Ultracold Hydrogen

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Research in the Ultracold Hydrogen Group centers on studies of the structure of atomic hydrogen, ultracold collisions, the properties of hydrogen as a quantum gas and ultrahigh precision spectroscopy. Principal activities during the past year include a study of the possibilities for trapping deuterium, the first demonstration of spectroscopy from the metastable 2S state of ultracold hydrogen, construction of a mode-locked laser for optical frequency metrology of hydrogen, and development of a new technique for trapping and cooling hydrogen that employs a thermalzing agent—a second species of trapped atom—and uses buffer gas cooling techniques.

1. Studies with ultracold deuterium

Spin-polarized deuterium has never been confined using the traditional techniques for confining spin-polarized hydrogen [1]. We have undertaken a study of the possibilities for trapping deuterium based on our methods for cooling hydrogen in a magnetic trap. The goals are to explore the optimal trapping conditions, and determine the number, density, and temperature of initially trapped deuterium. Once confined, the gas could be cooled by forced evaporative cooling, using “saddle point” evaporation over a magnetic barrier and RF evaporation.

Trapped deuterium could be detected using bolometric techniques that have been long employed for hydrogen. However, optical detection offers an attractive alternative. This is a well-established technique for hydrogen: the 1S-2S transition is excited, and the metastable 2S states are quenched by applying an electric field. The excited atoms radiate on the Lyman-alpha transition, which is readily detected.

In our current studies, two-photon 1S-2S transition in hydrogen (243 nm) is induced by radiation that is generated by frequency-doubling the output of a 486 nm laser. Our existing laser system would be capable of driving the deuterium 1S-2S transition. This method would allow us to detect the trapped atoms and it also opens the possibility of doing high-resolution spectroscopy on deuterium, as well as determining various scattering lengths and the 1S-2S density shift. The transitions frequencies for hydrogen and deuterium differ by 168 Ghz (at 486nm), while the linewidth of the transition is only a few kHz. As a result, the frequency search problem could be difficult. Fortunately, the tellurium spectrum provides a useful frequency reference, and using both unsaturated and saturated spectroscopy it would be possible to lock our laser less than 4 MHz from the deuterium line.

Part of the scientific interest in ultracold deuterium is its femionic nature, in contrast to hydrogen, which is bosonic and has displayed Bose-Einstein condensation. There is growing interest in trapping and cooling fermionic and fermionic-bosonic mixtures of atoms, and a series of experimental studies have been carried out with fermionic alkali atoms (c.f. [2].). At low temperature, fermionic atoms interact only by p-wave scattering, and as a result the scattering cross section vanishes. Because evaporative cooling requires collisions to maintain thermal equilibrium, it would not be possible to evaporatively cool deuterium at very low temperatures. It is not know where the threshold for p-wave collisions lies but it might be as high as 100 mK [3]. Below the threshold temperature, it could be possible to cool the atoms by using a gas of atoms in two hyperfine states [3]. Unfortunately, this is not possible for deuterium in out trap, since only the "stretched" hyperfine state has a long lifetime.

An alternative way to maintain thermal equilibrium at low temperature deuterium would be to employ hydrogen-deuterium mixtures, allowing us to cool the deuterium to Fermi degeneracy by thermal contact with the hydrogen in the trap. Possibly the deuterium would make it possible to cool the hydrogen more efficiently, with the deuterium serving as a trapped buffer gas. We will soon have two laser systems capable of exciting the 1S-2S transition in hydrogen or deuterium, which would allow us to do simultaneous spectroscopy on ultra-cold hydrogen-deuterium mixtures.

However, our attempts to trap deuterium have met with difficulties at several stages. We had difficulty in operating our cryogenic discharge loaded with deuterium. The deuterium discharge requires higher power to run than a discharge loaded with hydrogen. Our ability to load our magnetic trap depends on how fast we cool our cell after operating the discharge, and so this extra power and heating of the discharge constitutes an impediment.

