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A joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) and the Joint Physical Society of the Russian Federation was held on 29 October 2003 at the P N Lebedev Physics Institute, RAS. The following reports were presented at the session:

(1) **Strelkov A V** (Joint Institute for Nuclear Research, Dubna, Moscow Region) *Neutron storage*;

(2) **Nesvizhevskii V V** (Institut Laue – Langevin, Grenoble, France) *Investigation of quantum neutron states in the terrestrial gravitational field above a mirror*.

A brief presentation of the reports is given below.

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Neutron storage

A V Strelkov

While the storage of charged particles localized in a volume presents no serious difficulties, the very feasibility of such a trap for neutrons, which are devoid of electric charge, was rejected by E Rutherford in 1920 — long before the discovery of the neutron. Predicting the existence of the neutron, he wrote: "... the electron may be coupled much stronger with the H nucleus forming a kind of neutral doublet. The atom would then have quite peculiar properties. Its external field would be practically zero, ... and it may be impossible to contain it in a sealed vessel" [1, p. 396]. The development of a neutron trap attracts the attention of researchers due to the possibility (compared to a single neutron flight through an experimental volume) of observing trapped neutrons for a longer time, which furnishes a significant increase in the accuracy and sensitivity of experimental research on neutron – field and neutron – matter interactions.

Almost half the ambient substance consists of neutrons contained in atomic nuclei. In the free state, however, neutrons exist only in the period between the instant of escape from the nucleus (as the result of one nuclear reaction or another) and absorption into a substance. As shown in Fig. 1, fast neutrons that leave the source *1* (a reactor or an accelerator) collide with moderator nuclei to lower their energy down to the thermal vibrational energy of the moderator nuclei. Therefore, even the moderator *2* in some sense is in itself a neutron trap for thermal neutrons, but the neutron storage time does not exceed ~ 0.1 s even in weakly capturing moderators. Thermal neutrons, which have a near-Maxwellian velocity distribution, leave the moderator, and the slowest neutrons of this distribution that find their way into the vessel *3* may, on actuation of the shutoff gate, be confined in the vessel like a rarefied gas and experience multiple collisions with the walls.

Ya B Zel'dovich, A I Alikhanov, A I Akhiezer, I Ya Pomeranchuk, and E L Andronikashvili spoke of the possibility of storing very cold neutrons in the 1950s, but it was not until 1959 that Zel'dovich summarized their opinions by publishing a brief paper on this subject [2]. He called attention to the fact that slow neutrons, which experience total internal reflection at grazing incidence on the surface of the majority of materials, cannot penetrate such a material at all, even at normal incidence, if their velocity is low enough. Therefore, the possibility was opening up for the implementation of the long-term storage of neutrons locked in cavities of weakly neutron-absorbing materials (beryllium, graphite, etc.), from which they can disappear only as they decay, with a period of about 12 min.

The optical potential which accounts for neutron reflection from a surface was introduced by Fermi to describe the shift in optical atomic spectral lines versus pressure in a gas light source back in 1934 [3]. Later, he applied this method to explain the total reflection of neutrons from the surface. With the advent of atomic reactors — high-power neutron sources — in the early 1940s, Fermi for the first time determined the values of neutron scattering amplitudes for a number of elements by directing thermal neutron beams at small angles to the surface and measuring the magnitude of the maximum possible normal component (depending only on the optical potential of the material). In principle, at that time Fermi could have implemented a neutron trap made of conventional materials. It remains a mystery why he did not do this. As recounted by B M Pontekorvo [4], when talking to him, Fermi used to dream of a 'neutron bottle'. On the other hand, even in

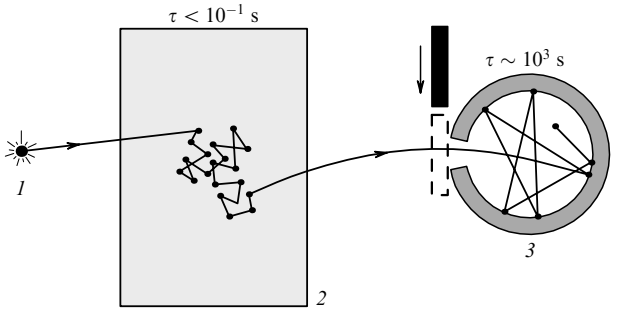

Figure 1.

