Resonance-enhanced two-photon spectroscopy of magnetically trapped atomic hydrogen

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We show that resonant enhanced two-photon spectroscopy is a very powerful and promising diagnostic method for trapped atomic hydrogen and antihydrogen. This method, in which photons of different wavelengths are used to excite H atoms from the 1S to the 3D or 3S level, uses the resonant enhancement of the intermediate 2P level to obtain high sensitivity while at the same time offering potentially much higher spectral resolution than single photon (Lyman-α) excitation.

1. Introduction

The first production of neutral antihydrogen $\overline{\mathrm{H}}$ atoms in 1996 [1] was the first true experimental proof of the existence of neutral (atomic) antimatter in the universe. This very fact drew much attention. However, the true challenge is to investigate antihydrogen in a qualitative way and the general consensus is, that to do this it will be necessary to store the $\overline{\mathrm{H}}$ atoms in a wall-free manner at sub-Kelvin temperature, using a magnetostatic trap. Slow, if steady, progress is being made toward this goal (see, e.g., [2,3]) but a description of this research lies outside the scope of this paper. What we will do is discuss an equally important goal: once the $\overline{\mathrm{H}}$ atoms exist in a trap it is essential that nondestructive diagnostic methods are available to study these atoms. In this paper we discuss one such method: resonance-enhanced two-photon spectroscopy (RETS) which we believe to be particularly suitable for the study of trapped antimatter. Trapped $\overline{\mathrm{H}}$ atoms are not yet available, hence, we will discuss experimental results obtained with ordinary hydrogen atoms.

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Aside from being an essential tool for neutral antimatter, RETS is also very useful for H atoms. In Amsterdam we have used RETS for Doppler and Zeeman thermometry of a dense trapped gas of H atoms. Here we took advantage of the so-called tunable transparency that the method offers to circumvent the problem of opacity of the sample for near resonant light at high H densities. One has the option of exciting Zeeman-free lines which allows for pure Doppler-effect thermometry at very low temperatures. Furthermore, the high resolution of the method can serve to resolve hyperfine components of the ground state which was used in experiments with high density H-samples in contact with superfluid helium [4].

Once wall free confinement of antihydrogen exists it will presumably be at relatively small densities. This requires a spectroscopic diagnostic tool of high sensitivity. On the other hand, to do meaningful experiments the possibility to obtain a high spectral resolution is also essential. Methods generally used for the diagnostics of H atoms are Lyman-α spectroscopy (1S–2P transition at 121.6 nm) and two-photon spectroscopy on the 1S–2S transition (using two photons of 243 nm). Neither of these satisfies both requirements. Lyman-α spectroscopy is very sensitive but the linewidth is limited by the lifetime of the 2P level (1.6 ns). 1S–2S spectroscopy, on the other hand, has an enormous potential for resolution (the limit to the linewidth is $\sim$1 Hz) but its sensitivity is low because it is a nonresonant two-photon transition. The method described here (RETS) is an excellent and flexible method combining the advantages of the above two methods. Its resolution is determined by the lifetime of the upper level. This is either the 3S level (corresponding linewidth $=$ 1 MHz) or the 3D state (linewidth 10 MHz, still 10 times less that the 100 MHz linewidth of the 1S–2P transition). The sensitivity on the other hand is greatly enhanced by using two different photon energies. By choosing the intermediate frequency close to one of the sublevels of the 2P manifold the sensitivity can be boosted to practically the same level as one photon Lyman-α spectroscopy as we discuss below. In fact resonance-enhanced 1S–3S spectroscopy offers the perspective of a spectral resolution that is two orders of magnitude better than one-photon Lyman-α spectroscopy, with, at the same time, a resonant cross section of up to 50% of the $3\lambda^2/2\pi$ single photon Lyman-α cross section.

