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).

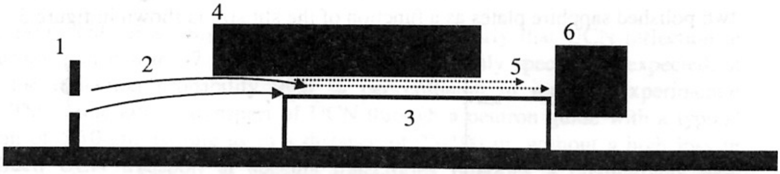

Figure 1. A principle scheme of the gravitational UCN spectrometer. From the left to the right the following: the vertical bold lines indicate the upper and lower plates of the input collimator (1); the solid arrows correspond to classical neutron trajectories (2) between the input collimator and the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

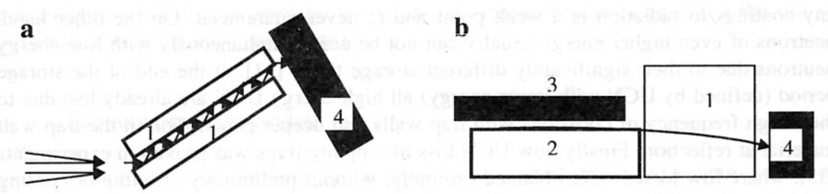

Figure 2. A scheme of the measurement of UCN transmission through a narrow long slit between two parallel vertical sapphire plates: a) view from above, b) side view. Arrows show the UCN beam. The two sapphire mirrors (1), the bottom glass mirror (2), the absorber (3) and the detector (4) are indicated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

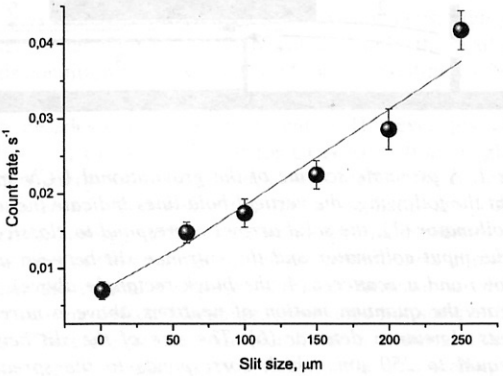

Figure 3. The total UCN flux between two vertical sapphire plates in function of the slit size is shown with circles. The solid curve corresponds to theoretical expectation, in which the probability of non-specular reflection is a free parameter.

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.

Acknowledgements

The author is grateful to colleagues without whom this work would not be possible: to V.N. Kurlov and P.A. Gurshijants for advice about properties of sapphire and for preparation of the samples, to colleagues in the collaboration on study of neutron quantum gravitational states for motivating this activity, to C. Krantz for help in the presented measurement, to ILL services for characterization of the samples.

