WHISPERING GALLERY STATES OF NEUTRONS AND ANTI-HYDROGEN ATOMS AND THEIR APPLICATION TO FUNDAMENTAL AND SURFACE PHYSICS

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ABSTRACT

The ‘whispering gallery’ effect has been known since ancient times for sound waves in air, later in water and more recently for a broad range of electromagnetic waves: radio, optics, Roentgen and so on. It is intensively used and explored due to its numerous crucial applications. It consists of wave localization near a curved reflecting surface and is expected for waves of various natures, for instance, for neutrons and (anti)atoms. For (anti)matter waves, it includes a new feature: a massive particle is settled in quantum states, with parameters depending on its mass. In this talk, we presented the first observation of quantum whispering-gallery effect for cold neutrons [1-2]. This phenomenon provides an example of an exactly solvable problem analogous to the ‘quantum bouncer’; it is complementary to recently discovered gravitational quantum states of neutrons [3]. These two phenomena provide a direct demonstration of the weak equivalence principle for a massive particle in a quantum state. Deeply bound long-living states are weakly sensitive to surface potential; highly excited short-living states are very sensitive to the wall potential shape. Therefore, they are a promising tool for studying fundamental neutron–matter interactions, quantum neutron optics and surface physics effects. Analogous phenomena could be measured with atoms and anti-atoms [4-5].

Keywords: neutron whispering gallery, gravitational quantum states, centrifugal quantum states, fundamental neutron physics, gravitational interaction of antimatter

1. INTRODUCTION

This short note is based on the talk on whispering gallery states of matter and anti-matter particles presented at ISINN-XX 2012. The note lists results published elsewhere in great details, in particular: recent observation of the neutron whispering gallery phenomenon [1-2, 6-9], and the proposal to measure whispering gallery states of anti-hydrogen atoms [5, 11]. The whispering gallery states of (anti)matter particles could be considered in a broader context including also observation of gravitational quantum states of matter (ultracold neutrons) [3, 12-13], and the proposal to measure gravitational quantum states of anti-matter (anti-hydrogen atoms) [4, 14]. All these phenomena have many common features in terms of physical nature, theoretical formalism, experimental methods and applications [15-16]. They are unique powerful tools for investigations in fundamental physics [17-19], and in surface science. They will be studied/used/prototyped using new GRANIT facility [20-22] at ILL. Experiments with anti-hydrogen atoms are planned within GBAR project [23] at CERN. Whispering gallery states (or centrifugal quantum states) of (anti)matter particles, as well as gravitational quantum states of (anti)matter particles, are perfect examples of “quantum bounces” [24-26], the phenomenon known from textbooks for nearly a century but only proven recently. The considered phenomena are (anti)matter-wave analogs of well-known whispering-gallery phenomena with sound and electromagnetic waves [27-30].

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The whispering gallery effect was known since ancient times for sound waves in air, and later in water: thus the internal walls of a round building reflect by “Garland” trajectories the sound waves produced by a human whisper so that the sound reaches a person on the opposite side of the building or even completes a full circle, imitating an “echo”. Lord Rayleigh explained and described quantitatively this phenomenon in his “Theory of Sound” [27-28]. He verified the theory using a whistle as a sound source and burning candles as the sound intensity “detectors”.

More recently the whispering gallery effect for a broad range of electromagnetic waves: radio, optics, Roentgen and so on [29-32] – attracted ever-growing interest owing to its multiple exciting applications. It is also known as “Mie scattering” in light scattering from aerosols and in nuclear physics. An optical analogue of a quantum particle bouncing on a hard surface under the influence of gravity or centrifugal potential has been demonstrated using a circularly curved optical waveguide [33]. In all of these cases, a curved mirror acts as a waveguide; and interference of the waves falling to the mirror and those reflected causes specific stationary whispering-gallery modes.

2. THE NEUTRON WHISPERING GALLERY EFFECT

For matter waves in the quantum limit, a new feature should appear: the radial motion of a massive object should be settled in quantum states with parameters which depend on its mass. Such centrifugal quantum states of atoms were extensively discussed in literature [34-35]. And centrifugal quantum states of neutrons in the vicinity of a curved mirror were observed recently for the first time using the method of neutron interferometry [1].