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1950 Fermi opined on the impossibility of making such 'bottles', saying that '... there exist, unfortunately, no vessels capable of keeping neutrons...' [5].

A year after the publication of Zel'dovich's paper, Vladimirskii [6] came up with the idea of storing slow neutrons in magnetic bottles by taking advantage of the existence of the magnetic moment of the neutron. In addition, his thorough paper introduced, as a development of Zel'dovich's idea, the idea of a converter (internal moderator) with assessment of its operating efficiency, proposed the use of vacuum channels for neutron transportation, and presented estimates of the effects of gravity and wall vibrations on the neutron storage in traps. The term 'ultracold neutrons' (UCNs), i.e., neutrons that have the capacity to be confined in traps, was first introduced in that paper. The term UCN is attributable to the fact that gas molecules for $T \sim 10^{-3}$ K possess about the same energy.

The neutron-reflecting potential of the trap wall is defined by the average value (with the averaging made over the volume of the vessel wall material) of the real neutron-nucleus interaction potential; for slow neutrons, use can be made of the Fermi quasi-potential instead:

$$U(\mathbf{r}) = \frac{h^2}{2\pi m}\, b\delta(\mathbf{r} - \mathbf{r}_0)\,,$$

where h is the Planck constant, m is the neutron mass, $\delta(\mathbf{r} - \mathbf{r}_0)$ is the delta function ($\mathbf{r}_0$ is the radius-vector of a nucleus), and b is the coherent scattering length for neutron scattering by bound nuclei, which is determined from the measurements of the cross section for neutron scattering by these nuclei: $\sigma_s = 4\pi b^2$. UCNs possess a relatively long de Broglie wavelength (~ 500 Å), which far exceeds the interatomic distances (~ 2 Å), and therefore the volume-averaged Fermi quasi-potential is the effective wall potential:

$$U_{\text{eff}} = \frac{h^2}{2\pi m}\, bN\,.$$

Here, N is the volume density of nuclei with the scattering length b.

The same expression for the effective potential is obtained by exactly solving the Schrödinger equation in the theory of multiple wave scattering based only on the amplitude of scattering by a single nucleus regardless of what potential generates this amplitude. For the majority of nuclei $b > 0$, and hence, U_{eff} is also positive for the materials of these nuclei. To penetrate into the material from a vacuum, neutrons must overcome the repulsive action of the material at the interface. When the kinetic neutron energy is lower than U_{eff}, the neutrons cannot find their way into the material at any angles of incidence whatsoever. This repulsive action of the material trap wall on neutrons is caused only by the strong neutron – nucleus interaction, which is on the order of 10 MeV. However, owing to the short range of the nuclear forces and the small nuclear volume, the quantity U_{eff} (which plays the role of the work function in the transition of a neutron from a vacuum into the material) turns out to be very small ($\sim 10^{-7}$ eV). The effective potential exhibits a relatively small dispersion of values for different materials (within one order of magnitude), because the cross section for neutron scattering by nuclei and the interatomic distance do not vary strongly from material to material ($\sigma_s \sim 3-10$ barn, $d \sim 2$ Å). The kinetic neutron energy corresponding to U_{eff} is termed the limiting UCN energy (E_{lim}) for a given wall. UCNs with $E \lesssim 10^{-7}$ eV have velocities $v \lesssim 5$ m s^{-1}, wavelengths $\lambda \gtrsim 500$ Å, and effective temperatures $T \lesssim 10^{-3}$ K. While reflecting from a wall, a UCN penetrates it by a very small depth:

