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Determination of the proton charge radius from the study of the hydrogen S-energy levels

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At present, four complementary methods are used to obtain the charge radii of light nuclei: an elastic scattering of electrons by nuclei, elastic scattering of muons by nuclei, spectroscopy of electron atoms, and high-precision laser spectroscopy in muonic atoms. Traditionally, elastic electron scattering was the first method to determine the internal structure of a proton. Elastic scattering of leptons by a target nucleus is described by form factors included in the theoretical expression for the scattering cross-section. A proton or other light nucleus is a compound particle, and its size is determined by the charge radius. It is related to the slope of the electric form factor of the proton $G_{pE}(q)$ at $q^2 = 0$. Over the past two decades, atomic laser spectroscopy has proven to be a powerful tool for determining the charge radii of light nuclei. Atomic spectroscopy of hydrogen is an indirect way of determining the charge radius r_{pE} of a proton from presision measurements of certain energy intervals. While electron scattering and spectroscopy of electron atoms have been available for a long time, muon spectroscopy became available only in 2010 due to the work of the CREMA collaboration. As a result of the first CREMA experiments in 2010, the value $r_{pE} = 0.84184(67)$ fm was obtained, which was 10 times more accurate than all previous values from experiments with electronic systems. Moreover, this value was significantly less than the CODATA value, $r_{pE} = 0.8768(69)$ fm. This difference is called the "puzzle" of the proton radius. In this work, a precision study of the structure of energy levels of S-states of hydrogen in quantum electrodynamics is carried out taking into account corrections for vacuum polarization, nuclear structure, relativism, as well as complex combined corrections that include the above. The frequency of the transition between the levels of S-states is calculated, which is necessary for comparison with the corresponding experimental data.

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