References

1. P.G.Harris, C.A.Baker, K.Green, P.Iaydjiev, S.Ivanov, D.J.R.May, J.M.Pendlebury, D.Shiers, K.F.Smith, M. van der Grinten, P.Geltenbort (1999). Physical Review Letters **82**(5): 904-907.
2. I.S.Altarev, Yu.V.Borisov, N.V.Borovikova, S.N.Ivanov, E.A.Kolomenskii, M.S.Lasakov, V.M.Lobashev, V.A.Nazarenko, A.N.Pirozhkov, A.P.Serebrov, Yu.V.Sobolev, R.R.Tal'daev, E.V.Shulgina, A.I.Yegorov (1987). Physics Letters B **276**(1-2): 242-246.
3. Yu.V.Borisov, N.V.Borovikova, A.V.Vasilyev, L.A.Grigorieva, S.N.Ivanov, N.T.Kashukeev, V.V.Nesvizhevsky, A.P.Serebrov, P.S.Iadjiev (1988). Journal of Technical Physics **58**(5).
4. V.V.Nesvizhevsky, H.G.Börner, A.K.Petukhov, H.Abele, S.Baeßler, F.J.Rueß, Th.Stöferle, A.Westphal, A.M.Gagarsky, G.A.Petrov, and A.V.Strelkov (2002). Nature **415**: 297-299.
5. W.Mampe, P.Ageron, C.Bates, J.M.Pendlebury, A.Steyerl (1989). Physical Review Letters **63**(6): 593-596.
6. V.V.Nesvizhevsky, A.P.Serebrov, R.R.Tal'daev, A.G.Kharitonov, V.P.Alfimenkov, A.V.Strelkov and V.N.Shvetsov (1992). JETP **75**(3): 405-412.
7. W.Mampe, L.N.Bondarenko, V.I.Morozov, Yu.N.Panin, A.I.Fomin (1993). JETP Letters **57**(2): 82-87.
8. S.Arzumanov, L.Bondarenko, S.Chernyavsky, W.Drexel, A.Fomin, P.Geltenbort, V.Morozov, Yu.Panin, J.Pendlebury, K.Schreckenbach (2000). Physics Letters B **483**(1-3): 15-22.
9. A.Pichlmaier, J.Butterworth, P.Geltenbort, H.Nagel, V.V.Nesvizhevsky, S.Neumaier, K.Schreckenbach, E.Steichele and V.Varlamov (2000). Nuclear Instruments and Methods in Physics Research **440A**(3): 517-521.
10. A.Serebrov, N.Romanenko, O.Zherebtsov, A.Lasakov, A.Vasiliev, A.Fomin, P.Geltenbort, I.Krasnoshekova, A.Kharitonov, V.Varlamov (2005). Physics Letters A **335**(4): 327-336.
11. E.V.Lychagin, D.G.Kartashov, A.Yu.Muzychka, V.V.Nesvizhevsky, G.V.Nekhaev, A.V.Strelkov (2002). Physics of Atomic Nuclear **65**(11): 1996-1998.
12. V.V.Nesvizhevsky (2002). Physics of Atomic Nuclei **65**(3): 400-408.
13. A.Steyerl, H.Nagel, F.-X.Schreiber, K.-A.Steinhauser, R.Gähler, W.Gläser, P.Ageron, J.M.Astruc, W.Drexel, G.Gervais, W.Mample (1986). Physics Letters A **116**(7): 347-352.
14. A.Steyerl, S.S.Malik (1989). Nuclear Methods and Instruments in Physics Research **A284**: 200-207.
15. I.S.Altarev, Y.V.Borisov, A.B.Brandin, V.F.Ezhov, S.N.Ivanov, G.K.Katsman, V.M. Lobashev, V.A.Nazarenko, V.L.Ryabov, A.P.Serebrov, and R.R.Tal'daev (1980). Physics Letters A **80**: 413.
16. I.S.Altarev, N.V.Borovikova, A.P.Bulkin, V.V.Vesna, E.A.Garusov, L.A.Grigorieva, A.I.Egorov, B.G.Erozolimski, A.N.Erykalov, A.A.Zakharov, S.N.Ivanov, V.Ya.Kezerashvili, S.G.Kirsanov, E.A.Kolomenski, K.A.Konoplev, I.A.Kuznetsov, V.M.Lobashev, N.F.Maslov, V.A.Mityukhlyaev, I.S.Okunev, B.G.Peskov, Yu.V.Petrov, P.G.Pikulik, N.A.Pirozhkov, G.D.Porsev, A.P.Serebrov, Yu.V.Sobolev, R.R.Taldaev, V.A.Shustov, A.F.Shchebetov (1986). JETP Letters **44**(6): 344-348.
17. A.P.Serebrov, V.A.Mityukhlyaev, A.A.Zakharov, V.V.Nesvizhevsky and A.G.Kharitonov (1994). JETP Letters **59**(11): 757-762.
18. A.P.Serebrov, V.A.Mityukhlyaev, A.A.Zakharov, A.G.Kharitonov, V.V.Nesvizhevsky, M.S.Lassakov, R.R.Tal'daev, A.V.Alduschenkov,

V.E.Varlamov, A.V.Vasilyev, G.Greene and T.Bowles (1995). JETP Letters **62**(10): 785-790.