$$X = \frac{h}{\sqrt{2mU_{\text{eff}}}} \approx 150 \text{ Å}\,.$$

While inside the wall material, UCNs may either perish due to the capture by nuclei or accelerate (and escape the UCN range) by gaining energy from the thermal nuclear vibrations (inelastic scattering). The UCN losses arising in these processes are described by adding to the effective potential a relatively small imaginary part, which is expressed by the dimensionless parameter

$$\eta = -\frac{\operatorname{Im} U_{\text{eff}}}{\operatorname{Re} U_{\text{eff}}} = -\frac{\operatorname{Im} b}{\operatorname{Re} b}\,.$$

On the strength of the optical theorem,

$$\operatorname{Im} b = -\frac{m}{2h}\,\sigma_{\text{tot}} v\,,$$

where σ_{tot} is the total neutron – material interaction cross section. The processes prevailing at low velocities are the capture and the inelastic scattering, which obey the $1/v$ law, and therefore the parameter η is independent of the UCN velocity and is in the $\sim 10^{-4} - 10^{-5}$ range for the majority of materials. The likelihood of losing a UCN in a single collision with the wall is $\mu = \eta\, v/v_{\text{lim}}$. Therefore, prior to its disappearance (due to its capture or heating) a UCN in a vessel can experience over 10^5 collisions, which corresponds to a storage time of $\sim 2 \times 10^3$ s in a trap measuring ~ 10 cm.

The effective potential of the vessel wall 'does not sense' the discreteness of the medium. Nor is it affected by the permanent thermal nuclear motion, because this random motion of atoms (nuclei) is averaged over an area measuring λ^2, which is defined by the UCN wavelength. This averaging does not take place in the regular translational motion of atoms at the wall surface (long-wavelength phonons, acoustic vibrations, and the motion of the wall as a whole), which may strongly change the UCN reflection coefficient of the surface and thereby reduce the UCN storage time. That is why UCNs stored in a vessel may sequentially experience a great number of elastic reflections from the vessel walls even in the case where the kinetic energy of the nuclei of the vessel walls at normal temperature ($\sim 10^{-2}$ eV) far exceeds the kinetic energy of the stored UCNs ($\sim 10^{-7}$ eV). Therefore, the stored neutron gas with $T \sim 10^{-3}$ K is rather well 'heat-insulated' from the vessel walls, which have a temperature of ~ 300 K, and the storage itself is a highly nonequilibrium process. In the long run UCNs are bound to assume the temperature of the vessel walls, but the time of this relaxation in some cases is far greater than the neutron beta-decay period, which will determine the time of UCN storage in the trap.

It is noteworthy that in 1966 L Foldy [7] proposed, independently of Zel'dovich, a bottle for neutrons with liquid helium walls. However, he allowed only equilibrium storage, whereby the stored neutron temperature would not exceed the wall temperature ($\sim 10^{-4}$ K). Years had passed after Zel'dovich's paper first appeared, but no one would venture to stage an experiment on neutron storage. At first,

physicists regarded the phenomenon of a neutron bottle as an exotic, amusing, unfeasible, and useless toy. Pessimism was added by I I Gurevich and L V Tarasov, the authors of a comprehensive monograph on slow neutrons [8], who stated that UCNs 'are unlikely to find use in experiments' owing to the extreme smallness of their fraction in the Maxwellian spectrum of thermal neutrons from a reactor. In such a spectrum, the flux of UCNs with an energy ranging from 0 to $E_{\rm lim}$ is

$$\Phi_{\rm UCN} = \frac{1}{8}\,\Phi_{\rm T}\left(\frac{E_{\rm lim}}{kT}\right)^2,$$