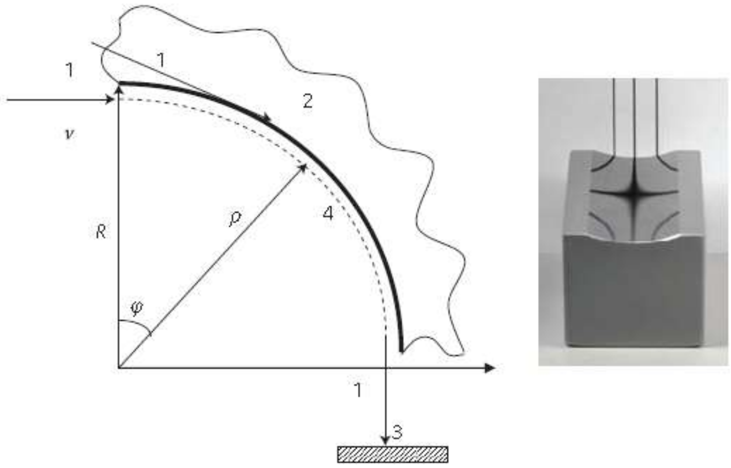

Fig.1. A scheme of the neutron centrifugal experiment [1]; 1: classical trajectories of incoming and outgoing neutrons, 2: cylindrical mirror, 3: neutron detector, 4: quantum motion along the mirror surface. Insert: A photo of the single-crystal silicon mirror used for the presented experiments, with an optical reflection of black stripes for illustrative purposes.

Consider the scattering of a cold neutron on a truncated cylindrical mirror shown in the insert to Fig. 1 [1]. Note that the reflection of a neutron from a material surface is described quite precisely in terms of effective step-like optical potential of the surface material, which emerges as a result of averaging of the interaction of a neutron with nuclei in the surface material. If the energy of the radial neutron motion is smaller than the value of the optical nuclear potential barrier, then the neutron is totally reflected, in the classical approximation, and thus it could follow the surface on a Garland trajectory. Such neutron is affected by the centrifugal acceleration and, under certain conditions, quasistationary quantum states are settled in the bounding well formed by the centrifugal potential and the mirror optical potential. In addition to evident conditions of sufficiently small roughness of the mirror surface (the roughness has to be significantly smaller than the characteristic spatial size of the centrifugal quantum states of 50 nm for typical experimental conditions), as well as sufficiently precisely defined shape of the cylindrical mirror, another condition for easy observations is that the number of quantum states in the bounding triangle potential should be equal to one or a few states.

The longitudinal neutron velocity, or the corresponding neutron wavelength, can be measured using the standard time-of-flight technique. The transversal velocity of a neutron at the cylindrical mirror exit can be calculated if the neutron escape angle is measured, for instance, in a position-sensitive neutron detector installed behind the exit from the mirror. When one measures both the longitudinal and transversal neutron velocity components, interference between centrifugal states can be observed as shown, for instance in Fig. 2.

Measurements of such interferometric patterns provide access to energies of centrifugal quantum states. Deeply bound states are almost insensitive to surface effects as the probability of their tunneling through the bounding triangle potential is negligible; they could therefore be used to probe extra fundamental short-range forces between a neutron and a surface [19]. As a matter of fact, such neutron constraints from out first exploratory measurements are competitive to the best existing constraints even today, before any dedicated efforts to improve sensitivity and precision have been done. Weakly bound states can tunnel through the barrier with high probability, and are therefore strongly affected by surface effects as long as they affect the tunneling probability. In contrast to the standard neutron reflectometry techniques with cold/thermal neutrons widely used all over the world, the method of whispering gallery states for surface studies provides not one but orders of magnitude larger number of quasi-classical bounces, thus orders of magnitude higher sensitivity to small effects. Today we can measure at least 100^{th} order of such an interference pattern, and define the line shape with an accuracy of at least 10^{-1} thus achieving 10^{-3} precision for the quantum states energies. A feasibility of even much more precise measurements is being explored.

