Zero-Point Energy of the Electron in a Penning Trap by Photo-Detachment Laser Spectroscopy

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Synopsis We discuss the confinement of an electron in a Penning trap as the realisation of a quantum-mechanical harmonic oscillator. In such a situation, the non-zero ground-state energy of the electron in the confining electric and magnetic fields of the trap (as compared to the classical zero of the energy of a free electron) can be directly measured with high precision in photo-detachment spectroscopy of confined negative atomic ions such as H^-. We detail a concrete implementation of such a measurement and discuss its implications.

In stark contrast to classical physics where confined particles can have exactly zero energy, quantum theory exhibits a finite zero-point energy (ZPE) that represents the lowest possible energy state of a system. This energy is an inherent feature of quantum systems, arising from the Heisenberg uncertainty principle. One significant remark comes from Feynman's lectures: 'The vacuum is not empty. It is filled with fluctuating fields. The ZPE is the lowest energy state of these quantum fluctuations, and its consequences are observable, as in the Casimir effect.' It is important to note that the Casimir effect refers to the ZPE of the pure electromagnetic field. However, the ZPE associated with a massive quantum-mechanical harmonic oscillator such as a confined particle remains largely unexplored experimentally.

We propose to directly measure the absolute value of the ZPE of a confined particle with high precision by laser photo-detachment spectroscopy of negative hydrogen ions H^- that are confined by the electric and magnetic fields of a Penning trap. The photodetached electron in the trap behaves as a quantum mechanical harmonic oscillator with energy levels $(N + 1/2)\,\hbar\omega$, where the electron's motional frequencies ω can be controlled by adjusting the electric and magnetic field strengths. In the ground state of the cyclotron motion, which gives by far the largest contribution, the ZPE $\hbar\omega^+/2$ of the confined electron leads to a measurable shift in the photodetachment threshold compared to the free-particle case.

This shift can be measured with high precision by laser photo-detachment spectroscopy. The photon energy $h\nu$ required to detach the electron is given by the electron affinity E_a = 0.754195(19) eV of the H^- anion. However, when the detached electron is not free to go to the continuum, but remains confined for example in a Penning trap, where it occupies the quantum-mechanical ground state of oscillation in the trap, the ZPE $\hbar\omega^+/2$ of the confined electron adds to this energy threshold, i.e. $h\nu = E_a + \hbar\omega^+/2$. A measurement of the photo-detachment cross section as a function of photon energy in the trap yields the threshold value $h\nu = E_a + \hbar\omega^+/2$. Subtracting the well-known free-particle value E_a provides a direct measurement of the ground-state ZPE $\hbar\omega^+/2$ [1]. (see Fig. 1).

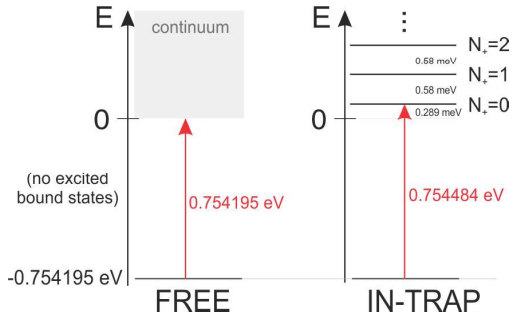

Figure 1. Energy level scheme for photodetachment laser spectroscopy of negative atomic hydrogen H^- in free space (left) and in a Penning trap (right).

References

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