HIGH RESOLUTION SPECTROSCOPY OF ATOMIC HYDROGEN

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Abstract

Two-photon spectroscopy of the extremely narrow 1S-2S transition has reached a resolution of better than 1 part in 10^{11}. Recent precision measurements of the 1S-Lamb shift, the hydrogen deuterium isotope shift, and the Rydberg constant are reported.

Introduction

As the simplest of stable atoms hydrogen may be studied, theoretically and experimentally with extraordinary accuracy. This offers unique opportunities for stringent tests of fundamental physics such as the theory of quantum electrodynamics (QED) as well as for ultra precise measurements of fundamental constants.[1] The experimental resolution of an optical atomic resonance is ultimately limited by its natural linewidths which for most transitions is typically on the order of several MHz. However, the hydrogen atom features an exceptionally narrow transition between the 1S ground state and the metastable 2S state. The

provided by a single mode dye laser near 486nm whose frequency is doubled in a nonlinear crystal (ß-Barium Borate). Sufficient conversion efficiency is obtained by placing the crystal in a passive resonator which enhances the fundamental light power by a factor of 50 resulting in about 6 mW ultraviolet radiation. The dye laser is electronically stabilized to a carefully designed ultrastable reference resonator made from dielectric mirrors with gyroscopic quality which are optically contacted to the front facets of a 40 cm long Zerodur spacer. The spacer is suspended by soft springs and placed inside a thermally stabilized vacuum chamber. A wooden cover improves thermal and acoustic isolation. The laser bandwidth of about 1kHz is determined by residual frequency fluctuations of the reference resonator due to seismic and acoustic noise.

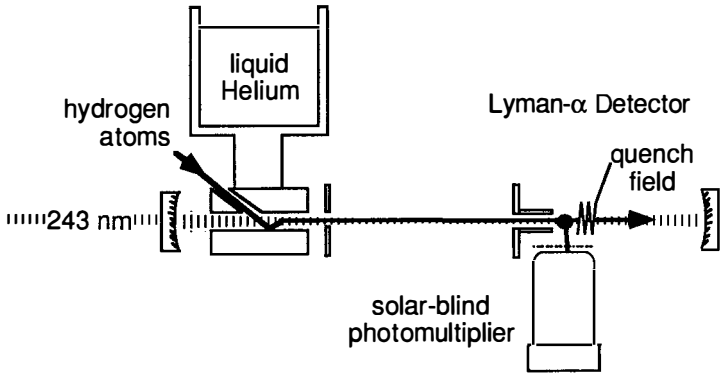

Fig. 1 Atomic beam apparatus for resolving the hydrogen 1S-2S transition with relative linewidth of better than 1 part in 10^{11}.

The spectra of the F=1 hyperfine component for different temperatures are shown in fig. 2. At room temperature, the asymmetric line shape is explained by the relativistic Doppler effect which shifts the atomic resonance due to time dilation of special relativity. The asymmetry reflects the thermal velocity distribution of the atomic beam. At lower temperature the Doppler broadening vanishes and at 8.6 K the resonance shape is almost entirely determined by transit broadening. The line width of 12 kHz in the ultraviolet corresponds to a resolution of 1 part in 10^{11}. For the heavier deuterium isotope, an even narrower line of 9 kHz has been observed.

lifetime of the 2S state - which for parity reason may not decay to the ground state by a single photon electric dipole transition - is determined by a two photon decay and limits the resolution to 1.3 Hz. The transition may be excited by two photon absorption from counterpropagating laser beams[2]. This has the advantage that the transition frequency is almost independend of the atomic velocity since the linear Doppler effect cancels for absorption from opposite directions. In addition the two photon transition splits the necessary photon energy and shifts the excitation wavelengthinto a range (243 nm) where continuous wave laser sources are available.

In this article we describe recent results of the Garching hydrogen project, all based on high resolution spectroscopy of the 1S-2S transition. A comparison of the 1S-2S transition frequency with the 2S-4S two photon transition has led to an improved value for the 1S Lamb-shift which for the first time exceeds the accuracy of the best reported measurements of the "classical" 2S Lamb shift.[3] Initially, the result did not agree with theory but now new improved calculations of higher order QED corrections [4] seem to solve the discrepancy. In a second experiment the 1S-2S transition frequency has been compared to the cesium clock by means of a phase coherent frequency chain and an intermediate frequency standard near 3.39μm.[5]. The result was used to derive an improved value of the Rydberg constant. Finally, the isotope shift between hydrogen and deuterium has been measured with 20-fold improved accuracy providing information about the charge radii of the proton and the deuteron.[6]