where $\Phi_{\rm T}$ is the total thermal neutron flux from the moderator and T is the neutron gas temperature in the moderator. Employing cooled moderators can substantially augment the fraction of UCNs in the spectrum but only to a certain limit, beyond which the neutron temperature ceases to decrease (owing to the neutron capture and the finite dimensions of the moderator), in spite of the further lowering of the moderator temperature. For $T = 300$ K, $E_{\rm lim} = 1.7 \times 10^{-7}$ eV (for copper), $\Phi_{\rm UCN} \approx 6 \times 10^{-12}\Phi_{\rm T}$. For a reactor with $\Phi_{\rm T} \sim 10^{14}$ cm^{-2} s^{-1}, the UCN flux will be ~ 600 cm^{-2} s^{-1} and the volume density of UCNs near the moderator $\rho \approx 16\,\Phi_{\rm UCN}/3v \approx 0.5$ cm^{-3}. Of course, this density will be lost to some degree in the UCN transportation from the reactor core to the neutron trap through a neutron guide, but it is quite sufficient for staging an experiment. For the sake of fairness, mention should be made here of the work [9] of the Munich Mayer – Leibniz school: to extract very cold neutrons with $E_{\rm n}$ up to $\sim 4 \times 10^{-4}$ eV from the reactor core, advantage was taken of a vertical, slightly curved evacuated copper neutron guide, which could be well employed, in principle, to fill a bottle with neutrons. However, the authors of this paper pursued other goals. Running a few steps forward we note that it was not until 10 years later that the neutron bottle was realized with an updated version of this neutron guide [10].

The first experiment involving the observation of UCN storage by way of multiple collisions of UCNs with a vessel wall was performed under F L Shapiro's supervision in Dubna in 1968 [11]. This was preceded by Shapiro's proposal [12] to employ UCNs for staging a fundamental experiment to search for the constant electric dipole moment (EDM) of the neutron, which would allow the verification of the T-invariance violation discovered in some decays of neutral K-mesons a short time previously. Somewhat later, independently of Shapiro, D A Kirzhnits made a similar proposal at a seminar at the P N Lebedev Physics Institute, Russian Academy of Sciences. To determine the neutron EDM, Shapiro initially proposed using a thermal neutron trap in the form of a system of single crystals wherein neutrons would move along closed trajectories owing to the Bragg reflection. Such a neutron trap was implemented in the Rutherford – Appleton Laboratory (Great Britain) as late as 1990. The average number of neutron reflections from the mirrors was $\sim 10^3$ while the neutron storage time did not exceed ~ 0.17 s [13].

More than thirty years have passed since the first UCN storage experiment, in which the UCN density in the vessel was only $\sim 10^{-5}$ cm^{-3}. During this period, UCN research has been pursued by more than ten geographically varied domestic and foreign institutes: Dubna, Moscow (four institutes), Gatchina, Alma-Ata, Dimitrovgrad, Lytkarino, and Sarov, as well as Germany, Canada, Great Britain, France, and the USA. A great diversity of research reactors have been employed to obtain UCNs, ranging from a university reactor with $W = 0.5$ MW to the high-flux SM-2 reactor with $W = 100$ MW, as well as high-current proton accelerators. Several groups have made every effort to investigate the production, transportation, spectroscopy, storage, and detection of UCNs. The highest UCN density in a vessel attained to date is $\sim 10^2$ cm^{-3} and the in-vessel UCN storage time has been brought up to $\sim 10^3$ s, which is entirely limited only by the neutron beta-decay period [14]. By now, all simple demonstration experiments on uncomplicated low-power UCN sources have been performed. More serious research calls for high-intensity UCN beams to produce monoenergy neutrons and obtain sufficient statistical accuracy when measuring subtle effects. High-intensity UCN sources are based on high-flux reactors. They involve rather complicated cryogenic equipment for liquid hydrogen moderators, which are far from being safe, and are equipped with high-technology mirror neutron guides for efficient UCN extraction from the reactor. The currently best source is the UCN source of the high-flux reactor at the Institut Laue – Langevin (ILL) in Grenoble (France). Meanwhile, the UCN sources of the new reactor in Munich (Germany) and of the proton accelerator at the Paul Scherrer Institut (Switzerland) are being prepared for commissioning. Their designers expect to obtain UCN fluxes much higher than those from the Grenoble reactor.