Surface recombination of deuterium in the initial states of loading is a major concern. The absorption energy of deuterium on a helium-4 surface is 3.1K, in contrast to 1.1 K for hydrogen. [4]**.** To reduce the rate of surface recombination, we have employed a mixture of helium-3 and helium-4 to coat our cell walls. The adsorption energy of deuterium on helium-3 is estimated to be about 1.5 K. At low temperatures, these isotopes phase separate, with the helium-3 lying above the helium-4. Not knowing initially the optimal ratio of helium-3 to helium-4, we planned on using trial and error with several different mixtures.

Unfortunately, with the current design of our trapping cell, it is impossible to efficiently remove helium-3. Despite its higher vapor pressure, helium-3 does not become superfluid and is not transported well through our capillary pump-out line. Removing the heium-3 requires heating the cell to about 10K. However, our current cell design includes a liquid helium jacket, to provide thermal conductivity from cell top to bottom. Filling and emptying this jacket is time costly, as well as potentially damaging to the cell and vacuum systems. For these reasons we could not test more than a few helium-3 /helium-4 ratios. We detect no trapped deuterium for any of these trials. We did, however, notice some promising effects when helium-3 was present: the deuterium atoms coming from the discharge pulses were slowed by the presence of our magnetic trap, demonstrating that not all were immediately lost to the walls.

For future deuterium experiments, it might be best to use a simpler cell design that allows for fast cooling and heating and systematically test different helium-3 to helium-4 ratios. In a new magnetic trap design, with significantly higher magnetic fields at the cell walls (the current fields are 1 Tesla, or 0.6 Kelvin), it might be possible to trap deuterium without any surface collisions, since the quantity determining the trap-loading loss is most likely the ratio of the cell wall surface potential to the trap field at the cell walls**.** This approach is described below in Section 4.

2. Spectroscopy of ultracold hydrogen

The spectroscopy of hydrogen has been a touchstone for testing fundamental theory and advancing metrology. Trapped ultracold hydrogen offers opportunities for major advances in hydrogen spectroscopy because of the long interaction times possible for a confined gas, the natural advantages in observing low energy, slowly moving atoms, and the relatively benign environment of the trap. Because of hydrogen's continuing role as a testing ground for atomic theory and quantum electrodynamics, the opportunities for scientific advance are large.

We have undertaken a program of ultraprecise spectroscopy of two-photon transitions of the type 2S – nS (n ~ 8-12), in order to improve our knowledge of the Lamb shift and the Rydberg constant. For this purpose we are constructing a series of lasers with which to excite transitions from the 2S level. The laser frequencies will be measured relative to the precisely known 1S-2S frequency of hydrogen (uncertainty: 1.8×10^{-14} [5]). The measurements will employ a Ti: Sa femto-second frequency comb currently under construction in our laboratory. This comb will be locked to the frequency-doubled dye laser that pumps the 1S-2S transition. Thus, the frequencies will all be referenced to hydrogen itself, permitting us to use hydrogen as our optical frequency standard. The comb will provide a frequency reference stretching across the red and near-infrared spectrum.

The cw lasers to pump the atomic transitions (wavelength range 656 – 780 nm) are homebuilt diode lasers that are stabilized by grating feedback. Each transition requires a laser source that can be locked to a tooth of the frequency comb, near the resonance, and a second source that is locked to the first with a variable frequency offset, that can be swept across the resonance. A source consists of a low-power grating-stabilized diode laser, and a higher power diode laser that is injection-locked to it. The first two-photon transition to be studied will be 2S-8S at 778 nm.

Precision frequency measurements of the 2S-nS transitions will be combined with theoretical calculations to yield new measurements of the 1S Lamb shift and the Rydberg constant. The current level of precision is 7.7×10^{-12} for the Rydberg constant and 2.7×10^{-6} for the 1S Lamb shift [6].

The precision of previous comparable measurements, for instance 2S –12D, has been limited by AC Stark shifts caused by the large laser fields needed to observe a signal in the relatively warm and quick moving hydrogen beams that were used. The AC Stark shifts are one of the limiting factors. The other is the second order Doppler effect. Because our hydrogen sample is trapped and extremely cold (100 uK vs. 4K), our laser-atom interactions times are vastly increased allowing us to use much lower light powers, and the second order Doppler effect is negligible. The limiting error in the first round of our experiments will probably be the DC Stark shift caused by stray electric fields in the trapping cell. By judicious choice of transition (DC Stark shifts increase as n^2 (linear) and n^7 (quadratic)) and efforts to reduce stray fields, we hope to reduce the error sufficiently to achieve a ten-fold increase in precision of the Rydberg constant and the Lamb shift.

