Reply to "Comment on 'Measurement of quantum states of neutrons in the Earth's gravitational field' "

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Possible false effects in the experiment on the measurement of quantum states of neutrons in the Earth's gravitational field are discussed. It is shown that the measured quantum states are defined mainly by a mirror and the gravitational field.

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Experimental evidence for the observation of the lowest quantum state of neutrons in the Earth's gravitational field was reported in [1]. The neutron transmission through a horizontal slit between a mirror and an absorber/scatterer was measured there as a function of the slit size Δh. The "signature" for the observation of the neutron quantum states in the potential well, formed by the gravitational field and a mirror, consisted of an abrupt change in the neutron transmission at a slit size approximately equal to the "height" of the lowest quantum state of $\sim 15\ \mu$m. The most probable false effects in this experiment were analyzed carefully in [1]. Other possible false effects are considered in the Comment [2], which states the following.

(1) The geometrical effects ("box" quantum states of neutrons between a mirror and nonperfect absorber/scatterer) could mimic the results attributed to gravity. A potential consisting of two infinite walls—a "neutron in an infinite box" (a mirror plus a nonperfect absorber/scatterer) produces quantum states with energies close to those in the Earth's gravitational field.

(2) To verify the importance of the "box" states one should turn the whole setup by 90 degrees so that the gravitational field effect would be "switched off." The "inverse geometry" experiment (180° rotation) is not sufficient to prove the nature of the states.

We will comment on these two main statements and show that we had considered the "box" quantum states and carried out this experiment in such a way that they cannot disturb at the currently achieved level of accuracy, and that they cannot explain the main observation of our experiment.

(1) There is nothing surprising in an approximate equality of neutron quantum energies in the Earth's gravitational field above a mirror and those in the potential box formed by two infinitely high potential walls. For a neutron in any deep confining potential of a range of $\sim 20\ \mu$m, the energy of the ground state, due to the uncertainty principle, is ~ 1 peV. The energy of the "box states" can be "adjusted" by varying the slit size and naturally therefore it can even be made precisely equal to the energy of the first gravitational level. However, we did not measure the energy. Instead we measured the transmission of neutrons through the slit between a mirror and an absorber/scatterer. While the authors of the Comment [2] are aware of this fact, they limit their discussion to the comparison of the energies and do not try to explain the measured transmission-versus-height curve and they do not discuss the lifetime of box states with higher energy.

(a) The box-like states should exist, in principle, for any slit size. In absence of the gravity, the energy E_n of the nth quantum state is a smooth function of the slit size Δh: $E_n = (\hbar^2/2m)(2\pi n/\Delta h)^2$, where $\hbar$ is the Planck constant and m is the neutron mass. E_1 for box states approaches zero if $\Delta h \rightarrow \infty$. Therefore there is no reason to have the observed sharp increase in the neutron transmission at the slit size of $\sim 15\ \mu$m.

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If one takes into account the Earth's gravitational field then the quantum state energies in the slit cannot approach zero value with the slit size increase. The lowest quantum state approaches $\sim$1.4 peV even for the infinitely high slit size. The "height" of the lowest quantum state in the Earth's gravitational field can be defined rather precisely, because the neutron wave function in the lowest quantum state decreases as $\exp\{-\frac{2}{3}((h-h_1)/h_0)^{3/2}\}$ above some characteristic value, $h_1 = 13.7\ \mu$m. This height corresponds to the classical turning point of a neutron with given energy in the gravitational field. $h_0 = 5.87\ \mu$m provides the characteristic scale for the problem. This sharp decrease in the probability to find a neutron above its classical turning point leads to a step-like increase in the neutron transmission for the slit size above h_1, as the overlap between the neutron wave function and the absorber/scatterer approaches zero in this case.

