Towards Laser Spectroscopy of Antihydrogen

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Abstract. Cold antihydrogen atoms in a magnetic trap will open exciting prospects for challenging CPT tests with ultrahigh-resolution laser spectroscopy. Equally exciting is the prospect for experiments on the gravitational acceleration of antimatter. For both types of experiment it is of great importance to have antihydrogen as cold as possible. Laser cooling of antihydrogen can be done on the strong 1S–2P transition at Lyman-α (121.56 nm). We describe the first source for continuous coherent radiation at Lyman-α and possible applications in experiments with antihydrogen.

1 Introduction

The theory of the hydrogen atom and experiments keep challenging each other at ever increasing levels of precision [1]. That interplay stimulated the development of ultrahigh precision laser spectroscopy of the hydrogen atom which has recently been employed to measure fundamental constants, to establish stringent tests of quantum electrodynamics and even to investigate hadronic structure [2,3,4]. It would be fascinating to use these advanced tools for the investigation of antimatter. High resolution laser spectroscopy of antihydrogen could then open a new field for precise tests of the fundamental CPT symmetry [5]. Furthermore, laser cooling and laser spectroscopy techniques are essential for a possible measurement [6] of the gravitational force on antihydrogen [7].

The recent production of a few *fast* antihydrogen atoms [8,9] has attracted considerable interest and has also given prospect to a new field of experiments with *cold* antihydrogen atoms. Simultaneous trapping of cold positrons and antiprotons has already been demonstrated [10] at the Low Energy Antiproton Ring (LEAR) at CERN which is no longer available for antiprotons [11]. The new Antiproton Decelerator (AD) at CERN [12] has recently been commissioned [13]. Two collaborations have been formed to use the slow antiprotons from the AD with the goal of precision measurements on magnetically trapped antihydrogen.

Initially the focus will be upon producing cold antihydrogen atoms. The rate for spontaneous radiative recombination of antiprotons and positrons is rather low because the emission of photons is a slow process on the time scale of collisions. Laser-stimulated recombination can increase the antihydrogen formation rate by orders of magnitude [14]. Other avenues towards antihydrogen production at low energies are pulsed-field recombination [15] or collisions of antiprotons with positronium [16].

The wavelength dependence of laser-stimulated recombination could be used to perform spectroscopy. The recombination rate is closely related to the distribution of positrons in energy and also to the population of bound levels close to the ionization threshold [17]. The spectral resolution for the first step of laser-stimulated recombination is thus limited by the energy distribution of the positrons. Laser-induced two-step recombination, first into a high-lying state with the subsequent stimulation of a bound-bound transition into a lower lying state, offers a first possibility for precise laser spectroscopy [18].

Precision experiments will most likely make use of magnetically trapped antihydrogen atoms [19]. The narrow 1S–2S transition is an especially intriguing candidate for ultimate precision experiments. The excitation rate for this two-photon transition, however, is typically rather small. Previous experiments on ordinary hydrogen compensated that by using many atoms (10^{15}–10^{17} atoms/s in a beam [20,21], 10^{10}–10^{13} atoms in a trap [22,23]). Given that the AD delivers about 10^7 antiprotons/minute at 100 MeV/c, it is clear, that new techniques need to be developed for experiments with antihydrogen.

The strongest transition of the antihydrogen atom, 1S $\rightarrow$ 2P, is situated in the vacuum ultraviolet (VUV) spectral region at 121.56 nm (Lyman-α). Narrowband continuous radiation at this wavelength is important for efficient laser cooling of antihydrogen atoms in a magnetic trap. Further, continuous radiation opens a possibility for ultrahigh resolution spectroscopy of the weak 1S–2S transition employing a "shelving" scheme that requires just a few antihydrogen atoms. In this contribution we describe the first source for continuous coherent radiation at Lyman-α and its possible application for experiments with antihydrogen.