Precise measurements of the hydrogen Lamb shift have provided critical tests of QED theory. Recent contradictory calculations of the unexpectedly large two-loop correction to the Lamb shift have raised pointed to problems in the execution of the theory [7]. The accuracy of our proposed experiment should help to resolve questions about these issues.

Interpretation of the experimental values for the Lamb shift is currently limited by uncertainty in the proton charge radius. There are currently at least two experiments seeking to improve the accuracy of the proton charge radius. A Lamb shift measurement in muonic hydrogen is underway at the Paul Schearer Institute in Zurich that aims to improve precision by a factor of 20 [8]. Such an improvement, coupled with our proposed hydrogen Lamb shift measurements would yield the required experimental accuracy to probe the two-loop correction results. A new electron scattering determination of the proton charge radius has also been proposed [9].

As a first step in developing the technology for optical spectroscopy in ultracold hydrogen, we observed the 2S-4P transition by measuring the decrease in the Lyman-alpha signal from the quenched 2S atoms as the laser was scanned across the 2P fine structure spectrum. The results are shown in Figure 1. The 2S-3P one-photon transition is also being investigated, to work through technical issues in alignment, experimental timing and signal collection. We are also pursuing absorption spectroscopy of iodine. The rich molecular structure of iodine provides absorption lines within a few 10's of MHz of all of the hydrogen transitions of interest. We will use these absorption lines as a fingerprint to tune a diode laser to the comb line nearest to the 2S-nS transition frequency under investigation.

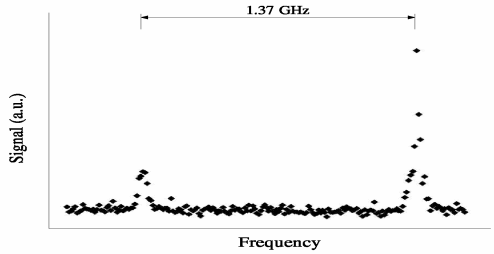

Figure 1. Observation of the 2S-4P transition in hydrogen. The baseline is the signal from 2S atoms in the trap: the increase in signal corresponds to a decrease in the 2S atoms in the trap.

3. Femtosecond Optical Comb Generator

To carry out the program of spectroscopy described above, we have constructed a frequency comb generator, which is referenced to the 1S-2S transition while simultaneously covering the 2S-nS spectral range completely.

The frequency comb is generated directly out of a prismless Kerr-Lens Modelocked Ti:sapphire without the need for external broadening in a fiber [10]**.** This method employs a novel ultrabroadband dispersion -compensating laser mirrors ("double-chirped mirror pair" design), which control the intracavity dispersion from 600-1200 nm. The laser emits sub-10 fs pulses at a repetition rate of 79 MHz with a spectrum covering more than 2/3 of an octave in a 3dB bandwidth. Typical frequency comb setups make use of commercial mode-locked lasers which produce 30-100 fs pulses and typical spectra 10 times narrower than our laser. The dispersion in these systems is usually controlled with intracavity prisms. This, together with the need for a microstructure fiber to generate spectrum via self-phase modulation introduces instabilities and phase noise into the system. Our prismless setup has the advantage of great long term stability. Because we do not need to couple into a fiber, there is no problem of burning the fiber tip, and we obtain higher power per mode. We obtain up to 150 mW directly from the laser in a well-behaved beam.

The comb has been locked to the to the laser that drives the 1S-2S: our stabilized cw-dye laser at 486 nm. The 486 nm output from this laser is heterodyned with the second harmonic of the comb spectrum at 972 nm. The doubling is achieved without loss of power per mode, using broadband sum-frequency mixing in a 10 mm potassium-niobate crystal. The beat signal is then phase locked to a stable RF synthesizer through transducers in the laser cavity, which control the cavity length and therefore the frequency of each mode comb. Figure 2 displays a spectrum from the laser. Recent improvement in bandwidth of our Ti:ssapphire laser permits a self-reference locking scheme in which the comb offset frequency can be measured directly from the laser. In that way, every comb mode frequency is directly derived from the 1S-2S frequency in H. In these experiments we aimfor a precision of 1 part in 10^{12}. By merely exciting the 2S atoms we can readily control the frequency of the 1S-2S frequency to 1 part in 10^{13}, which is adequate for these initial experiments.

