Spectroscopy of Ultracold Hydrogen

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High resolution two-photon spectroscopy of the $1S$-$2S$ transition is a powerful tool for the study of magnetically trapped atomic hydrogen. We employ this intrinsically narrow transition as a sensitive probe for the temperature and density of the evaporatively cooled sample. Our measurement of the density-dependent $1S$-$2S$ cold-collision frequency shift [1] led to the first observations of Bose-Einstein condensation (BEC) in hydrogen [2].

We have studied the time evolution of the condensate. In the hydrogen condensate the population is only a few percent of the trapped sample [2]. The non-condensed atoms constitute a large reservoir that continually replenishes the condensate as atoms are lost through dipolar relaxation. This replenishment dramatically increases the lifetime of the condensate to more than 10 s, which is long compared to the characteristic decay time due to dipolar relaxation: for a peak condensate density of 2×10^{15} cm^{-3}, $\tau_{dip,c} \simeq 1.5$ s. We have observed the replenishment by obtaining spectra at various hold times after the end of the forced evaporation. The condensate population is inferred from its contribution to the $1S$-$2S$ spectrum (Fig. 1). The observed time evolution is compared to a simulation of the loss processes in the trap, dipolar decay and evaporation. This allows us to set a limit on the peak density of the condensate. Using the peak shift observed in the condensate spectrum, we determine the shift per density to be $-3.9(8)$ Hz/10^{10} cm^{-3} [3], which is in agreement with the shift per density for excitations from a nondegenerate sample [1].

We recently redesigned our trapping apparatus for better suppression of stray electric fields and improved rf evaporation. In initial experiments, we have been able to excite as many as 10^7 atoms into the $2S$ state with a single 1 ms laser pulse. This excited state is also magnetically trapped. Its lifetime has been observed to be as long as 100 ms, close to the natural lifetime of 122 ms. This corresponds to stray electric fields of less than 20 mV/cm. We have also improved the detection efficiency, allowing us to sweep the $1S$-$2S$ resonance more quickly and permitting better time resolution for studies of the dynamics of the trapped sample.

The improvements to the apparatus should enable us to investigate condensate formation, which is only partially understood. Recent experiments carried out with sodium indicate qualitative agreement between theory and experiment, but the very first stages of formation have not been observed in detail. The slow collision rate in trapped hydrogen gas makes it a good candidate for observing a condensate in its nascent stages. We intend to study the formation dynamics of the condensate by quickly removing some or all of the condensate by rf ejection, and monitoring the re-establishment of the condensate using $1S$-$2S$ spectroscopy.

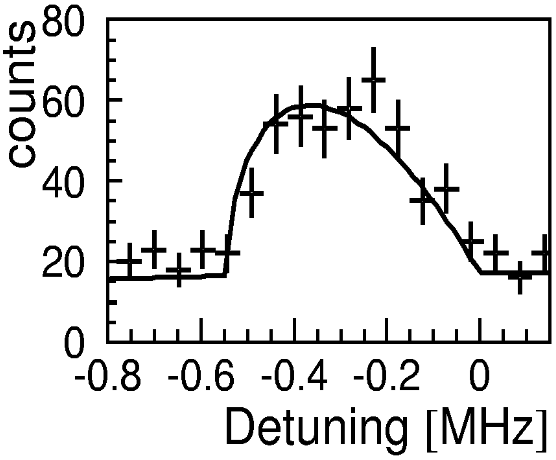

Figure 1: Doppler-sensitive 1S-2S spectrum of a hydrogen condensate. The condensate contribution is red-shifted from the center of the Doppler profile due to the cold collision frequency shift. The shape of the spectrum is in agreement with the expected density distribution for the condensate in the Thomas-Fermi approximation.

The generation of a substantial population of trapped atoms in the metastable $2S$ state makes precision measurements of transitions originating from the $2S$ state feasible. Of particular interest are the magnetic field insensitive $2S$-nS two-photon transitions. The frequencies of these transitions, combined with the $1S$-$2S$ transition frequency, yield values for the Lamb shift and Rydberg constant. As an example, the $2S$-$8S$ frequency has recently been measured to an accuracy of 1.3×10^{-11} [4] in a beam of metastable atoms. An order of magnitude improvement could be possible using a sample of ultracold $2S$ atoms.

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[2] D. G. Fried, T. C. Killian, L. Willmann, D. Landhuis, S. C. Moss, D. Kleppner, and T. Greytak, *Phys. Rev. Lett.* **81**, 3811 (1998).

[3] L. Willmann, D. Landhuis, S. C. Moss, D. G. Fried, T. C. Killian, T. Greytak, D. Kleppner, *publication in preparation.*

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