Two Photon Spectroscopy of the 1S-2S Transition

To minimize line broadening due to collisions and transit time effects, the hydrogen atoms are observed by longitudinal excitation of a cold atomic beam [7] (fig.1). The hydrogen atoms are produced by dissociation of H_2 in a radio frequency gas discharge and enter the vacuum chamber through a nozzle which is mounted at the bottom of a cryostat. The atoms thermalize by wall collisions inside the nozzle and form a atomic beam parallel to the axis of a standing wave resonator. The resonator builds up the incident ultraviolet laser light to about 20-50 mW circulating power and provides the two counterpropagating laser beams for Doppler free two photon excitation. At the end of the 15 cm long atomic beam, the excited atoms are detected by mixing the 2S and the 2P state with a small electric field (10V/cm) which stimulates a rapid radiative decay. The emitted Lyman-α photons are counted by a photomultiplier. The ultraviolet light near 243nm is

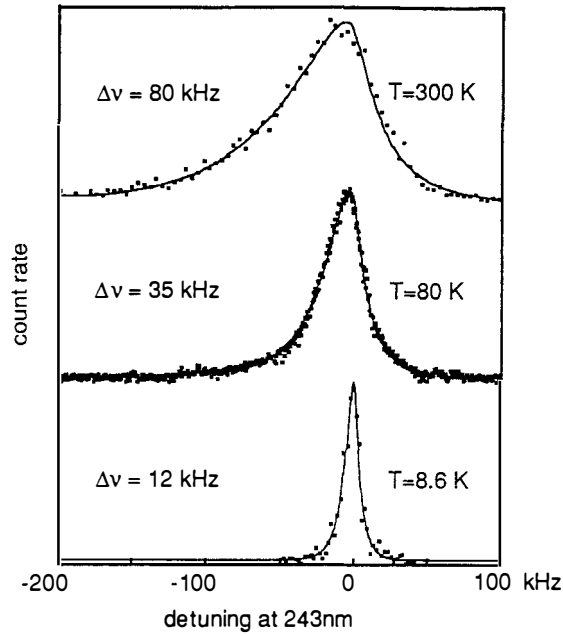

Fig.2 Spectra of the F=1 hyperfine component of the hydrogen 1S-2S two photon transition at different temperatures.

The 1S-2S energy interval is determined by the Dirac energy, by the 1S Lamb shift, by well understood corrections due to the motion of the nucleus, by the 2S Lamb shift and by the hyperfine interaction. The latter two contributions are both precisely measured. Thus, the 1S-2S transition mainly provides information about the 1S Lamb shift and the Dirac energy. An independent determination of both entities is possible by observing a linear combination of two hydrogen transition frequencies. If for instance the 1S-2S transition frequency is subtracted from four times the 2S-4S transition frequency all energy contributions proportional to n^{-2} cancel and with it the main part of the Dirac energy (n is the principle quantum number). The compound frequency which is on the order of several GHz is therefore dominated by quantum electrodynamic corrections and a precise value for the 1S Lamb shift may be derived. In combination with an absolute measurement of the 1S-2S frequency interval the precise knowledge of the compound frequency also allows to determine a new value for the Rydberg constant.

Precision Measurement of the 1S Lamb shift

The 2S-4S transition is observed by longitudinal excitation of a metastable hydrogen beam. The hydrogen atoms are excited into the 2S state by electron collisions which in addition deflect the atoms onto the axis of a standing wave resonator with 50 W circulating power near 972 nm. At the end of the beam the metastable atoms are observed by applying an electric field and observing the Lyman-α fluorescence with a channeltron detector. If the laser is tuned on resonance some of the atoms are excited into the 2S-4S from where they decay rapidly into the ground state via the 2P or 3P level and a drop of the metastable flux is observed. With an additional fluorescence detector we also record the emitted Balmer-β photons during the decay into the 2P state. The excitation light is provided by a single mode titanium sapphire laser which is electronically stabilized to an ultrastable reference resonator. Part of the laser output is frequency doubled in a potassium niobate crystal and superimposed with light from the dye laser. The resulting beat signal is recorded with fast photodiode and an electronic counter.

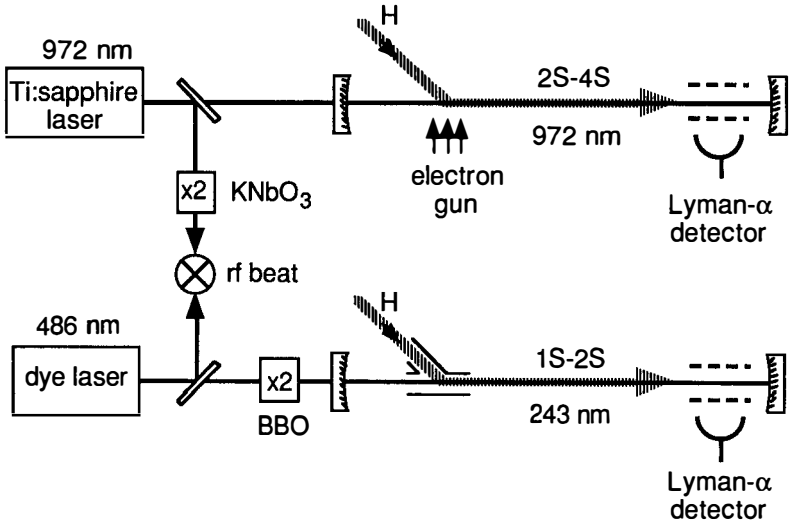

Fig. 4 Experimental apparatus for comparison of the 1S-2S two photon transition frequency with the 2S-4S transition frequency.