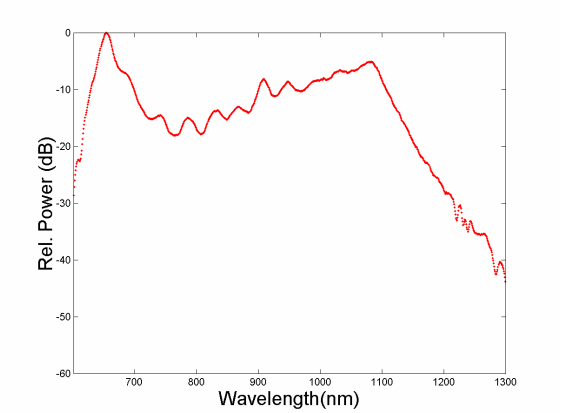

Figure 2. Spectrum of a Ti:sapphire mode-locked laser operating on the double-chirped mirror pair design. Repetition rate: 80 Mhz; average power: 150 mW.

4. Accelerated hydrogen cooling

The rate of evaporative cooling of hydrogen is limited by hydrogen's extremely small S-wave scattering cross section. The elastic scattering rate for hydrogen at a given temperature is typically a thousand times lower than for the alkali metal atoms. Because elastic collisions are essential for maintaining thermal equilibrium during evaporation, the time scale for cooling hydrogen is very long. Due to the presence of loss processes, the long time for evaporation of hydrogen makes evaporative cooling of hydrogen not only slow but also inefficient.

We propose to accelerate the evaporative cooling of hydrogen by introducing a second species with a large S–wave cross section, to act as a thermal moderator. The process should be distinguished from sympathetic cooling, in which one species is used to cool another. Coté *et al* [11] have calculated the H-Li triplet scattering length, and obtain a value of 65 bohr. This large value, combined with lithium's relatively small mass, make lithium an attractive candidate for a moderator.

To implement this strategy we propose to employ a new approach, and an entirely new apparatus, for cooling hydrogen. Our studies of ultracold hydrogen have been carried out in an apparatus that has evolved over many years. We have initiated a project to create and study ultracold hydrogen using accelerated cooling in an apparatus that takes advantage of our long experience.

Seminal to the new method is the use of buffer gas loading [12]. Hydrogen and lithium atoms are introduced into a magnetic trap along with a buffer gas of cold helium-3. The atoms diffuse toward the walls of the trap, inhibited by the magnetic barrier. The helium-3 is rapidly removed from the cell, and the atoms rapidly evaporate to a temperature well below the magnetic field barrier. At this point, evaporative cooling can be commenced following well-established methods. Major features of this approach include:

- Absence of liquid-helium films. Buffer gas loading avoids the need to initially themalize or transport the hydrogen on a helium-coated surface, since the atoms never reach the surface.
- Spherical quadrupole trap. Initial loading is in a spherical quadrupole trap that provides a magnetic barrier several times larger than possible with the linear quadrupole design currently used.
- Linear quadrupole trap (Ioffe-Pritchard trap). After the atoms have been initially cooled in the spherical quadrupole trap, an Ioffe-Pritchard trap will be turned on. This trap is used for final cooing, and it can be used to transfer the atoms to a separate observation region. This trap's relatively small conductors and open geometry provides a flexible, open, geometry.

- Accelerated cooling. Lithium atoms will serve as a thermal moderator.
- Laser ablation source. In place of the traditional discharge source for providing atomic hydrogen to the trap, we plan to employ laser ablation of Li H. Ideally this will provide both hydrogen and lithium atoms in a 1:1 ratio.
- New cryogenic apparatus. This project will employ a new dilution refrigerator and cryogenic apparatus. This will avoid a number of shortcomings of our existing apparatus, including a tendency to develop insidious leaks.

Status: During the past year the dilution refrigerator was delivered, and the installation largely completed. The general design of the apparatus has been established and final design and construction is underway.

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