19. A.P.Serebrov, V.A.Mityukhlyaev, A.A.Zakharov, T.Bowles, G.Greene and J.Sromicki (1997). JETP Letters **66**: 802.
20. B.V.Bagrjanov, M.I.Kuvshinov, I.G.Smirnov, D.G.Kartashov, A.Yu.Muzychka, G.V.Nekhaev, A.D.Rogov, A.D.Stoica, A.V.Strelkov and V.N.Shvetsov (1999). Physics of Atomic Nuclei **62**(5): 844-850.
21. U.Trinks, F.J.Hartmann, S.Paul, and W.Schott (2000). Nuclear Methods and Instruments in Physics Research A **440**: 666.
22. I.Altarev, F.J.Hartmann, S.Paul, W.Scott, U.Trinks. Internal Report TUM-E18 (2000)
23. C.L.Morris, J.M.Anaya, T.J.Bowles, B.W.Fillipone, P.Geltenbort, R.E.Hill, M.Hino, S.Hoedl, G.E.Hogan, T.M.Ito, T.Kawai, K.Kirch, S.K.Lamoreaux, C.-Y.Liu, M.Makela, L.J.Marek, J.W.Martin, R.N.Mortensen, A.Pichlmaier, A.Saunders, S.J.Seestrom, D.Smith, W.Teasdale, B.Tipton, M.Utsuro, A.R.Young and J.Yuan (2002). Physical Review Lettes **89**: 272501.
24. C.-Y. Liu, S.K.Lamoreaux, A.Saunders, D.Smith and A.R.Young (2003). Nuclear Methods and Instruments in Physics Research A **508**: 257.
25. A.Saunders, J.M.Anaya, T.J.Bowles, B.W.Filippone, P.Geltenbort, R.E.Hill, M.Hino, S.Hoedl, G.E.Hogan, T.M.Ito, K.W.Jones, T.Kawai, K.Kirch, S.K.Lamoreaux, C.Y.Liu, M.Makela, L.J.Marek, J.W.Martin, C.L.Morris, R.N.Mortensen, A.Pichlmaier, S.J.Seestrom, A.Serebrov, D.Smith, W.Teasdale, B.Tipton, R.B.Vogelaar, A.R.Young, J.Yuan (2004). Physics Letters B **593**: 55-60.
26. R.Golub, D.J.Richardson and S.K.Lamoreaux (1991). Ultracold Neutrons. Bristol, Adam Higler.
27. R.Golub, and K.Boning (1983). Z. Phys. B **51**: 91.
28. Z.-Ch. Yu, S.S.Malik and R.Golub (1986). Z.Phys. B **62**: 137.
29. C.Y.Liu, A.R.Young and S.K.Lamoreaux (2000). Physical Review B **62**: R3581.
30. Yu.N.Pokotilovki (1995). Nuclear Methods and Instruments in Physics Research A **356**: 412.
31. R.Golub, and J.M.Pendlebury (1975). Physical Letters A **53**: 133.
32. C.A.Baker, J.Butterworth, P.Geltenbort, K.Green, M.G.D. van der Grinten, P.S.Iaydjiev, S.N.Ivanov, J.M.Pendlebury, D.B.Shiers, M.A.H.Tucker, and H.Yoshiki (2003). Physics Letters A **308**(1): 67-74.
33. V.K.Ignatovich, E.V.Lychagin, A.Yu.Muzychka, G.V.Nekhaev, V.V.Nesvizhevsky and A.V.Strelkov (2002). Physics of Atomic Nuclear **65**(3): 2029-2035.
34. A.I.Frank, and R.Gaehler (2000). Physics of Atomic Nuclei **63**:545.
35. ILL Internal Report TEST-691 (2004).
36. V.V.Nesvizhevsky, H.G.Börner, A.M.Gagarsky, G.A.Petrov, A.K.Petukhov, H.Abele, S.Baessler, T.Stöferle and S.M.Soloviev (2000). Nuclear Instruments and Methods in Physics Research **440A**(3): 754-759.

CONSTRAINTS FOR QUASI-ELASTIC REFLECTIONS OF NEUTRONS IN THE RANGE $\Delta E \sim 10^{-12}$-10^{-9} eV

Nesvizhevsky V.V.

Institut Laue-Langevin, Grenoble, France

Abstract

A restrictive constraint for any quasi-elastic process was obtained in the previously inaccessible energy range $\Delta E \sim 10^{-12}$-$3 \cdot 10^{-10}$ eV for reflections of ultracold neutrons from surfaces in the experiment on neutron quantum states in the earth's gravitational field. This could be useful for precision neutron spectrometry experiments and for the verification of extensions of quantum mechanics.

Introduction

One of the remarkable properties of ultracold neutrons (UCN) is their capacity for long storage in material traps with no significant change of their energy. This provides for a very broad range of applications for UCN in the investigation of neutron properties and their fundamental interactions: the measurement of the neutron lifetime [1-5]; the search for non-zero neutron electric dipole moment [6-7]; the study of the neutron quantum states in the gravitational field [8-9]; or the search for non-zero neutron electric charge [10] etc.

This precise conservation of UCN energy following their reflection from a surface is due to their long wavelength of ~10^2 A, which is two orders of magnitude larger than the average distance ~1 A between nuclei in reflecting matter. UCN are therefore reflected by the almost immovable average potential of a huge number of nuclei.

