Scientists confirm surprisingly small proton radius

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The initial results puzzled the world three years ago: the size of the proton (to be precise, its charge radius), measured in exotic hydrogen, in which the electron orbiting the nucleus is replaced by a negatively charged muon, yielded a value significantly smaller than the one from previous investigations of regular hydrogen or electron-proton-scattering. A new measurement by the same team confirms the value of the electric charge radius and makes it possible for the first time to determine the magnetic radius of the proton via laser spectroscopy of muonic hydrogen (*Science*, January 25, 2013).

The experiments were carried out at the Paul Scherrer Institut (PSI), Villigen, Switzerland, which is the only research institute in the world providing the necessary amount of muons. The international collaboration included the Max Planck Institute of Quantum Optics (MPQ) in Garching near Munich, the Swiss Federal Institute of Technology ETH Zurich, the University of Fribourg, the Institut für Strahlwerkzeuge (IFSW) of the Universität Stuttgart, and Dausinger & Giesen GmbH, Stuttgart. The new results fuel the debate as to whether the discrepancies observed can be explained by standard physics, for example an incomplete understanding of the systematic errors that are inherent to all measurements, or whether they are due to new physics.

The hydrogen atom has played a key role in the investigation of the fundamental laws of physics. Hydrogen consists of a single positively charged proton orbited by a negatively charged electron, a model whose success in explaining spectroscopy data dates back to its proposal by Bohr in 1913. The energy levels of this simplest of atoms can be predicted with excellent precision from the theory of quantum electrodynamics. However, the calculations have to take into account that—in contrast to the point-like electron—the proton is an extended object with a finite size, made of three quarks bound by so-call ‘gluons’. Therefore, the electric charge as well as the magnetism of the proton is distributed over a certain volume. The extended nature of the proton causes a shift of the energy levels in hydrogen.

Hence the electric and the magnetic charge radii can be deduced from a measurement of the level shifts.

In 2010, the first results on the spectroscopic determination of the shift of the so-called 2S energy level in muonic hydrogen were published. The exotic atoms were generated by bombarding a target of regular hydrogen with muons from an accelerator at PSI. Muons behave a lot like electrons, except for their mass: muons are 200 times heavier than electrons. The atomic orbit of the muon is therefore much closer to the proton than the electron’s orbit in a regular hydrogen atom. This results in a much larger sensitivity of the muon’s energy level to the proton size and hence to a stronger shift of the energy levels. Measuring the level shifts is very technologically demanding: muonic hydrogen is very short-lived (muons decay after about two millionths of a second), so the light pulses for the excitation of the resonance have to be fired onto the hydrogen target only nanoseconds after the detection of a muon. The new disk laser technology developed by the Institut für Strahlwerkzeuge (IFSW) of the Universität Stuttgart was an important element to fulfil this requirement. The lasers necessary for exciting the resonance were developed by the Max-Planck-Institute of Quantum Optics in cooperation with the Laboratoire Kastler Brossel (Paris).

In the experiment described in the newly published *Science* article, the energy shift was determined for another transition. This leads to a new measurement of the electric charge radius of the proton. Its value of 0.84087(39) femtometers (1 fm = 0.000 000 000 000 001 meter) is in good agreement with the one published in 2010, but 1.7 times as precise. The discrepancy with existing radius measurements made in regular hydrogen or by electron-proton-scattering, the so-called proton size puzzle, has thus been reaffirmed. In addition, the new measurement allows a determination of the magnetic radius of the proton for the first time by laser spectroscopy of muonic hydrogen. This results in a value of 0.87(6) femtometers, in agreement with all previous measurements. Though the precision is, at present, of the same order as in other experiments, laser spectroscopy of muonic hydrogen has the potential of achieving a much better accuracy in the determination of the magnetic proton radius in the future.

Background
Physicists around the world are actively seeking a solution to the proton size puzzle. Previous measurements in regular hydrogen and by electron-proton-scattering are being reanalyzed and even repeated. Theorists of various disciplines suggested ways to explain the discrepancy. Very interesting proposals explain the discrepancies by physics beyond the standard model. Other explanations suggest a proton structure of higher complexity than assumed today which only reveals itself under the influence of the heavy muon. New measurements are needed to check on these possibilities. Muon-proton-scattering experiments are being developed at PSI, new precision measurements at the electron accelerator in Mainz are being considered, and the PSI team plans to measure, for the first time ever, laser spectroscopy of the muonic helium atom in the course of this year.

The required modifications of the current laser system are being investigated in the frame of the project “Thin-disk laser for muonic atoms spectroscopy” which (financed by the Swiss National Science Foundation (SNSF) and the Deutsche Forschungsgemeinschaft (DFG)) is carried out at the ETH Zürich (Prof. Dr. Klaus Kirch, Dr. Aldo Antognini) and at the IFSW (Prof. Dr. Thomas Graf, Dr. Andreas Voß). The Project “Muonic Helium” is also generously supported by the European Research Council (ERC) by an ERC Starting Grant held by Dr. Randolf Pohl from the MPQ in Garching.

How big is the proton? [1]

Source: Paul Scherrer Institute [2]

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