POLISHED SAPPHIRE FOR ULTRACOLD NEUTRON GUIDES

Nesvizhevsky V.V.

Institut Laue-Langevin, Grenoble, France

Abstract

We showed that polished sapphire allows us to efficiently reflect ultracold neutrons (UCN) at specula trajectories. The probability of specula UCN reflection at sapphire surface in the 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 a few tens meters. Polished sapphire can be used for specula neutron guides at steady and pulsed UCN sources. It can be used also in experimental installations, in particular for building compact gravitational spectrometers and for study of the resonance transitions between the neutron quantum states in the gravitational field.

Introduction

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 limiting factor in many experiments such as the search for non-zero electric dipole moment of neutrons [1, 2], the search for non-zero electric charge of neutrons [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 these systematic effects. Besides, higher density would play a decisive role for any application of UCN to physics of surface or nanoparticles, as for instance in [11-12].

Therefore many researchers try to significantly increase the UCN density/flux. The method of liquid or solid converters is well developed during last decades [13-30]. Down-scattering of neutrons in liquid ^{4}He is investigated as well [26, 31-32]. The method of equilibrium neutron thermalization by ultra-cold nanoparticles was proposed in [12]. At least for the first mentioned method, the neutron transport from a UCN source to an experimental installation is of principal importance. Thus, 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 [20, 33] has better efficiency, but it is more complicated methodically and it does not provide permanent flux.

The main reason for UCN loss consists in their diffusive (non-specula) scattering at neutron-guide walls. For pulsed UCN sources [20, 30] this effect is even more important, as the diffusive scattering does not allow so-called time-focusing of a UCN pulsed beam [34]. Let us consider a solution for these problems, assuming the use of polished-surface sapphire guides for UCN.

Sapphire neutron-guides

A typical UCN guide is a pumped out polished-inside tube 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 (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-specula) 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. This is of particular importance for the vertical extraction of neutrons: the neutrons which are reflected back to the source due to 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 equal approximately to $\sim\left(\frac{\Delta d}{\lambda}\right)^2$, where Δd is the average surface roughness and λ is the UCN wavelength of 10-20 nm. Thus, high probability of specula reflection (much better than 99 %) is possible if only the wall roughness is smaller than ~1 nm. This condition was never satisfied for any existing UCN guide!

On the other hand, the roughness of required size is typical for guides of cold neutrons, used for a few decades in many research centers. However, just copying of the method to extract cold neutrons is not sufficient for UCN extraction, as glass or silicon walls have too low critical energy (it should be at least as high as the critical energy of a typical deuterium converter of ~100 neV). On the other hand any coating with a substance with higher critical energy suffers from worse specula properties of the surface as well as from small wholes in the coatings, which are nevertheless 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 all mentioned requirements: highly specula UCN reflection due to excellent polishing of surfaces to ~1 nm or better, 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 a guide. A good candidate for material of UCN guide is artificial single-crystal sapphire: it can be sufficiently polished and flat, it is hard, in particular it is not broken at sharp edges (a broken edge would produce diffusive scattering), it survives radiation, its critical energy of ~150 neV is sufficiently high to use it without any coating. Otherwise, resistance of any coatings to radiation is a weak point and is never guaranteed. On the other hand, neutrons of even higher energy usually can not 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 [35], 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 specula reflection of UCN at polished sapphire surface.

Measurement of specula reflection of UCN at polished sapphire surface

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

The measurement was carried out using the installation for investigation of the quantum states of neutrons in the earth's gravitational field, which is a gravitational UCN spectrometer of high resolution [4, 36] (see figure 1).

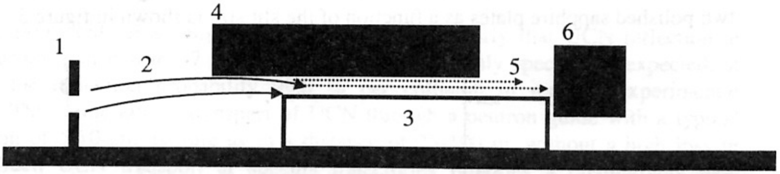

Figure 1. A principle scheme of the gravitational UCN spectrometer. From the left to the right the following: the vertical bold lines indicate the upper and lower plates of the input collimator (1); the solid arrows correspond to classical neutron trajectories (2) between the input collimator and the 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 square 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 ±7 cm/s.

The UCN beam produced in the gravitational spectrometer has a small spread of the vertical velocity components of ±7 cm/s, which corresponds to the slit size between the bottom mirror and the absorber of ~250 μm. It was then transmitted through a narrow long slit between two vertical parallel identical sapphire plates. A scheme of the corresponding measurement is shown in figure 2.