Residual thermal fluctuations of such a potential are extremely small due to the averaging of thermal fluctuations of a huge number of independent wall nuclei [11-12]. The probability of quasi-elastic scattering of UCN by the thermal fluctuations of a flat surface or by phonons in solids under normal conditions is expected to be equal to 10^{-14}-10^{-10} per collision. The energy change is 10^{-8}-10^{-7} eV - that is of the order of a typical effective potential. Such probability values are below present experimental sensitivity. The most sensitive upper limit was therefore measured at ~10^{-8} [13] per collision. Quasi-elastic neutron reflections with an energy change of 10^{-12}-10^{-9} eV are much less probable than this.

More intensive quasi-elastic scattering was observed at more weakly-bound surface areas. Thus, for the recently discovered phenomenon of coherent quasi-elastic scattering of UCN off weakly-bound surface nanoparticles in a state of permanent thermal motion [13], the probability of such scattering was as high as 10^{-8}-10^{-2} per collision with a surface containing nanoparticles, while the average energy transfer was 10^{-8}-10^{-7} eV per collision, as expected.

In both the cases mentioned the energy of the main fraction of reflected neutrons did not change significantly. Moreover, for UCN storage at a flat solid surface free of nanoparticles, all reflections need to be highly elastic. This property of UCN reflection allows us to investigate any fundamental process which would change UCN energy.

In particular, as discussed in refs. [14-15], an extension of quantum mechanics with an additional logarithmic term in the Schrödinger equation assumes quasi-elastic scattering of UCN at the surface, with extremely small, but nevertheless measurable, energy changes. Such spectral measurements with UCN of high resolution were themselves methodologically challenging. They were also motivated by a long-standing anomaly in the storage of UCN in traps [16]. These experiments [17-18] allowed the authors to constrain such quasi-elasticity at ~10^{-11} eV per collision, under the assumption of a "random walk" in phase space at each neutron collision with the wall: a non-zero result at this level was reported in ref. [17] at the limit of experimental sensitivity, but was not confirmed later in ref. [18], measured in the same setup with slightly better statistical sensitivity but with worse energy resolution.

A significant increase in the accuracy of neutron gravitational spectrometry was achieved in the recent experiment on quantum states of neutrons in the earth's gravitational field, using the high-resolution position-sensitive neutron detectors presented in ref. [19]. It has allowed us to improve many times over the upper limit for the probability and for the minimum energy transfer values for quasi-elastic scattering of UCN at the surface. Moreover, we can now consider energy changes at a single reflection, rather then having to follow the integral effects of many collisions, as in refs. [17-18]. In addition to this, the present limit concerns one specific component of the neutron velocity along the vertical axis before reflection and after it. Also any deviation from the conventional quantum mechanics can be verified in a more direct way in the quantum limit used here of the minimal possible initial energy, or velocity.

Such constraints, however, present a broader interest and could be considered in a more general model-independent way: how precisely do we know that UCN conserve their energy at wall reflections or during UCN storage in material traps?

Experiment

One should note that the present constrain was obtained as a by-product of the main experiment; the installation was not therefore optimized. It also contained extra components, not important for studying the quasi-elasticity (as, for instance, the mirror (2) in fig. 1). The experiment to study the quantum states of neutrons in the gravitational field, using position-sensitive neutron detectors [19-22], consists in the following.

A neutron beam with a horizontal velocity component of ~5 m/sec and a vertical velocity component of 1-2 cm/sec, which corresponds to the energy of the lowest neutron quantum state in the gravitational field above a mirror, is selected using a bottom mirror (1) and a scatterer/absorber (3) positioned above it at the height of ~20 μm. A second mirror (2) is installed lower by 21 μm than the first mirror (1). If the UCN bounce elastically on the mirror (2) surface in the zone between the scatterer's (3) exit edge and the position-sensitive detector (4), the measured spatial variation of the neutron density versus height would correspond to that shaped by the mirrors (1,2) and the scatterer (3) in the zone upstream of the scatterer's (3) exit edge. If they do not, then the excess number of neutrons observed in the higher position would be attributed to their quasi-elastic reflection from the mirror (2) surface. The experimental installation is designed in such a way that any known parasitic effects (vibration of the mirrors and the scatterer, residual magnetic field gradients, quasi-specular reflections of UCN from mirrors or at residual dust particles) should be small enough not to cause a significant change in the spectrum of vertical neutron velocities (see refs. [8-9,19-22]). The precision of the optical components' adjustment and the neutron detection resolution are equal to ~1 μm. The typical result of a few-days detector exposure in such an experiment is presented in fig. 2.

