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Polished sapphire for ultracold-neutron guides

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Abstract

We show that polished sapphire allows one to efficiently reflect ultracold neutrons (UCN) at specular trajectories. The probability of specular UCN reflection at sapphire surface under typical experimental conditions was measured to be at least 99.8%. That could provide nearly loss-free transport of UCN between a source and an experimental installation at a distance of some 10 m. Polished sapphire can be used for specular neutron guides at steady and pulsed UCN sources. It can also be used in experimental installations, in particular, for building compact gravitational spectrometers and for study of the resonance transitions between neutron quantum states in the gravitational field.

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Keywords: Ultracold neutrons; Sapphire; Specular reflection

1. Introduction

Ultracold neutrons (UCN) are intensively used in fundamental physics and probably could be applied to surface and nanoparticles physics. However, the low density/flux of UCN is an important limiting factor in many experiments, such as the search for a non-zero electric dipole moment of the neutron [1,2], the search for a non-zero electric charge of the neutron [3], and the experiments using quantum states of neutrons in the Earth's gravitational field [4]. When experiments are limited by systematic errors (such as the precision measurements of the neutron lifetime [5–10]), higher density would be useful as well as it can allow one to reveal easier systematic effects. Besides that, higher density would play a decisive role for any application of UCN to physics of surface or nanoparticles, as, e.g., shown in Refs. [11,12].

Therefore, many laboratories try to significantly increase the UCN density/flux. The method of liquid or solid converters has been well developed during the last decades ([13–21] and references therein). Downscattering of neutrons in liquid ^{4}He is investigated as well [20,22,23]. The method of equilibrium neutron thermalization at ultracold nanoparticles was proposed in Ref. [12]. At least for the first mentioned method, the neutron transport from a UCN source to an experimental installation is of basic importance. Currently, the typical loss of neutron density in the neutron guide between a source and an experimental installation is higher than an order of magnitude. An alternative method of UCN transport in a closed vessel [17,24] has better efficiency, but it is more complicated methodically and it does not provide permanent neutron flux.

The main reason for UCN loss consists in their diffusive (non-specular) scattering at neutron-guide walls. For pulsed UCN sources [17,21], this effect is even more important, as the specular reflections could allow the so-called time focusing of a UCN pulsed beam [25]. We propose a solution to these problems by using polished-surface sapphire guides for UCN.

2. Sapphire neutron guides

A typical UCN guide is an evacuated polished tube with a round or rectangular cross-section of 5–10 cm size and

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with a length of 10–20 m. The width is usually defined by geometrical constraints in the vicinity of a source (an active reactor zone or a spaliation target). The length is defined by minimum sufficient distance between the cold neutron source (inside a nuclear reactor or a spaliation source) and an experimental installation. In order to obtain a reasonable UCN density inside solid/liquid converters one has to use maximum initial neutron density. UCN experiments require low neutron- and gamma background; therefore, the neutron-guide length cannot be significantly decreased and the neutron-guide width cannot be significantly increased. With typical sizes of the neutron guides, and correspondingly $>10^2$ collisions of UCN with the 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 of 10^{-4}–10^{-5} per collision. This is of particular importance for the vertical extraction of neutrons: the neutrons, which are reflected back to the source due to the diffusive scattering, or even increased significantly their perpendicular-to-the-guide-axis velocity component, are lost in the source or in the guide material above its Fermi potential. As known, the probability of diffusive scattering of a wave at a rough surface is approximately given by $\sim(\Delta d/\lambda\!\!\!^{-})^2$, where Δd is the average surface roughness and $\lambda\!\!\!^{-}$ the UCN wavelength of 10–20 nm. Thus, high probability of specular reflection (much better than 1%) is only possible if the wall roughness is smaller than ~1 nm. This condition was up to now never satisfied for any existing UCN guide!

On the other hand, adequate roughness existed for guides of cold neutrons, used for a few decades in many research centers. However, just copying the method to extract cold neutrons is not sufficient for UCN extraction. Glass or silicon walls have a too low critical energy (it should be at least as high as the critical energy of a typical deuterium converter t.i. >100 neV). On the other hand, any coating with a substance with higher critical energy suffers from worse specular properties of the surface as well as from small holes in the coatings, which are important, as UCN with energy higher than the critical energy of the wall material are lost with high probability through any coating defect. Moreover, glass does not survive high radiation inside nuclear reactors. Therefore, we had to search for a material that satisfies the following requirements: highly specular UCN reflection due to excellent polishing of surfaces to ~1 nm or better, high mechanical hardness excluding mechanical deterioration of surfaces during assembly and cleaning, high resistance to radiation, high critical energy, and finally low UCN loss during storage inside such a guide. A good candidate for material of UCN guide is sapphire [26]: it can be sufficiently polished and flatened, it is hard, in particular, it is not broken at sharp edges (a broken edge would produce diffusive scattering), it survives radiation, and its critical energy of ~150 neV is sufficiently high to use it without any coating. Otherwise, resistance of any coatings to radiation would be weak and is never guaranteed. On the other hand, neutrons of even higher energy often cannot be used simultaneously with low energy neutrons due to their significantly different storage times [11]: at the end of the storage period (defined by UCN with lower energy), all high-energy UCN are already lost due to their high frequency of collisions with trap walls and deeper penetration in the trap wall material at reflection. Finally, low UCN loss in sapphire traps was proven in experiments [27], where low losses were obtained promptly, without preliminary cleaning or cooling of surfaces as this is usually done for other materials in order to improve UCN storage times. These and other methodical aspects motivated us to measure specular reflection of UCN at polished sapphire surface.

