Determination of the Rydberg Frequency

Principal Investigator

Prof. Daniel Kleppner

Project staff

Joel C. DeVries and Dr. Theodore W. Ducas (Wellesley College)

Sponsors

National Science Foundation (PHY-96024740)

The Rydberg frequency, cR_∞, is one of the fundamental constants of physics. Because it set the frequency scale for the spectrum of the hydrogen atom, it plays an important role in many precision experiments. In particular, it provides a key to extracting the Lamb shift from the hydrogen spectrum. At the current time, the accuracy of the Lamb shift is limited by the accuracy of cR_∞, so it is vital that the Rydberg frequency be known reliably. Recent advances in optical frequency techniques have made it possible to measure cR_∞ to slighty better than 1 part in 10^{11}.[1,2]

The goal of this experiment is to measure the frequency of a particular transition in atomic hydrogen which is not in the optical, but in the millimeter-wave region of the hydrogen spectrum. Because our technique is totally different from that used in previous measurement, this new determination provides an important independent avenue for verification and possible improvement. We study the transition between two highly excited "circular Rydberg" states, each with a principle quantum number, n, between 27 and 30. The QED and proton structure corrections to these states are small and are not a barrier to extracting the Rydberg frequency to our accuracy goal of 1 part in 10^{11}. The frequencies of transitions between these circular Rydberg states are relatively small, around 300 GHz, and can easily be measured with respect to a cesium clock. The optical measurements, in contrast, rely on intermediate standards which have been previously calibrated and on separate measurements to account for QED and proton structure corrections. Thus our result will be an independent check, in a different regime, of the optical measurements. Furthermore, our measurement will help provide a frequency calibration of the spectrum of hydrogen, enabling the creation of a comprehensive frequency standard extending from the radio frequency regime to the ultraviolet.

The experiment employs an atomic beam configuration to reduce Doppler and collisional perturbations. Atomic hydrogen is excited to the low angular momentum n=27 or 29, m=0 state by two-photon stepwise absorption. The excited atoms are then transferred to the longer lived n=27, $|m|$=26 or n=29, $|m|$=28 "circular" state by absorption of circularly polarized radio frequency radiation.[3] The atoms enter a region of uniform electric and magnetic fields in which the frequency of the transition (n=27, $|m|$=26) $\rightarrow$ (n=28, $|m|$=27) or (n=29, $|m|$=28) $\rightarrow$ (n=30, $|m|$=29) is measured by the method of separated oscillatory fields. The final state distribution is analyzed by a state-sensitive electric field ionization (EFI) detector. The resonance signal appears as a transfer of atoms from the lower state to the upper state as the millimeter-wave frequency is tuned across the transition.

Figures 5 and 6 illustrate the main features of the apparatus.

Atomic hydrogen or deuterium is dissociated from H_2 or D_2 in a radio frequency discharge. The beam is cooled by collisions with a cryogenic thermalizing channel in order to slow the atoms and thereby increase the interaction time. After the beam is collimated, the atoms pass through two layers of magnetic shielding and an 80 K cryogenic shield before entering the interaction region. The interaction region is logically divided into three sections: the circular state production region, the separated fields region, and the detection region. These are described briefly below.

In the circular state production region, the hydrogen atoms are excited from the $1s$ ground state, through the $2p_{3/2}$ state, to the n=27 or 29, m=0 state by two-photon stepwise excitation. The laser system has been detailed in the 1995 and 1996 Progress Reports. The optical excitation is performed in an electric field to provide selective population of a particular m=0 level. The electric field is then rapidly reduced to an intermediate value as the atoms pass through the center of a circle of four electrodes. The antennas are fed by a 1.8 GHz RF source with a 90° phase delay between adjacent pairs. This creates a circularly polarized field which drives the atoms into the n=27, $|m|$=26 or n=29, $|m|$=28 circular state through a multiphoton absorption process. A pulsed EFI detector in the circular state production region monitors the efficiency of the optical excitation and angular momentum transfer processes.

