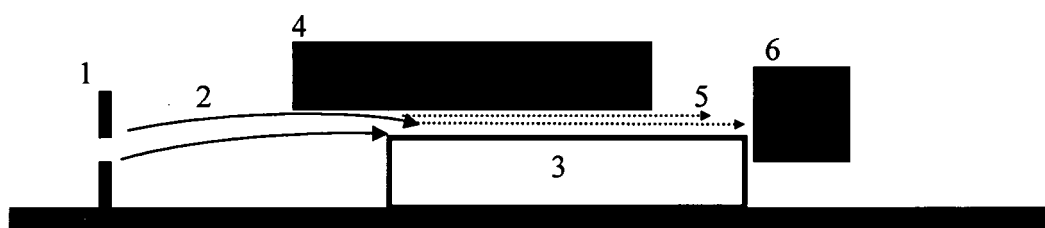


Figure 1

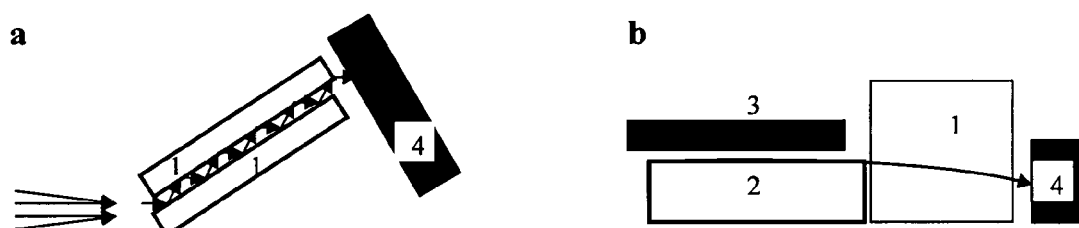


Figure 2

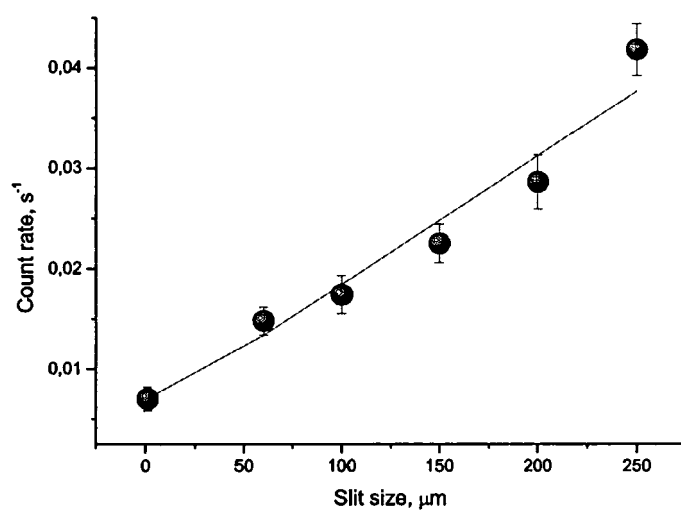
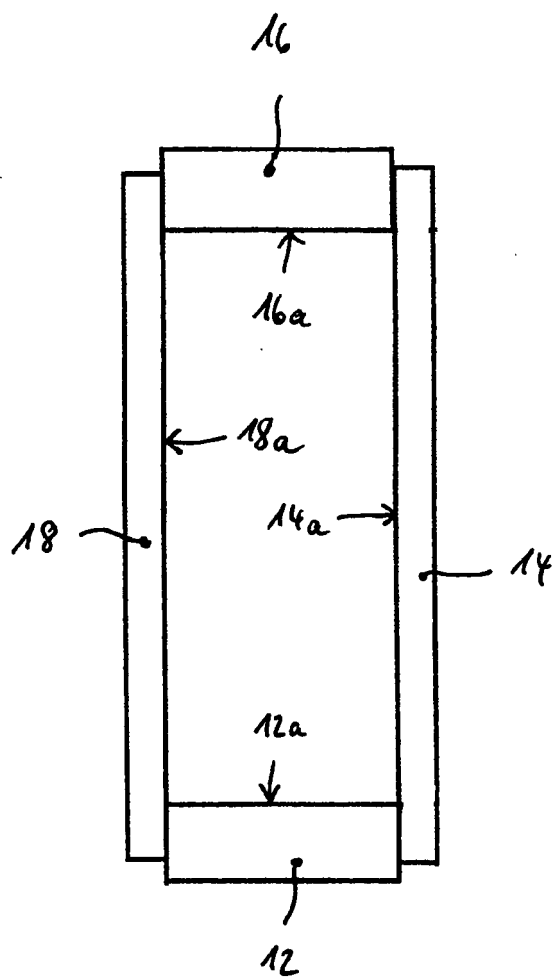


Figure 3



Figur 4



European Patent
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EUROPEAN SEARCH REPORT

Application Number
EP 05 29 2756

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	NESVIZHEVSKY ET AL: "Polished sapphire for ultracold-neutron guides" NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH, SECTION - A: ACCELERATORS, SPECTROMETERS, DETECTORS AND ASSOCIATED EQUIPMENT, ELSEVIER, AMSTERDAM, NL, vol. 557, no. 2, 14 November 2005 (2005-11-14), pages 576-579, XP005269101 ISSN: 0168-9002 * the whole document * -----	1-9	INV. G21K1/06
			TECHNICAL FIELDS SEARCHED (IPC) G21K
The present search report has been drawn up for all claims			
Place of search		Date of completion of the search	Examiner
Munich		25 September 2006	Korb, Wolfgang
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REFERENCES CITED IN THE DESCRIPTION

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