2 Source for Continuous Coherent Radiation at Lyman-α

Producing coherent radiation at 121.56 nm (Lyman-α) is still a technological challenge as there are no tunable lasers and nonlinear crystals available for that spectral region. Sum-frequency generation of several incident laser beams utilizing the nonlinear susceptibility of atomic vapors and gases is commonly used to produce coherent radiation in the VUV. Four-wave mixing (FWM) can produce the sum-frequency of three fundamental colors. Many *pulsed* Lyman-α sources based on FWM with high-power lasers have been build over the years [24,25,26,27,28]. Several FWM schemes have been described in the literature which demonstrate the feasibility to produce *continuous* radiation in the VUV (down to 133 nm, where 11 pW has been obtained) [29,30,31,32].

The yield of near-resonant four-wave mixing scales as

$$P_1 \cdot P_2 \cdot P_3 \left[\text{density} \cdot \frac{\text{dipole-moments}}{\text{resonances}} \cdot \text{phasematch-integral} \right]$$

where P_1, P_2, and P_3 denote the powers of the fundamental beams [33]. For FWM with continuous wave beams the incident power levels are rather low. Tight focusing is therefore used to obtain high intensities. Especially important

for continuous FWM is the resonant enhancement of the nonlinear susceptibility. An exact two-photon resonance is essential. Near resonances at one and three photon heights are chosen to give maximum enhancement without too much absorption. It is necessary to select a medium with strong dipole moments on transitions with convenient wavelengths so that powerful fundamental laser beams are possible. Note that the requirements for efficient continuous wave FWM are rather different from pulsed FWM: Tight focusing and resonances are generally avoided for pulsed FWM with high-power lasers as they would lead to rapid saturation due to multi-photon ionization.

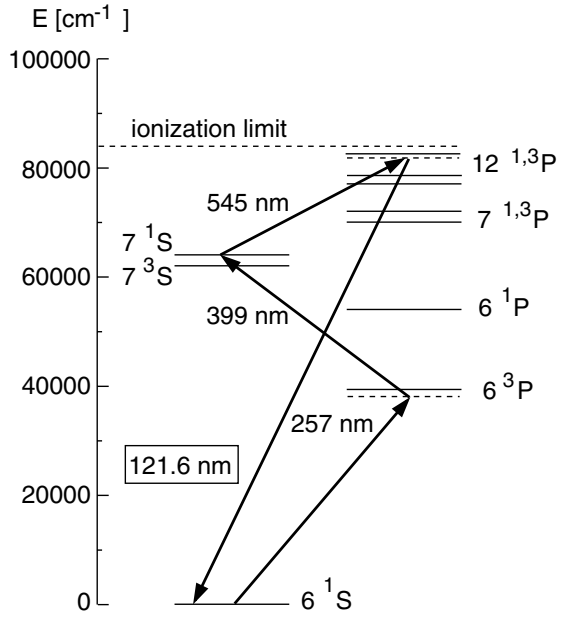

Fig. 1. Four-wave mixing scheme to produce radiation at Lyman-α in mercury vapor

Our Lyman-α source is based on FWM in mercury vapor. The scheme in Fig. 1 shows relevant energy levels of mercury and the wavelengths that are used. The first fundamental beam at 257 nm is on the long wavelength side of the transition 6s $^1S_0 \rightarrow$ 6p $^3P_1$ in mercury at 253.7 nm. This beam is obtained by frequency doubling the radiation from a single-mode Ar^+-laser. A nonlinear optical crystal (β-barium borate, BBO) placed in an enhancement cavity produces up to 900 mW of power at 257 nm. The second fundamental beam at 399 nm establishes an exact two-photon resonance with the 7 $^1S_0$ state. This beam is obtained by frequency-doubling the radiation from a titanium-sapphire laser. A nonlinear optical crystal (lithium borate, LBO) placed in an enhancement cavity produces up to 920 mW of power at 399 nm. The third fundamental light field at 545 nm comes from a dye-laser which operates on rhodamine 110 and produces

up to 1.7 W. The wavelength of this third fundamental beam is chosen such that the sum-frequency is at Lyman-α. Bound states in mercury such as 11p $^1P_1$ and 12p $^1P_1$ contribute significantly to the non-linear susceptibility [34].