(b) One has to investigate not only the energy but the lifetime (or width) of a corresponding state. To do that, in our previous article, we developed a microscopic model sufficiently more sophisticated than that proposed in the Comment [2]. In our model, the potential is formed by a mirror, by the gravitational field, and by an absorber. The latter one was considered as a complex potential with big imaginary part (strong absorption). The obtained results were presented in Figs. 6 and 7 in [1] (see also [3]). From Fig. 7, one sees clearly that, for a small slit size Δh, the energy dependence from Δh scales as $(\Delta h)^{-2}$, i.e., like in a box formed by a mirror and an absorber. However, the lifetime (Fig. 6) of this state is extremely short (with respect to the average time of flight of neutrons through the mirror and absorber/scatterer slit): these states quickly die and there are no neutrons transmitted through the slit. Once Δh is big enough, the ground state energy tends to that in the gravitational field, the lifetime becomes comparable with the average time of flight, i.e., the ground state appears and one observes a sharp increase in the neutron transmission.

(c) Let us consider the general behavior of the count rate $N(\Delta h)$ for large Δh. For the gravitational-like states and efficient absorber/scatterer one obtains experimentally a $(\Delta h)^{3/2}$ behavior as expected from classical [formula (5) in [1]] or from quantum mechanical treatment [formula (8)]. The box-like states follow a different law. In our experiment we investigated the case with two mirrors and one obtained a behavior where the energy scales with Δh [formula (6) in [1]]. This measurement was repeated in more details in a second experiment in 2002, and will be published soon.

One should underline that the absorber/scatterer efficiency was measured in [1] using different methods and it was sufficiently high: comparable to a unit in a quasiclassical approximation. This fact allows selection of one or a few quantum states only, in contrast to the "box" potential with many quantum states. One more argument related to the experiment with the reverse geometry is discussed below.

(2) We agree that the importance of the "box" quantum states can be verified by turning the whole apparatus by 90°. This option was considered when designing our experiment but it was rejected due to technical reasons: the turning of the whole setup by 90° is not possible with the chosen absorber/scatterer positioning system and many other components of the installation. Such a test would be welcomed, but it would require to build a new experimental installation.

On the other hand, the main idea of such a "zero" experiment—to "change" the gravitational field in order to verify the measured results—was used in [1]. Instead of turning the device by 90° (in order to switch off the effect of the gravitational field) we turned it by 180° (in order to reverse the gravitational field sign with respect to the mirror and absorber/scatterer)—see Fig. 5(b) in [1]. One can see a very important measured difference in the neutron transmission in these two geometries (by a factor of $\sim$25). The box-like states would be not sensitive at all to this change. Note that the argument in the Comment [2] about a possible importance of 3 cm difference between a mirror and an absorber/scatterer is not valid. The "inverse geometry" experiment was carried out with a quite big slit size where a significant part of neutrons had energies high enough to "jump over" these 3 cm and thus their density was not so much suppressed. The width and the angular divergence in the neutron beam at the entrance to the mirror-absorber slit were by a factor of $\sim$10 larger than the size of the slit and the angular acceptance of the spectrometer, respectively. Besides that the neutron transmission in the direct geometry does not depend noticeably on the mirror-absorber slit length (as soon as it is sufficiently long to remove higher states) and therefore the 3-cm difference in the direct and inverse geometry is not important from this point of view as well.

Finally, there is another possibility to investigate this system using a position-sensitive detector with extra-high spatial resolution. In contrast to doubts about its practical feasibility expressed in [2], this experiment is actually possible. A position-sensitive detector with the spatial resolution of $\sim$1 μm was proposed in [4], tested [5], and used in the second run of our experiment (in 2002). The results of this measurement are not yet published and therefore could not be known to the authors of the Comment [2]. An absorber/scatterer in this measurement was used for the preliminary shaping of the neutron spectrum only, and therefore it did not disturb the corresponding neutron wave functions. In this case a discussion of "box" states cannot be applied: there was no absorber/scatterer above mirror in front of the detector. A detailed description and theoretical analysis of the results of the second run of our experiment will be published soon.

To summarize: We have shown that geometrical effects as suggested in [2] cannot mimic the gravity effect. In the actual experiment [1] the measured quantum states are defined mainly by a mirror and the Earth's gravitational field.

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