UCN storage facilities are commonly located near reactors. The UCN gas expands from the reactor core into free space to find its way into a UCN storage vessel via neutron guide tubes. The main losses of the UCNs in their transportation take place when the UCNs collide with the walls of the neutron guide. That is why it is critically important to minimize the number of UCN – wall collisions by employing neutron guides with high-reflectivity walls. To this end, the roughness of the neutron guide walls should be much smaller than the UCN wavelength (~ 500 Å). Unlike thermal and cold neutrons in classical mirror neutron guides, where any off-specular reflection results in the loss of a neutron, a UCN after an off-specular reflection remains in the volume of the neutron guide, whose shape may have sharp bents and narrowings. However, off-specular reflections significantly hinder the passage of UCNs through a neutron guide. Even in the best neutron guides, the UCN losses in the transportation from the reactor core to the neutron bottle are relatively high. To avoid the UCN loss in neutron guides, Bagryanov et al. [15] resorted to the method of UCN transport in movable sealed vessels over a distance of more than 10 m from the core of a pulsed reactor. The pulsed thermal neutron flux of a pulsed reactor exceeds the thermal fluxes of stationary reactors by several orders of magnitude. Since the UCN flux is proportional to the thermal neutron flux, during the reactor operation time its moderator should emit UCN pulses with a high density, far greater than the UCN density from stationary reactors [16]. The resultant UCN density was found to be ~ 25 cm^{-3}, which was much less than the calculated one, and therefore this UCN extraction method invites further investigation.

In the majority of experiments it is vital to know the UCN velocity distribution and the variation of this velocity spectrum during the storage time. Best suited for this purpose is a gravitational UCN spectrometer. When traveling upwards and overcoming the force of gravity, a neutron

with the kinetic energy of the vertical velocity component v can rise to a height $h = v^2/2g$ (numerically, this height in centimeters is almost equal to the neutron energy expressed in nanoelectron-volt units: $1h\,[\text{cm}] = 0.98E\,[\text{neV}]$). If a barrier of height h that is impermeable to the UCNs is placed in their path in front of the trap, it is possible to completely prevent neutrons with energies below mgh from entering the trap. If a UCN absorber is additionally placed at a height H in the spectrometer, the trap will be filled only with neutrons whose energies are in the $\Delta E = mg(H - h)$ range. Malik et al. [17] described a gravitational spectrometer with an attained resolution of ~ 0.5 neV.

Any neutron detection technique is appropriate for recording UCNs. However, the existence of the surface potential U_{eff} in the detector material leads to the UCN reflection from the detector surface. UCNs penetrate the detector to a depth of only ~ 150 Å, which is obviously insufficient for a UCN absorption in a single collision. When UCNs are pre-accelerated to an energy exceeding U_{eff} for the detector, it is possible to attain a nearly 100 % UCN detection efficiency. This is most often accomplished with the gravitational acceleration of UCNs, for which purpose the detector is placed some distance (~ 0.5 m) below the outlet level of the UCN trap.

From the first UCN observation experiment up to the mid-1970s, studies had been made of the behavior of UCNs and the techniques for manipulating them were refined. Subsequently, UCNs became an instrument for a number of basic studies. Initially, at the St. Petersburg Institute of Nuclear Physics (PINP) in Gatchina and later at the ILL in Grenoble, a start was made on experiments to discover the neutron EDM. The EDM measurement can be reduced to the determination of the very low energy of the interaction with a known electric field applied to a neutron. Since the uncertainty of energy measurement is inversely proportional to the measurement time, changing from a beam experiment (with a measurement time of $\sim 10^{-2}$ s) to an experiment on UCNs with a storage time of $\sim 10^2$ s results in an increase in sensitivity by four orders of magnitude, to say nothing of the suppression of some systematic errors that limit the potentialities of the beam experiments. To date, the neutron EDM has not been discovered in the experiments by the Gatchina and Grenoble groups, while its upper limit has been lowered to $(1.0 \pm 3.6) \times 10^{-26} e$ cm [18]. Therefore, despite the persevering search, time invariance violation has not been discovered in elementary processes, with the exception of K_0-meson decays. This circumstance has called into being new proposals for carrying out an experiment on UCN storage in a quest for the EDM [19].