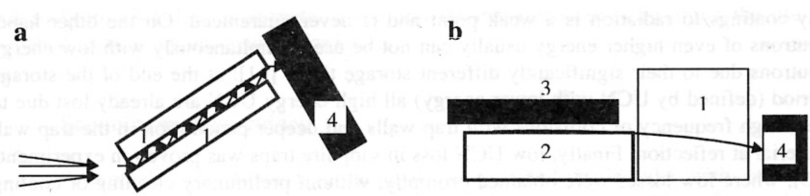

Figure 2. A scheme of the measurement of UCN transmission through a narrow long slit between two parallel vertical sapphire plates: a) view from above, b) side view. Arrows show the UCN beam. The two sapphire mirrors (1), the bottom glass mirror (2), the absorber (3) and the detector (4) are indicated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

Average angular spread of the horizontal velocity components at the entrance to the experimental setup was equal to $\pm 3^0$, the angle between the plates and the initial neutron beam axis was equal to 30^0. 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 "centre of mass" of the UCN beam.

Result of the measurement of the total UCN flux through the vertical slit between two polished sapphire plates as a function of the slit size is shown in figure 3.

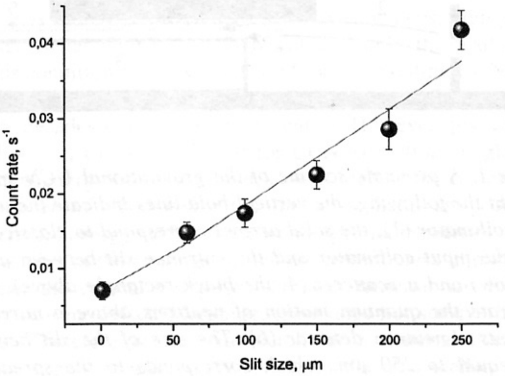

Figure 3. The total UCN flux between two vertical sapphire plates in function of the slit size is shown with circles. The solid curve corresponds to theoretical expectation, in which the probability of non-specular reflection is a free parameter.

As one can conclude from figure 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 non-specular scattering; the first two contributions are expected to be negligible at the level discussed in the present article. The total losses were measured to be equal to $(4\pm9)\cdot10^{-4}$ per one collision. The theoretical dependence corresponds to the condition $F(\Delta x)=\alpha\cdot\Delta x\cdot(1-\mu)^{\frac{L\cdot tg(\varphi)}{\Delta x}}$, where $F(\Delta x)$ is the UCN flux in function of the slit size Δx, μ – the total loss probability per collision, φ – is the angle between the initial beam direction and the sapphire plates plane, and α is a normalization coefficient.

One should note that the condition "specula reflection" is defined in this experiment in a very strict and conservative way, namely: UCN are reflected in specula direction if only the resulting deviation (after up to 10^3 subsequent reflections) in vertical plane does not exceed ~0.04 rad, which 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 specula reflections are even less severe). The surfaces of the sapphire plates were not further treated after their polishing and standard cleaning. The accuracy of setting the slit size and their 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 measurements allow us conclude clearly that UCN reflection at sapphire surface polished to ~7 Å average roughness is highly specula, as expected, at least with the reflection probability 99.8 % per collision in realistic experimental conditions. This value allows transport of UCN through a neutron guide with a typical cross section of 5-10 cm as long as to a distance of 25-100 m, without a high loss in intensity. Such UCN transport at specula trajectories provides a qualitatively new experimental situation: 1) Neutrons can be transported from the neutron source to an experimental installation without significant losses, which would improve quality of almost any existing or planning UCN sources; 2) We have got 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 [22]); 3) The specula sapphire guides is an elegant solution for UCN extraction from pulsed UCN sources [20, 30, 34].

Conclusion

We have studied specula reflection of UCN on polished sapphire surface in the experimental conditions typical for UCN transport through neutron guides. The measured probability of the total losses was equal to $(4\pm9)\cdot10^{-4}$ per collision, which corresponds to the probability of specula reflection at least as high as 99.8 %. This is sufficient for UCN transport from a neutron source to an experimental installation to a distance of a few tens meters 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 realization of the idea 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 specula trajectories or for compact neutron gravitational spectrometers with high sensitivity for small samples. In particular, such guides could allow practical realization of a solid deuterium UCN source at the ILL with the density at the entrance to an experimental installation of $>10^4$ 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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