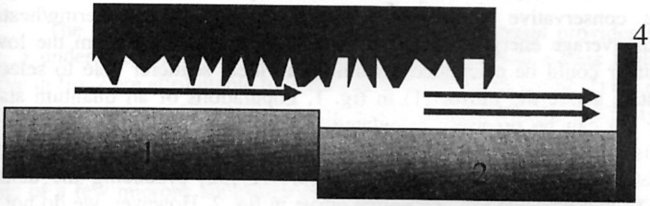

Fig. 1. Scheme of the experiment to study neutron quantum states in the gravitational field using position-sensitive neutron detectors. 1,2 – mirrors; 3 – scatterer/absorber; 4 – position-sensitive neutron detector. Horizontal arrows illustrate the neutron trajectories. The mirrors are optical glasses polished to the roughness of ~10 A.

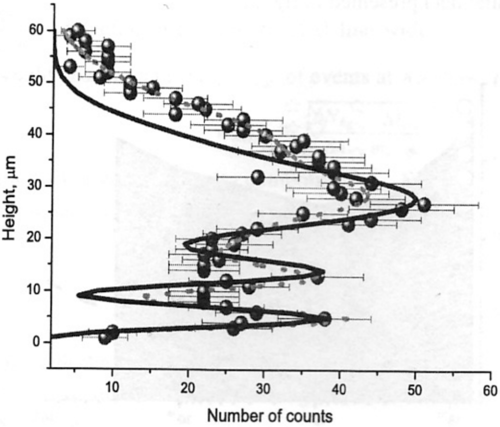

Fig. 2. The neutron density distribution in the gravitational field is measured using position-sensitive detectors of extra-high spatial resolution. The circles indicate experimental results. The solid curve corresponds to the theoretical expectation under the

assumption of an ideally efficient scatterer able to select a single quantum state above the mirror (1) and no parasitic transitions between the quantum states above the mirror (2). The dotted curve corresponds to the more realistic fit using precise wave-functions and free values for the quantum states populations. The detector background is constant in the range from -3 mm to +3 mm below and above the presented part of the detector.

Constraint on a quasi-elastic reflection

We shall not discuss the physical reasons and conditions for possible quasi-elastic reflections of UCN at surfaces; we shall just consider this problem in phenomenological terms. A simple conservative upper limit for the quasi-elastic scattering/heating probability (versus average energy transfer) following UCN reflection from the lower polished glass mirror could be calculated, assuming an ideal scatterer able to select a single quantum state above the mirror (1) in fig. 1. Populations of all quantum states above the mirror (2) can be precisely calculated in this case [20]. They provide the neutron density distribution, presented by the solid curve in fig. 2. Actually we know that a few neutrons at higher quantum states should survive [22] producing the density distribution close to that presented by the dotted curve in fig. 2. However, we do not try to take such neutrons into account intentionally sacrificing the sensitivity of the present limit in favour of maximum reliability and transparency. Such an estimation could be further improved with the present experimental data using more sophisticated theoretical analysis based on ref. [22]. It would however be slightly model-dependent in such a case. For the simplified approach chosen, the solid line in fig. 2 is considered as "background" for the measurement of quasi-elasticity and any additional events above this line would be supposed to be due to quasi-elastic scattering. Fig. 3 illustrates the results of the treatment of the experimental data presented in fig. 2.

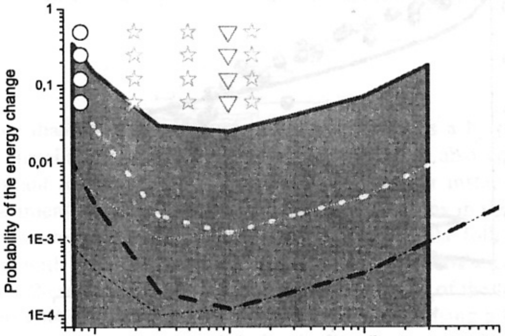

Fig. 3. The solid curve corresponds to constraints for quasi-elastic scattering of UCN at a flat glass surface: the total probability of such a scattering per one quasi-

classical bounce versus average energy transfer at "3σ" confidence level. The dotted curve shows the possible improvement of such constraints in the flow-through measuring mode. The dashed curve indicates a further increase in sensitivity in the storage measuring mode. The circles correspond to theoretical predictions for the present experiment in accordance with refs. [14-15, 17]. The stars indicate analogous predictions for measurements with the experimental installation [8-9, 19-22] inclined to various angles. The triangles show the value of the energy change expected in refs. [14-15, 17] (for a higher initial neutron velocity than that in the present experiment). The thin dotted and dashed curves indicate schematically the constraints, for which the initial spectral shape line would be taken into account.