It should be noted that a simplified interpretation of this phenomenon assuming independent longitudinal and tangential motions can be complemented by a precision solution of the corresponding scattering problem [2] when needed; however even this simplified description is extremely precise in the actually used limit of quantum state sizes much lower than the cylindrical mirror radius.

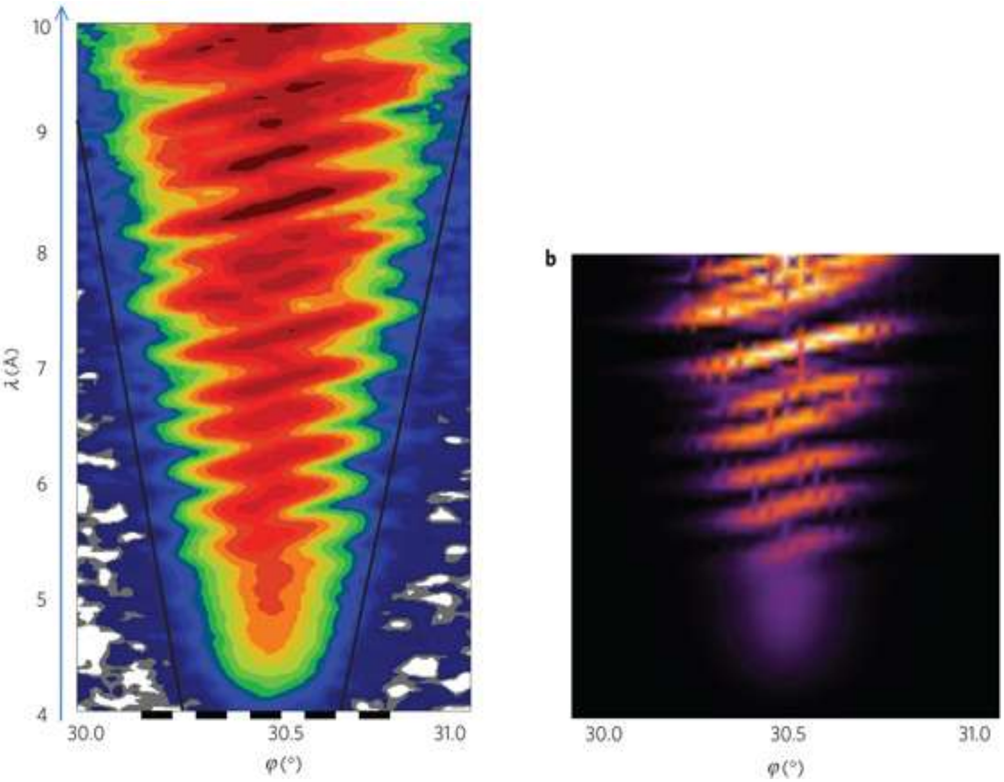

Fig.2. Interference of centrifugal quantum states of neutrons; the scattering probability as a function of neutron wavelength (Å, vertical axis) and deviation angle (degrees, horizontal axis). The maximum probability is shown in red (the experimentally measured interference pattern is shown on the left, and the theoretical expectation for this pattern is given on the right). Neutrons enter through the entrance edge of a cylindrical mirror with the geometrical size of 30.5 degrees. The figure is copied from [1].

3. THE ANTI-HYDROGEN WHISPERING GALLERY EFFECT

As shown in [36-37], ultracold (anti)atoms, in particular ultracold (anti)hydrogen atoms, will be efficiently reflected from surfaces, and thus we can observe whispering gallery states of anti-atoms [5] in essentially the same way as the analogous states of ultracold neutrons. The difference consists of the nature of reflection: while ultracold neutrons are reflected from neutron-nuclei optical potential, (anti)atoms are reflected from sharply-changing attractive van der Waals/Casimir Polder potential due to so-called quantum reflection phenomenon.

