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Experiments with hydrogen atoms at ultra-low energies

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We present a recent progress towards experiments with hydrogen atoms at ultra-low energies, nearly at rest. This work is a part of an international collaboration GRASIAN (Gravity, Spectroscopy and Interferometry with Atoms and Neutrons) [1]. The motivation for the work proposed here is associated with weak short-range forces exerted by yet undiscovered light bosons, direct checking of the equivalence principle, CP violation and comparison of the properties of matter and antimatter. We will probe the ultra-low energy domain with hydrogen, the lightest and simplest of neutral atoms, which has served as a test probe of the fundaments of physics throughout the era of modern physics. However, the thermal motion of atoms has set limits to the accuracy of experiments. Therefore, using hydrogen atoms nearly at rest one expects to obtain unprecedented levels of precision.

We have demonstrated magnetic capture and confinement of 10^{15} H atoms at temperature below 50mK using a world largest Ioffe-Pritchard type trap (IPT) recently built in our laboratory [2]. The loading of H into the sample cell (SC) was performed at a fixed temperature of the SC using a temperature controller. The flow of 10^{13}atoms/s was observed by detecting the recombination heat of H on the SC wall. H flux into SC detected by bolometers and SC thermocontroller. Bolometer is a graphite film resistor painted to Kapton foil 50(or 30) μm with gold electrodes.

We will release ultra-slow atoms from the trap onto the ideally flat surface of superfluid helium, from which their quantum reflection will lead to formation of gravitational quantum states (GQS) in the potential well created by the surface and Earth gravity. Precise measurements of the GQS energies will improve constraints on the existence of the unknown short-range forces between atoms and materials surface. Atom-fountain experiments with optical Ramsey spectroscopy will improve the accuracy of the 1S-2S interval. Bose-Einstein condensation (BEC) of H bound in the GQS will be attained and used for matter-wave interferometry. Our methods and results will be useful for experiments with antihydrogen pursued at CERN.

Experiments with gravitational states of ultracold neutrons opened a new way for studies of fundamental properties of matter and gravity [3], and similar experiments are suggested for atomic hydrogen and antihydrogen [4, 5]. Recent developments in production and cooling of antihydrogen in CERN demonstrate that such experiments are realistic in the nearest future. Although, there is no reason to expect that gravitational properties of antimatter differ substantially from that of the matter, observation of even a small difference would have a strong impact on our fundamental understanding of nature.

Reaching a natural linewidth (NLW) of ∼1.3 Hz for the 1S-2S transition is an ambitious goal for ultrahigh-resolution spectroscopy. Progress in the laser technology allows nowadays reaching the laser linewidth close to 1 Hz [6, 7]. Using such a state-of-the-art light source for studies of ultra-slow atoms, we will push the 1S-2S H spectroscopy to the NLW level. The total estimated uncertainty due to systematic effects was estimated to be at the level of 0.02 Hz for atoms at 1 mK. Since we are planning to work at much lower temperatures with large numbers of atoms, this level seems plausible to be reached. The absolute accuracy will be limited by the precision of the frequency standard available for the project. For our location in Turku the best solution is to use a GPS clock and an active local reference (Cs or hydrogen maser) using a frequency comb for laser locking. Accuracy of approaching 10^{-15} can be reached using such a system.
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