The straightforward calculation of such a constraint provides the solid curve in fig. 3 under the following assumptions: 1) all additional events higher than the solid curve in fig. 2 are attributable to quasi-elastic scattering/heating; 2) the energy is assumed to change in one step (due to the low probability of such an event); 3) we take the number of quasi-classical collisions in such a system [22].

The rather sharp decrease with height of the neutron density at a characteristic scale of a few microns simplifies considerably the present calculation. For large enough ΔE values, any excess counts above the constant background level $\frac{\Delta N_{bg}}{\Delta h}$ in the height range $h > 60\mu m$ are attributed to quasi-elastic scattering/heating. Quasi-elastically scattered neutrons could be observed at any height between zero and $\frac{E_0 + \Delta E}{m_n \cdot g}$, where E_0 is the initial energy of vertical motion, ΔE is the energy gain, m_n is the neutron mass, and g is the gravitational acceleration. If $\Delta E >> E_0$, the total number of background events is $\sim \frac{\Delta N_{bg}}{\Delta h} \cdot \frac{\Delta E}{m_n \cdot g}$, neglecting the initial spectral line width $h < 60\mu m$. At "$3 \cdot \sigma$" confidence level, we would observe an excess $N_{q.el.}$ of events at $h > 60\mu m$, if it is equal to:

$$N_{q.el.} = 3 \cdot \sqrt{\frac{\Delta N_{bg}}{\Delta h} \cdot \frac{\Delta E}{m_n \cdot g}} \tag{1}$$

With the horizontal velocity component V_{hor} and the mirror length L between the scatterer's exit edge and the detector (see fig. 1), the total number $N_{q.cl.}$ of quasi-classical bounces is:

$$N_{bounces} = \frac{L}{\frac{2}{g} \cdot \sqrt{\frac{2 \cdot E_0}{m_n}} \cdot V_{hor}} \tag{2}$$

Thus, with the total number N_0 of neutrons in the initial spectral line, we would be able to observe quasi-elastic scattering at "$3 \cdot \sigma$" confidence level if its probability $P_{q.el.}(\Delta E)$ is equal to:

$$P_{q.el.}(\Delta E) = \frac{N_{q.el.}}{N_0 \cdot N_{bounce}} = \frac{3}{N_0 \cdot L} \cdot \sqrt{\frac{\Delta N_{bg}}{\Delta h} \cdot \frac{\Delta E}{m_n \cdot g}} \cdot \frac{2}{g} \cdot \sqrt{\frac{2 \cdot E_0}{m_n}} \tag{3}$$

As is evident from eq. (3), $P_{q.el.}(\Delta E)$ increases as $\sqrt{\Delta E}$, thus decreasing sensitivity of the present constraint at large energy changes. The sensitivity is also lower at energy changes smaller than the initial spectral line width of ~60 μm (here the constraint is estimated numerically). Therefore the best sensitivity is achieved at the energy change comparable to one or few initial spectral line widths, as shown in fig. 3.

Analysis and prospects for strengthening constraint

The presented constraint shows the high degree of elasticity of neutron reflections in the range $\Delta E \sim 10^{-12}$-$3\cdot10^{-10}$ eV; this is important for the further development of precision neutron spectrometry experiments. Further improvements in the sensitivity of such constraints by an order of magnitude are feasible in the flow-through measuring mode, by improved shielding of the neutron detectors (a factor $\sqrt{\frac{\Delta N_b}{\Delta h}}$ in eq. 3), by increasing the length of the bottom mirror (a factor $\frac{1}{L}$ in eq. 3), by further increasing the scatterer efficiency, and by using of more narrow initial neutron spectrum (a factor $\sqrt{E_0}$ in eq. 3). On the other hand, a broader initial spectrum could allow us to increase a factor N in eq. 3 and to improve therefore the sensitivity at higher ΔE values (sacrificing the sensitivity at lower ΔE values).

An almost order-of-magnitude gain in minimal measurable energy change could be achieved by providing a proper theoretical account (in accordance with ref. [22], for instance) of the spectrum-shaping properties of the scatterer, or by a differential measurement of the vertical spectrum evolution using bottom mirrors of different length. Possible improvements in the flow-through mode are illustrated by the dotted curve in fig. 3. One should note that any jumps in energy by the value significantly lower than 1 peV would clearly contradict to the observation of quantum states of neutrons in the gravitational field [8-9, 19-22] and therefore they are not analyzed in the present article. The minimal considered energy increase corresponds to the energy difference between neighboring quantum states in the gravitational field.