From the measured beat note of 4797.340(11) GHz we find a 1S Lamb shift of 8172.86(5) GHz with an accuracy, which for the first time exceeds the best measurements of the "classical" 2S Lamb shift.[3] Good agreement with theory is obtained if the Mainz value[8] for the proton charge radius is assumed to be correct and very recent new calculations of quantum electrodynamic two loop corrections [4] are taken into account. The result of these calculations have been somewhat surprising since they reveal an unexpected large QED contribution which in the past has been underestimated by about an order of magnitude.

Transition Frequency of the 1S-2S Transition and a New Rydberg Constant

For an absolute measurement of the 1S-2S frequency interval the dye laser is electronically locked to the 1S-2S resonance and its frequency is compared to the cesium clock by means of an intermediate frequency standard near 3.39 μm. This standard was built in the laboratory of V. Chebotaev in Novosibirsk and is based on a helium neon laser which is locked to the Lamb dip of a methane resonance observed in an intracavity gas cell. The standard was calibrated with a reproducibility of better than 10^{-12} at the Physikalisch Technische Bundesanstalt (Braunschweig, Germany) in direct comparison with a cesium frequency standard. We synthesize a violet reference frequency near 424 nm by generating the 8th harmonic in three steps of second harmonic generation. Because of the poor conversion efficiency after each step a phase locked laser transfer oscillator boosts the power before the light is send into next doubling stage. In this way the full accuracy of the helium neon standard is transferred to the violet frequency at 707 THz which by now represents the highest optical frequency that has been sysnthesized with an accuracy of better then 10^{-12}. Simultaneously, we generate the sum frequency between the dye laser and the helium neon standard in an additional nonlinear crystal resulting in a frequency which by coincidence is close to the 8th harmonic of the helium neon standard. A remaining frequency mismatch of about 2 THz is bridged by 6372 longitudinal modes of the dye laser reference resonator which mode spacing has been calibrated with an accuracy of better than 1 Hz. As result we find a 1S-2S frequency interval of 2466 061 413.182(45) Hz with an 18 fold improved accuracy compared to the best previous measurement. [9] From comparison with theory together with the measured 1S-Lamb shift a new value for the Rydberg constant of 109 737.315 684 1(31) cm^{-1} has been derived with a relative uncertainty of $2.8 \cdot 10^{-11}$. In the meantime our measurement has been fully confirmed by a recent measurement carried out at the Ecole Normale Superieure

in Paris.[9] As the best known fundamental constant the Rydberg constant not only serves as an important corner stone for the adjustment of fundamental constants but also establishes an entire system of accurately known reference frequencies from the vacuum ultraviolet to the visible, infrared and microwave region, because the frequencies of all other hydrogen transitions can now be predicted with improved precision, provided that QED is correct.

The hydrogen deuterium isotope shift

The 1S-2S energy interval of deuterium is shifted relative to hydrogen by 672 nm due to its heavier nucleus and its different nuclear charge radius. Since the proton/deuteron mass ratio is known very accurately a precise measurement of the isotope shift may yield to an improved value of the electron/proton mass ratio provided that the nuclear size corrections are known e. g. from measurements of the 1S Lamb-shift. To measure the isotope shift we tune the dye laser half way between the hydrogen and the deuterium 1S-2S resonance. A novel fast electrooptic modulator [10] generates optical sidebands at ± 84 GHz which serve as frequency markers close to both atomic resonances. A second identical stabilized dye laser system is alternatingly locked to the maximum of the hydrogen and the deuterium resonance and its frequency is compared to the sideband marker frequencies by recording the beat signal on a fast photodiode. The measured isotope shift of 670 994 337 (22) kHz is almost 25 times more accurate than the best previous measurement and so far limited by slow frequency drifts of the reference laser.[6] Comparison with the theoretical value of 670 994 414 (22) kHz reveals a discrepancy of 3.5 standard deviations which is yet to be explained. A recent analysis of K. Pachucki et al.[11] which includes contributions due to the deuteron polarizability reduces the 1S-2S interval by about 20 kHz.

Tabletop spectroscopic experiments are thus beginning to reach to effects of nuclear structure and dynamics in a regime of low energy and momentum transfer which is inaccessible to experiments with large colliders. High resolution spectroscopic experiments of hydrogen and hydrogen like atoms most notably antihydrogen[12] continue to hold fascinating challenges. Perhaps the biggest surprise in the endeavour would be if we found no surprise.

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