After the atoms are prepared in the circular Rydberg state, the beam enters the millimeter-wave separated fields region. Because Rydberg atoms interact strongly with external fields, accurate measurement of the energy level structure requires careful control of the interaction environment. Thermal radiation is reduced by cooling the entire interaction region to ≈4 K with a liquid helium flow system. The ambient magnetic field is reduced by the double-wall high-permeablility shields and a uniform magnetic field of ≈150 mG is applied. A small electric field, which defines the quantization axis of the atoms, is applied with high uniformity by field plates above and below the atomic beam. The millimeter-waves intersect the atomic beam at two locations separated by 50 cm. The millimeter-wave optical system was described in the 1990 Progress Report. The millimeter-wave zones inside the interaction region consist of two Fabry-Perot cavities which determine the spatial field of the millimeter-wave radiation.

The state distribution of the atoms emerging from the interaction region is analyzed by a state-selective EFI detector. Within the detector, the atoms enter a region of increasing electric field produced by a pair of symmetric ramped plates held at constant potential. Atoms in different states are selectively ionized at different fields and the charged nuclei are detected at different positions. The detection electronics record the state and arrival time of each atom to reach the detector. Because the laser system is pulsed, the time resolution of the ionization signal allows contributions to the resonance pattern from each velocity class to be analyzed individually, providing a valuable check on possible systematic errors.

To find the frequency of the circular state to circular state transition, we measure the population inversion as the millimeter-waves are tuned through resonance. The inversion is defined as

$$\mathcal{I} = \frac{N_{upper} - N_{lower}}{N_{upper} + N_{lower}}$$

where N_{lower} and N_{upper} are the number of ion counts detected in each electron multiplier. As a preliminary diagnostic step, we can leave open only one of the millimeter-wave ports, in which case the resonance curve is a single peak – a "Rabi curve". If both millimeter-wave ports are open, we see the interference fringe characteristic of the Ramsey separated oscillatory fields technique.

This year we have concentrated on the elimination of systematic errors in our measurement of the Rydberg

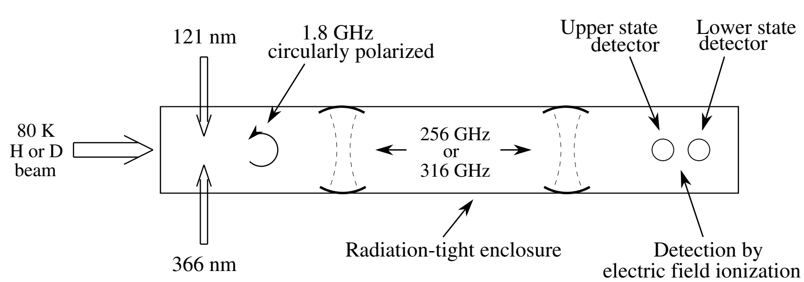

Figure 5: Schematic top view of the apparatus.

frequency. We have increased the signal rate to the point that our statistical error is about 1 parts in 10^{11} for one day of data acquisition, allowing us to look for systematic errors at that accuracy level. Parameters we have varied include the static electric field, the magnetic field, the intensity of the millimeter-wave beams, polarization of the excitation lasers, the end-to-end phase of the millimeter-wave beams, and the time standard employed for the frequency measurement. This work has allowed us to identify and control some of the sources of systematic error.

The most conspicuous systematic was due to 60 Hz phase noise on the frequency reference due to line noise. Since we were triggering the experiment at the line frequency, we were sensitive to the phase noise. That is, every time we triggered the experiment, the millimeter-wave phase would vary in the same way and cause an apparent frequency shift in the transition. To resolve this problem, we now trigger the experiment at 61.00 Hz and the effect of the 60 Hz phase noise averages out over the period of one second.

The second major systematic problem was an asymmetry of the Ramsey fringes due to polarization of the electron spins in the hydrogen beam. This polarization produces an uncertainty in our measurement because it affects the relative weighting of two fine structure transitions, which we do not completely resolve. We have found that linearly polarizing the laser beams and applying a uniform magnetic field of $\approx$ 150 mG reduces the polarization to less than 0.1 percent, thereby reducing the associated uncertainty in the extracted Rydberg frequency to an acceptable level.