A much higher increase in sensitivity could be achieved in the storage measuring mode with the long storage of UCN at specular trajectories in a closed trap (the dashed curve in fig. 3 or better).

As an example of a possible application of the present constraint, let us compare it to the theoretical prediction in accordance with refs. [17-18]. This model assumes the replacement of "continuous interaction" of UCN with a gravitational field by a sequence of "collisions with the field". The time interval $\delta\tau$ between the "collisions" is defined as the time during which the mass "does not know that there is an interaction" since the kinetic energy change δE (by falling) is too small to be resolved. From the uncertainty principle:

$$\delta\tau\cdot\delta E = \frac{\hbar}{2}, \text{ or } \delta E = \sqrt{\frac{\hbar\cdot m_n\cdot g\cdot V_{vert}}{2}} = \sqrt{33\cdot V_{vert}}\,(peV) \qquad (4)$$

where $V_{vert}[m/s]$ and $peV = 10^{-12}eV$.

For the vertical velocity component $V_{vert} \sim 2.5cm/s$ in our present experiment, the expected energy change is $\delta E \sim 8 \cdot 10^{-13} eV$ (shown as the circle in fig. 3). The "100%" probability of quasi-elastic scattering is slightly higher than the "$3 \cdot \sigma$" experimental constraint (the solid line in fig. 3). However, considering the expected probability value of ~10% and low experimental sensitivity at small ΔE values, one needs to further improve the sensitivity of present constrain.

On the other hand, a slight modification of the experimental setup would allow one to verify clearly the considered hypothesis. Namely, the whole apparatus should be turned by a significant angle relative to the direction of the gravitational field. In this case, the vertical velocity component is comparable to the longitudinal velocity of 5-10 m/s. The transversal velocity component (relative to the bottom mirror) is very small, just equal to that in the experiment [8-9, 19-22]. All sensitivity estimations for quasi-elastic scattering/heating are analogous to those given above (see fig. 3). However, the theoretically predicted effect could be as high as $\sim 10^{-11}$ eV (as a function of the inclination angle) – just in the range of the best sensitivity of the present constraint: the stars in fig. 3. In order to measure a hypothetical cooling of UCN at their quasi-elastic reflections one should preliminary select a higher quantum state (n>1) and then to follow evolution of the corresponding neutron spectrum. The sensitivity estimations in the energy range $0 < \Delta E < E_0$ would be about as strong as those for the quasi-elastic heating if the experiment is optimized for this purpose. Such measurements would be significantly easier to perform than the measurement of the gravitationally bound quantum states because they do not require such record levels of energy and spatial resolution.

Conclusion

As a side-product of the experiment to study the neutron quantum states in the earth's gravitational field, we have constrained the quasi-elastic interaction of neutrons with flat solid surfaces in an energy transfer range of 10^{-12}-10^{-9} eV, a range not previously accessible for experiments with neutrons. This constraint could be useful for precision neutron spectrometry experiments, in particular for those using the neutron quantum states in the gravitational field [23], and also for the verification of various extensions of quantum mechanics. The constraint obtained from measurements with inclined bottom mirrors could reliably verify the hypothesis [14-15, 17] of the slight spectral evolution of UCN during their storage in traps. Further improvements in sensitivity by many orders of magnitude could be obtained, if they present further methodical or theoretical interest.

Acknowledgement

The author is grateful to prof. A.Steyerl for discussions and clarification of the theoretical hypothesis considered.

References:

1. W.Mampe, P.Ageron, C.Bates, J.M.Pendlebury, A.Steyerl, *Physical Review Letters* **63**(6), 593 (1989).
2. V.V.Nesvizhevsky, A.P.Serebrov, R.R.Tal'daev, A.G.Kharitonov, V.P.Alfimenkov, A.V.Strelkov and V.N.Shvetsov, *JETP* **75**(3), 405 (1992).
3. W.Mampe, L.N.Bondarenko, V.I.Morozov, Yu.N.Panin, A.I.Fomin, *JETP Letters* **57**(2), 82 (1993).
4. S.Arzumanov, L.Bondarenko, S.Chernyavsky, W.Drexel, A.Fomin, P.Geltenbort, V.Morozov, Yu.Panin, J.Pendlebury, K.Schreckenbach, *Physics Letters B* **483**(1-3), 15 (2000).
5. A.Pichlmaier, J.Butterworth, P.Geltenbort, H.Nagel, V.V.Nesvizhevsky, S.Neumaier, K.Schreckenbach, E.Steichele and V.Varlamov, *Nuclear Instruments and Methods in Physics Research* **440A**(3), 517 (2000).
6. I.S.Altarev, Yu.V.Borisov, N.V.Borovikova, S.N.Ivanov, E.A.Kolomenskii, M.S.Lasakov, V.M.Lobashev, V.A.Nazarenko, A.N.Pirozhkov, A.P.Serebrov, Yu.V.Sobolev, R.R.Tal'daev, E.V.Shulgina, A.I.Yegorov, *Physics Letters B* **276**(1-2), 242 (1987).
7. P.G.Harris, C.A.Baker, K.Green, P.Iaydjiev, S.Ivanov, D.J.R.May, J.M.Pendlebury, D.Shiers, K.F.Smith, M. van der Grinten, P.Geltenbort, *Physical Review Letters* **82**(5), 904 (1999).
8. V.V.Nesvizhevsky, H.G.Börner, A.K.Petukhov, H.Abele, S.Baeßler, F.J.Rueß, Th.Stöferle, A.Westphal, A.M.Gagarsky, G.A.Petrov, and A.V.Strelkov, *Nature* **415,** 297 (2002).
9. V.V.Nesvizhevsky, H.G.Börner, A.M.Gagarski, A.K.Petukhov, G.A.Petrov, H.Abele, S.Baeßler, G.Divkovic, F.J.Rueß, T.Stöferle, A.Westphal, A.V.Strelkov, K.V.Protasov, A.Yu.Voronin, *Physical Review D* **67**,102002 (2003).
10. Yu.V.Borisov, N.V.Borovikova, A.V.Vasilyev, L.A.Grigorieva, S.N.Ivanov, N.T.Kashukeev, V.V.Nesvizhevsky, A.P.Serebrov, P.S.Iadjiev, *Journal of Technical Physics* **58**(5), 1 (1988).
11. S.T.Belyaev, A.L.Barabanov, *Nuclear Methods and Instruments in Physics Research* **440A**(3), 704 (2000).
12. V.V.Nesvizhevsky, *Physics of Atomic Nuclear* **65**(3), 400 (2002).
13. E.V.Lychagin, D.G.Kartashov, A.Yu.Muzychka, V.V.Nesvizhevsky, G.V.Nekhaev, A.V.Strelkov, *Physics of Atomic Nuclear* **65**(11), 1996 (2002).
14. A.Steyerl, S.S.Malik, *Annals of Physics* **217**(2), 222 (1992).
15. A.Steyerl, S.S.Malik *Physics Letters A* **217**(4-5), 194 (1996).
16. V.P.Alfimenkov, A.V.Strelkov, V.N.Shvetsov, V.V.Nesvizhevsky, A.P.Serebrov, R.R.Tal'daev and A.G.Kharitonov, *JETP Letters* **55**(2), 84 (1992).
17. A.Steyerl, S.S.Malik, P.Geltenbort, S.Neumaier, V.V.Nesvizhevsky, M.Utsuro and Y.Kawabata, *Journal de Physique III* **7**(10), 1941 (1997).
18. T.Bestle, P.Geltenbort, H.Just, Y.Kawabata, S.S.Malik, V.V.Nesvizhevsky, S.Neumaier, K.Okumura, A.Steyerl and M.Utsuro, *Physics Letters A* **244**(4), 217 (1998).
19. V.V.Nesvizhevsky, H.G.Börner, A.M.Gagarsky, G.A.Petrov, A.K.Petukhov, H.Abele, S.Baessler, T.Stöferle and S.M.Soloviev, *Nuclear Instruments and Methods in Physics Research A* **440**(3), 754 (2000).
20. V.V.Nesvizhevsky, *Uspekhi Fizicheskikh Nauk* **47**(5), 515 (2004).
21. V.V.Nesvizhevsky, H.G.Boerner, A.K.Petoukhov, A.M.Gagarski, G.A.Petrov, L.Lukovac, H.Abele, S.Nahrwold, S.Baessler, S.Raeder, T.M.Kuzmina, J.Schrauwen, V.M.Tischenko, K.V.Protasov, A.Yu.Voronin. Grenoble, Institute Laue-Langevin Annual report 2004 (unpublished).
22. V.V.Nesvizhevsky, A.K.Petukhov, H.G.Boerner, T.A.Baranova, A.M.Gagarski, G.A.Petrov, K.V.Protasov, A.Yu.Voronin, S.Baessler, H.Abele, A.Westphal, L.Lukovac, hep-ph/0502081.
23. V.V.Nesvizhevsky, K.V.Protasov (2005), (unpublished).