2. Principle of RETS

We now describe the principle of RETS. More details are given in [5] and particularly in [6]. In figure 1 the relevant levels are drawn together with the laser frequencies used in RETS: 122 nm (close to the Lyman-α frequency) and 656 nm (close to Balmer-α), respectively. The principle of the method for RETS of the 3D level (for the 3S level it is essentially the same) is as follows: for a given magnetic field (the bias field of the magnetic trap) we choose a fixed detuning δ of the Balmer light from the resonance frequency of the 2P–3D transition. Now we apply the Lyman light which is frequency-scanned (as here, in the rest of the paper we shall often drop the subscripts α).

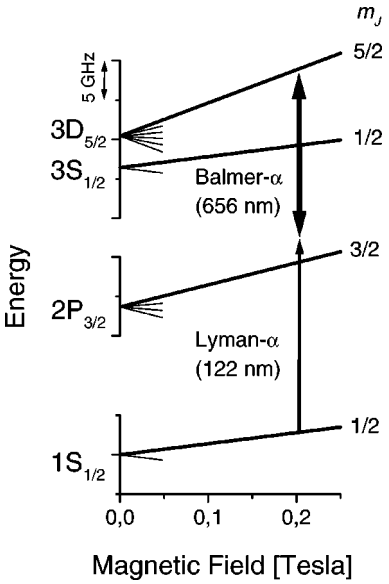

Figure 1. Simplified scheme showing levels and transitions involved in RETS. For simplicity the $3D_{3/2}$ levels are not shown. The transition indicated, $1S_{1/2}(1/2)$–$3D_{5/2}(5/2)$, is the only one allowed if both lasers are σ^+ polarized. In this case the only relevant intermediate level is $2P_{3/2}(3/2)$. If the Lyman laser is polarized σ^+ and the Balmer laser σ^-, one can excite the transition to the $3S_{1/2}(1/2)$ level. This transition is Zeeman-free and can be used for pure Doppler thermometry.

This light will be absorbed by the H atoms on two separate resonances: firstly on the 1S–2P transition (this is the ordinary Lyman-α transition which is also present in the absence of the 656 nm light). A second resonance occurs when the detunings of the Lyman light from the 1S–2P transition (Δ) and of the Balmer light (δ) are exactly opposite. This is the two-photon transition where the sum of the two frequencies is equal to the 1S–3D splitting. We can look at RETS in the following way: one can define an effective cross section for absorption of Lyman light as a function of its frequency. This cross section depends on parameters of the Balmer light such as the intensity, polarization and detuning δ. In [6], the following equation, valid for weak Lyman but arbitrarily strong Balmer light, for this cross section is derived:

$$\sigma = \sigma_0 \gamma_a \left[\gamma_a + \frac{\gamma_b \Omega_{\mathrm{B}}^2/4}{(\delta+\Delta)^2+\gamma_b^2} \right] \left[\left(\Delta - \frac{(\delta+\Delta)\Omega_{\mathrm{B}}^2/4}{(\delta+\Delta)^2+\gamma_b^2} \right)^2 + \left(\gamma_a + \frac{\gamma_b \Omega_{\mathrm{B}}^2/4}{(\delta+\Delta)^2+\gamma_b^2} \right)^2 \right]^{-1}, \tag{1}$$

where Ω_{B} is the Rabi frequency of the Balmer light, γ_a and γ_b are the half-widths of the 2P and the 3D level, respectively, and σ_0 is the resonant cross section of the Lyman-α transition. In the absence of Balmer light, eq. (1) reduces to a Lorentzian of width γ_a which is just the lineshape function of the single photon Lyman-α transition.