While in experiments staged in search of the EDM the time of neutron storage in a trap does not exceed $\tau \sim 200$ s and is quite sufficient for such experiments, measuring the lifetime of a free neutron necessitates UCN traps with much longer storage times. The technique of UCN storage has enabled a significant improvement in the accuracy of determining the neutron decay lifetime in comparison with previous measurements of this quantity with thermal neutron beams. Such an experiment with UCNs is seemingly very simple: on filling a bottle with UCNs one only has to record the exponential time dependence of the UCN density in the bottle. However, the decrease in the UCN density in the bottle is determined not only by neutron radioactivity, but by some losses of the UCNs in the bottle walls as well. In bottles that store UCNs well the UCN losses in the walls do not exceed $\sim 2-3\%$ of UCN losses arising from neutron decay. Despite the relative smallness of the UCN losses in the trap walls, these losses should be taken into account in precise measurements of the UCN lifetime to beta decay. As of now, there exist data obtained by three experimental groups (ILL, Russian Research Center 'Kurchatov Institute', and PINP, Gatchina, in collaboration with the Joint Institute for Nuclear Research, Dubna) on the neutron lifetime, which diverge in the method of accounting for UCN absorption in the walls. The accuracy obtained in the three experiments is more or less similar and amounts to $\sim 0.4\%$ of the average neutron lifetime derived in these experiments: $\tau_\beta = (885.9 \pm 1.7)$ s [20]. This figure differs by two standard deviations from the average τ_β derived from beam experiments: $\tau_\beta = (894.2 \pm 4.2)$ s [20].

So far, no suggestions have been made for performing a UCN experiment in search of the neutron charge that would have an advantage over the beam (neutron-optical) version of such an experiment, because the measured trajectory displacements or phase shifts in the electric field are automatically 'smeared' due to the chaotic motion of the UCN gas in traps.

The first experiments on UCN storage exhibited a relatively short storage time, which was related to UCN absorption in the walls. Attempts to radically get rid of such losses were made employing magnetic traps, where the UCNs do not 'see' the wall material at all and the total reflection from the walls takes place due to the repulsion of the neutron magnetic moment μ from the gradient of the magnetic field B at the wall: $E_{\text{UCN}} = mv^2/2 = \pm\mu B$. The first realized gravimagnetic UCN bottle demonstrated the fundamental feasibility of this storage technique, when the neutrons bounce off the magnetic field from below and off the terrestrial gravitational field from above. However, the UCN storage time in such a bottle amounted to ~ 35 s and did not exceed the storage time attained with bottles of any other material [21] at that time. A somewhat larger trap made according to the same scheme did not justify hopes, either. The UCN storage time in it did not exceed ~ 300 s and was still much shorter than the neutron decay time [22]. The superconducting toroidal magnetic trap for the storage of neutrons (with somewhat higher velocities than UCN velocities) showed a storage time of ~ 900 s, but only for some orbits, whose fraction was very insignificant in the total flux of the neutrons stored in the trap; the storage time for the entire flux was much shorter [23]. After unsuccessful experiments with bulky gravimagnetic traps, the recent results of the Gatchina group came as a pleasant surprise: it was possible to attain a storage time of ~ 900 s in a simple small trap assembled of powerful permanent magnets.