3. Measurement of specular reflection of UCN at polished sapphire surface

In order to determine the quality of specular reflections, we used rectangular plates of artificial single-crystal sapphire with size $50\times50\times5\,\mathrm{mm}^3$. Their surfaces were polished to ~7 Å average roughness, measured using X-ray scattering, and flattened to $<1\,\mu$m.

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 [4,28] (see Fig. 1).

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.

The average spread of the horizontal velocity components at the entrance to the experimental setup was ±3°, and 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

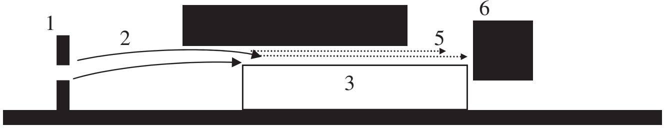

Fig. 1. A principal scheme of the gravitational UCN spectrometer. From the left to the right the following: the vertical bold lines indicate the upper and lower plates of the input collimator (1); the solid arrows correspond to classical neutron trajectories (2) between the input collimator and the entrance 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.

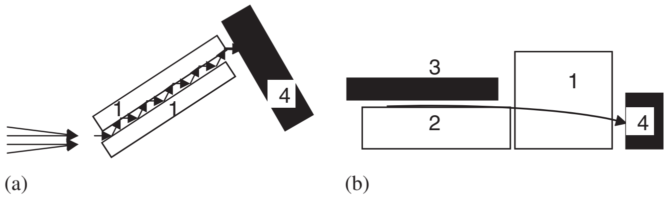

Fig. 2. A scheme of the measurement of UCN transmission through a narrow long slit between two parallel vertical sapphire plates: (a) view from above and (b) side view. Arrows show the UCN beam. The two sapphire mirrors (1), the bottom glass mirror (2), the absorber (3), and the detector (4) are indicated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

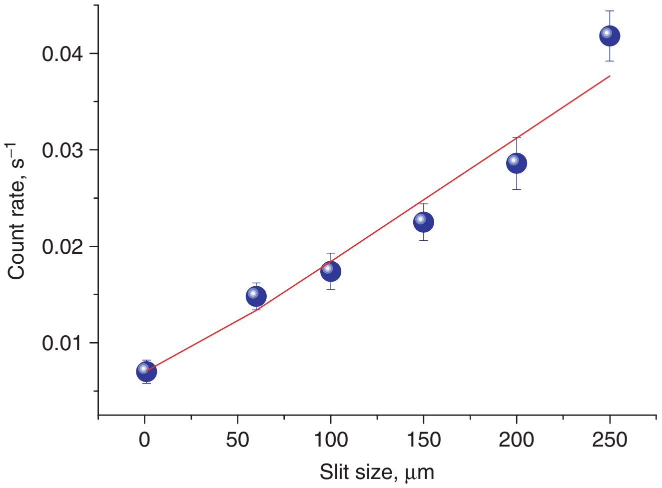

Fig. 3. The total UCN flux between two vertical sapphire plates in function of the slit size is shown with circles. The solid curve corresponds to theoretical expectation, in which the probability of diffusive reflection is a free parameter.

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.

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.

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 $(0.4\pm0.9)\times10^{-3}$ per collision. The theoretical dependence could be described by $F(\Delta x) = \alpha\Delta x(1-\mu)^{Ltg(\varphi)/\Delta x}$ with $F(\Delta x)$ is the UCN flux in function of the slit size Δx, μ the total loss probability per collision, φ the angle between the initial beam direction and the sapphire plates plane, and α the normalization coefficient.

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 10^3, 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; hence, the wavelength is even longer and 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.

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) UCN 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 spaliation source, to a specially constructed UCN hall with low-background conditions, specialized equipment and no spatial constraints (could be important, e.g., for Ref. [18]); (3) the specular sapphire guides are an elegant solution for UCN extraction from pulsed UCN sources [17,21,25].

4. Conclusions

We studied specular reflections of UCN at polished sapphire surfaces under experimental conditions, which are typical for UCN transport through neutron guides. The measured probability of the total losses was measured to be $(0.4\pm0.9)\times10^{-3}$ per collision. This corresponds to a probability of specular reflection as high as at least 99.8%. This is sufficient for UCN transport from a neutron source to an experimental installation to a distance of several 10 m without significant losses. It allows UCN transport to a separate UCN low-background hall, in analogy to cold/thermal neutron-guide halls. It provides a tool for the realization of "time focusing" of UCN beams from pulsed sources. Sapphire neutron guides can be used to build neutron experiments with long storage of UCN at specular trajectories or for compact neutron gravitational spectrometers with high sensitivity for small samples. In particular, such guides could allow the construction of a solid deuterium UCN source at ILL with a density at the entrance to an experimental installation of $>10^4\,\mathrm{n/cm^3}$, for small and medium-volume experiments, as our proposed experiment on observation and applications of the resonance transitions between the quantum states of neutrons in the Earth's gravitational field.

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