Unfortunately, there is still an as yet unknown systematic error plaguing our experiment and causing shifts in the measurement that vary from day to day, yielding measurements that vary by several parts in 10^{11}. Figure 7 shows the clearly inconsistent results from the last four runs. We are now considering candidates for this observed systematic. On the top of our list is any errors due to lower order spatial modes of the millimeter-wave cavities. These lower order modes perturb the phase of the millimeter-wave radiation and cause frequency shifts in the transition. Thus, it comes down to controlling the power in these modes, and understanding their effect on the frequency of the transition.

We will continue to acquire resonance data and check the reproducibility of our Rydberg frequency measurements. The accumulation of several consistent experimental runs will allow us to approach an uncertainty of 1 part in 10^{11}.

References:

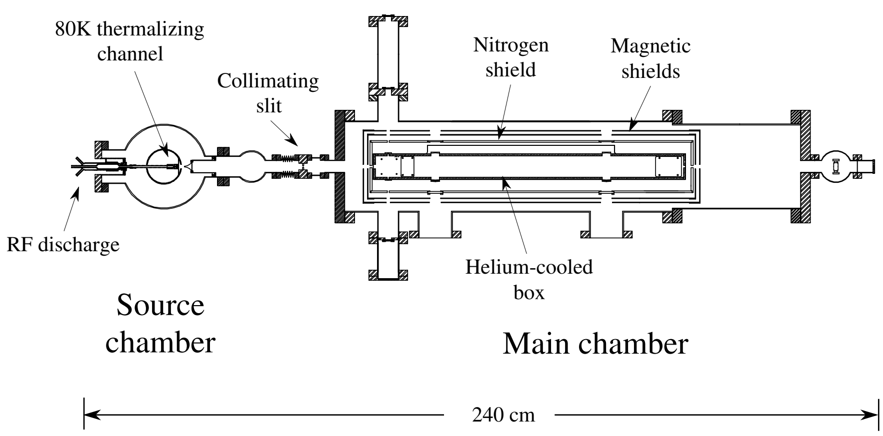

Figure 6: Top view of the atomic beam vacuum apparatus.

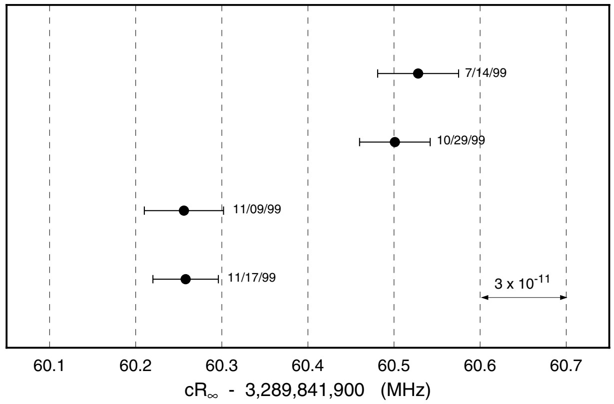

Figure 7: Results from four days of running. The statistical error is small, but there is a systematic error which varies from day to day that we are attempting to bring under control.

[1]B. de Beauvoir et al., "Absolute Frequency Measurement of the $2S{-}8S/D$ Transitions in Hydrogen and Deuterium: New Determination of the Rydberg Constant," Phys. Rev. Lett. 78(3): 440-443 (1997).

[2]Th. Udem et al., "Phase-Coherent Measurement of the Hydrogen $1S{-}2S$ Transition Frequency with an Optical Frequency Interval Divider Chain," Phys. Rev. Lett. 79(14): 2646-2649 (1997).

[3]R. Lutwak, J. Holley, P.P. Chang, S. Paine, D. Kleppner, and T. Ducas, "Circular states of atomic hydrogen," Phys. Rev. A 56(2): 1443-1452 (1997).