If Ω_{B} is nonzero, a second line appears near the resonance condition of the two-photon transition $\Delta + \delta \approx 0$. This is the two-photon line. In fact this resonance occurs

when $\Delta + \delta = \Omega^2/4\Delta$, where the small deviation form zero on the r.h.s. is the light shift due to the Balmer light. For large Δ the line is approximately Lorentzian with half width γ_{B}. In the limit of $|-\delta| \approx |\Delta| \gg \gamma_a$, we obtain from eq. (1) that:

$$\sigma_{2\mathrm{phot}} \approx \sigma_0 \left[2 + \frac{\gamma_b}{\gamma_a}\frac{4\Delta^2}{\Omega_{\mathrm{B}}^2}\right]^{-1}, \qquad \gamma_{2\mathrm{phot}} \approx \gamma_b \sqrt{1 + \frac{\gamma_a}{\gamma_b}\frac{\Omega_{\mathrm{B}}^2}{2\Delta^2}}. \tag{2}$$

Here $\sigma_{2\mathrm{phot}}$ is the cross section of the two-photon transition at the resonance condition $\Delta + \delta = \Omega^2/4\Delta$, where the last term is the light shift, and $\gamma_{2\mathrm{phot}}$ is the width of the two-photon transition. When we choose $\Delta^2 \geqslant 2\Omega^2\gamma_a/\gamma_b$, then the linewidth becomes limited by the lifetime of the upper level whereas the cross section can be still within a factor 4 of that of the single photon value. For even larger detuning δ the expressions eq. (2) reduce to the perturbative result in which case the cross section diminishes proportional to $1/\delta^2$ or alternatively $1/\Delta^2$.

3. Experiments with trapped H

The experiments with RETS are performed with two separate light sources. The Balmer light, tunable around 656 nm, is produced with a cw dye laser (Coherent 699). The Lyman light is obtain by pulsed amplification of cw light from a Ti:Sapphire laser (730 nm) followed first by frequency doubling and then by third harmonic generation in a gas cell containing a phase-matched mixture of Kr and Ar. The spectra are recorded by measuring the transmission of the Lyman-α beam through the gas cloud. On successive pulses the Balmer light is alternately on and off. By subtraction the curves for odd and even points we obtain a pure two-photon signal. The trapping experiment itself is performed in a dilution refrigerator running at temperatures around 100 mK. Details of various aspects of the light sources and the cryogenic system can be found in [5–7].

Experimental demonstrations of RETS on samples of cold trapped H atoms are given in figures 2 and 3. In figure 2 we show the absorption spectra of the Lyman light in the presence of Balmer light of various detunings. It can be clearly seen that if δ is small the two lines "repel" each other and change role as δ changes sign (avoided crossing). This effect is the well known Autler–Townes effect [8] which is most easily understood in terms of a dressed atom picture [9]. For somewhat larger detuning the results of figure 2 are similar to the predictions of eq. (2). The fact that the linewidth is bigger than predicted by eq. (2), as a consequence the signal appears weaker, is due to additional broadening mechanisms: Doppler broadening, inhomogeneous (Zeeman) broadening due to a distribution of magnetic field values over the gas cloud, and, most importantly, the instrumental broadening. The latter effect is almost entirely due to the finite bandwidth (150 MHz) of our Lyman-α source. To take full advantage of the high resolution of RETS, it will be necessary to use a narrow band source of 122 nm light such as the cw Lyman-α source recently developed in Garching [3,10].

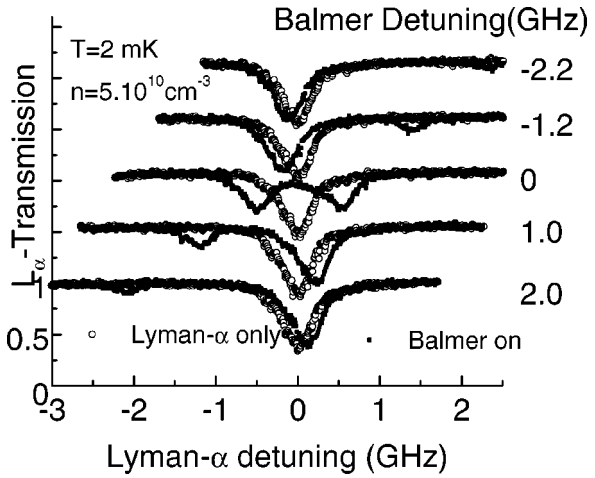

Figure 2. Measured absorption spectrum for Lyman-α light with (full symbols) and without (open symbols) Balmer-α light, as a function of Balmer detuning δ. The strong line near the center of the graph is the one-photon (Lyman) absorption. The other feature is the RETS signal. For $\delta = 0$ both lines are mixtures of the one- and two-photon line (Autler–Townes doublet). Their splitting in this case is twice the light shift. The absorption feature is drawn which reflects that what is measured is the transmission of the probe beam through the gas cloud. The transition used here is the one indicated in figure 1.