In order to get well-defined long-living whispering-gallery quantum states of (anti)hydrogen atoms, one has to provide large probability of reflection of (anti)hydrogen atoms from surface. In the worse case of conducting metallic surface, the reflection probability is shown in Fig. 3 as a function of the incident (radial) energy. As you see, the reflection coefficient is quite high in the lowest-energy limit. Experiments with gravitational and whispering gallery states are planned within GBAR project [23] at CERN. The principle motivation for performing these experiments consists of the possibility of achieving the highest precision (among precisions of all considered alternative methods) for measuring gravitational properties of antimatter.

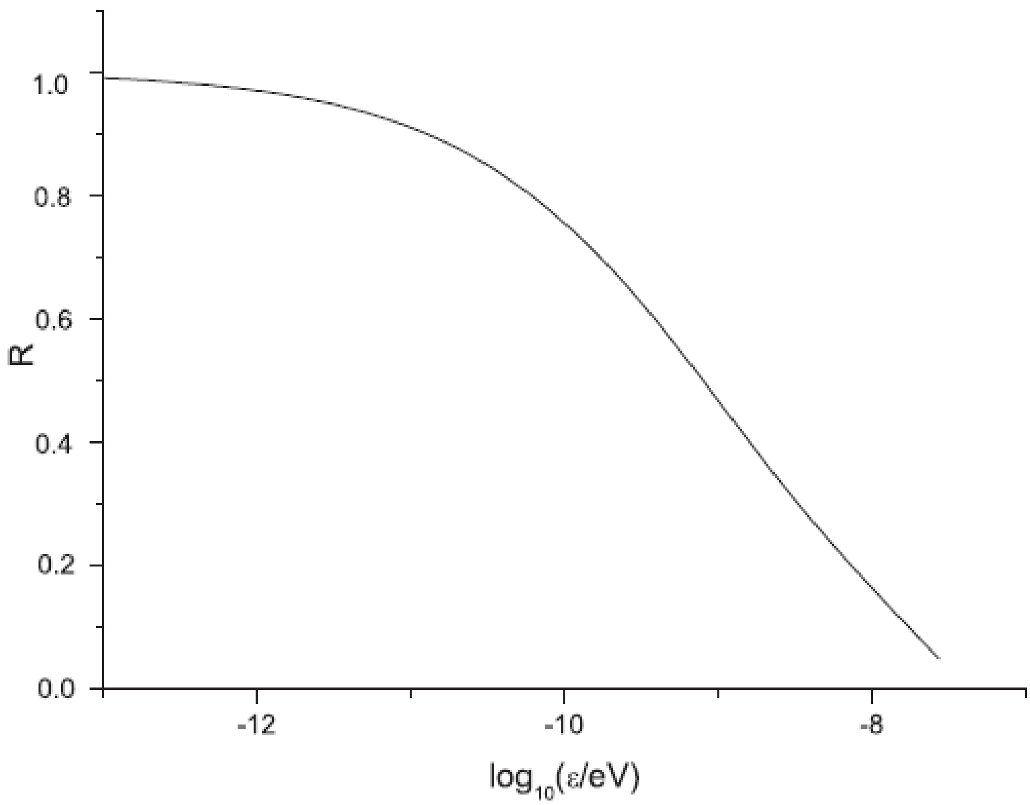

Fig.3. The coefficient of reflection of (anti)hydrogen atoms from the vdW/CP interaction potential as a function of the incident (radial) energy.

4. CONCLUSION

We listed briefly the latest developments related to studies of/with recently observed whispering gallery states of ultracold neutrons at ILL (GRANIT project), as well as to the proposal to measure analogous states of anti-hydrogen atoms at CERN (GBAR project). Experiments with whispering gallery states of both kinds could provide relatively high accuracy, thus, on one hand, providing a powerful tool for searches for extra short-range fundamental interactions (matter-matter for ultracold neutrons and antimatter-matter for anti-hydrogen atoms), and on another hand providing a very sensitive method to study surfaces. These presented phenomena should be considered in a broader context of studies of quantum bounces on one hand, and of whispering gallery states of various natures on another hand.

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