Applied research involving UCN storage also holds promise, especially for the physics of surfaces. UCNs can 'see' well only the atoms on the surface, since they spend all their time in flight in a vacuum between collisions (in which they are not absorbed) and in the surface material layer of thickness ~ 150 Å. At this time, experiments are being carried out in the elemental surface analysis with the use of the (n, α) and (n, γ) reactions, as are experiments to study the thermal vibration dynamics of surface atoms with the possibility of scanning the depth of a material in the range from 0 to 300 Å. Also of interest is the unique possibility of studying excitations in superfluid ^{4}He films from inelastic UCN scattering (heating) by these films.

Beginning with the first experiments, all observations have shown that the UCN storage time is much shorter than

the theoretical value. The maximum attainable number of successive collisions of a UCN with a beryllium trap wall turned out to be 100 times (and for a solid oxygen trap wall 1000 times) smaller than the calculated one. The nature of this discrepancy has not been fully understood [24]. It is likely that the anomalous UCN losses are related to the recently observed quasi-elastic UCN scattering from trap walls of different materials with a probability of $\sim 10^{-7}$ per impact, whereby the energy of the UCN increases nearly twofold [25, 26]. Also observed, with a probability an order of magnitude lower, were processes of further cooling of UCNs at a wall whose temperature (300 K) is six orders of magnitude higher than the temperature corresponding to the UCN temperature (10^{-3} K). Fundamentally, such processes are not forbidden, but their intensity proved to be 5–6 orders of magnitude higher than expected. Experiment has shown that the observed phenomenon is caused by inelastic UCN scattering by very small particles with an atomic mass of $\sim 10^7$ weakly coupled to the surface, which are in the state of thermal motion determined by the wall temperature. These nanoparticles can be discerned by modern microscopy techniques. However, investigation of their dynamics seems to be inaccessible for other methods except the UCN technique.

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Investigation of quantum neutron states in the terrestrial gravitational field above a mirror

V V Nesvizhevskii

1. Introduction

Quantum mechanics implies that an elementary particle or any other material object resides in bound quantum states in a sufficiently deep potential well irrespective of the nature of the attractive potential. This means that the set of allowed energy levels is defined by the particle mass and the shape of the attractive potential, while the probability that the particle is at an arbitrary point in space is equal to the squared modulus of its wave function in the corresponding quantum state at this point. And the particle-retaining potential may be any of the four known kinds: electromagnetic, strong, weak, or gravitational. A natural example of quantum states of matter is the states of electrons in atoms [1] and, in a strong nuclear field, the states of neutrons and protons in nuclei [2]. The observation of a similar phenomenon in the gravitational field is complicated by the extreme weakness of gravitational interaction in laboratory conditions. However, it is nevertheless possible when the terrestrial gravitational field makes up one of the walls of a potential well and the other wall is a horizontal mirror that reflects the particle and thereby bounds the domain in which it can move. The Schrödinger equation that describes the quantum states of a particle of mass m moving in the terrestrial gravitational field with the acceleration of gravity g above a perfect horizontal mirror has been analytically solved in textbooks on quantum mechanics [3–7] and theoretically investigated in many papers, for instance in Refs [8–10]. For macroscopic objects under ordinary conditions, the corresponding quantum effects are negligible, but they may be significant for bodies with a small mass, e.g., for elementary particles [11], in particular, for neutrons [12, 13] or atoms [14, 15]. The dominant interaction for charged particles is the electromagnetic one, which makes observing their quantum states in the gravitational field practically unfeasible. Experiments with neutrons and neutral atoms are in principle possible, even though they are hampered by many methodical factors like, for instance, the extremely low phase-space density of neutrons with sufficiently low energy (the effective neutron temperature in the lower quantum state is ~ 20 nK !) or the difficulties associated with developing a perfect mirror for neutral atoms. The technique of measuring the quantum states of neutral atoms in a gravitational field was elaborated, for instance, in Refs [14–18]. As a mirror for atoms, Refs [14–18] employed a standing laser wave [19–21] decaying exponentially at the interface between two media