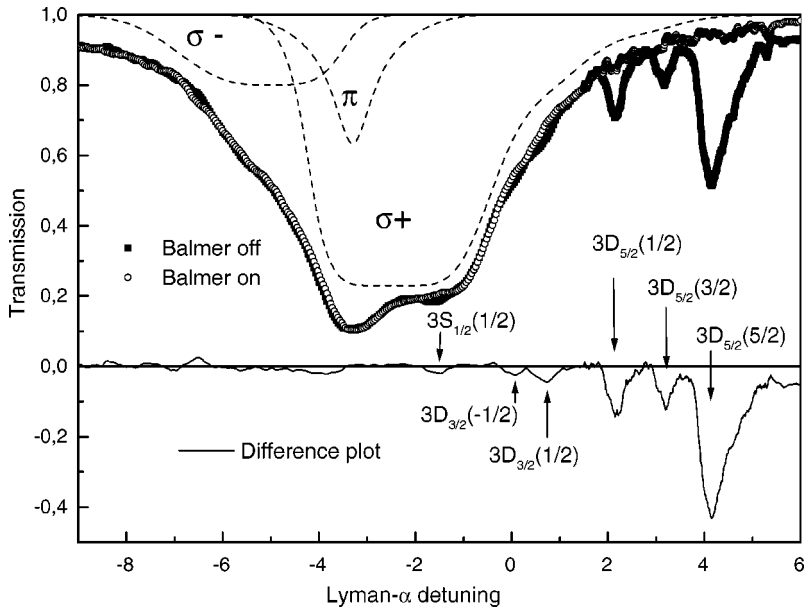

Figure 3. Lyman-α and RETS spectrum for the case where the Balmer polarization is σ^+ but the Lyman polarization is a mixture of σ^+, σ^-, and a little bit of π. Consequently, more RETS lines than just the one involving the $3D_{5/2}(5/2)$ level are visible. The density of H atoms is so high that the gas is opaque for the Lyman resonance. For the $3D_{5/2}$ lines visible on the r.h.s. of the figure the Balmer detuning δ is high enough to take these lines out of saturation. This is tunable transparency.

Figure 3 shows a more complicated RETS spectrum. The difference spectrum (odd minus even points) gives the RETS contribution. The fact that there is more than one peak is due to the fact that the Lyman light here is not purely σ^+ polarized. Hence, more than one intermediate substate participates and consequently more than one final sublevel in the 3D manifold can be observed. Figure 3 shows another noteworthy feature: the single photon lines look rather like a featureless blob. This is due to the fact that the gas is opaque near resonance. The light is almost completely absorbed. It is only for very large detuning that the sample becomes transparent. As a result the three different lines that can be excited (one σ^+, one σ^-, and one π line) are not resolved. The RETS lines can be resolved simply because the detuning δ is chosen sufficiently large to reduce the optical density to less than one. This property we have called tunable transparency. The possibility to reduce the sensitivity is the opposite of what was described above (the high sensitivity obtained for smaller δ). It clearly shows that RETS is a very flexible diagnostic tool, useful for an enormous range of densities.

In summary, we have demonstrated that RETS is a powerful and very flexible spectroscopic tool with properties that are ideal both as a diagnostic method for continued H research, and as a tool to study trapped antihydrogen in the future. For the latter purpose, the use of a narrowband Lyman-α source, such as the cw scheme developed in Garching [3,10], will allow full advantage to be taken of the high resolution possible with RETS.

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