The mode profile and the overlap of the fundamental beams is very critical. The frequency-doubled beams have an elliptical profile and are astigmatic. This is compensated for by cylindrical lenses. Telescopes with spatial filtering enlarge the beams to match focussing parameters. The three fundamental beams of parallel and linear polarization are then focussed to a beam waist of 30 µm in the middle of a 15 mm long zone of mercury vapour at 20–30 Torr. The overlap is preadjusted with a pinhole and alignment beams obtained from a reflection of the entrance window. The 257 nm and the 399 nm foci are aligned further by maximizing fluorescence at 1.014 µm which originates from the decay of the two-photon resonant 7s $^1S_0$ to the 6p $^1P_1$ level. The 545 nm focus is then aligned by maxinizing the generated radiation in the vacuum ultraviolet.

The generated radiation at Lyman-α is separated from the fundamental beams with the help of the dispersion of a MgF_2 lens. The focal length for the fundamental beams is several centimeters longer than the focal length for the generated beam in the vacuum ultraviolet. Most of the radiation produced at Lyman-α can thus pass a small mirror which reflects the fundamental beams being placed at their focus. A set of up to three narrowband VUV interference filters provides additional separation of the Lyman-α beam. The setup has been described in detail elsewhere [35]. Several refinements of the four-wave mixing setup allow now for a VUV yield at Lyman-α of up to 20 nW.

The Lyman-α beam has been used recently for spectroscopy of atomic hydrogen. The 1S $\rightarrow$ 2P transition has been driven for the first time with continuous coherent radiation. Results and a detailed description of the atomic hydrogen beam apparatus will be described elsewhere [36].

3 Laser Cooling and Shelving Spectroscopy

Let us now turn to possible applications of the continuous source for radiation at Lyman-α. Laser cooling of antihydrogen with pulsed Lyman-α radiation has been discussed by some authors [27,37,38]. A continuous source has clearly significant advantages over pulsed sources. Typical pulsed sources for radiation at Lyman-α have pulse lengths of nanoseconds. The lifetime of the 2P states is 1.6 ns. Hence sources with nanosecond pulses cause at most a few excitations per pulse. Laser cooling is effectively limited by the pulse repetition rate. Therefore a continuous source can provide a larger rate for laser cooling. Furthermore, the spectral bandwidth of a continuous source can be much lower. This provides higher selectivity for magnetic substates of atoms in a trap thereby reducing losses due to spurious optical pumping to untrapped magnetic sublevels.

The resonant absorption cross section for radiation at Lyman-α can be as high as $3\lambda_\alpha^2/2\pi$ [39]. Consider a volume of 1 mm diameter being illuminated with 1 nW resonant radiation at Lyman-α. The excitation rate for an atom is then $5\,s^{-1}$. Suppose that we would like to cool antihydrogen atoms in a magnetic

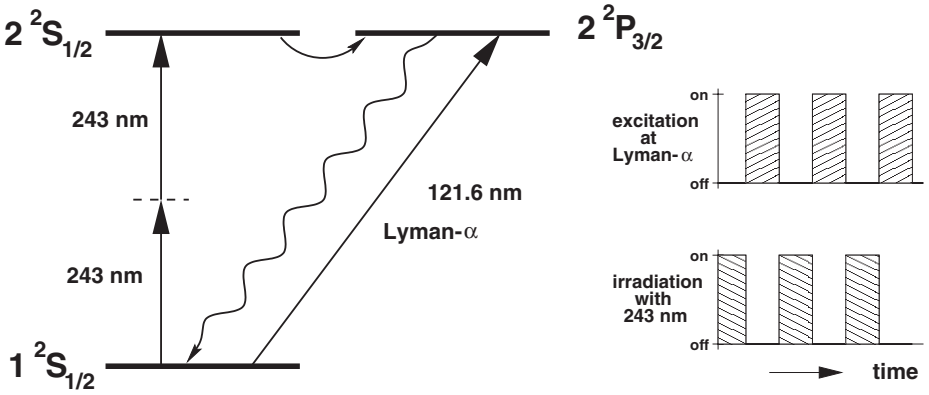

Fig. 2. Excitation scheme for shelving spectroscopy of antihydrogen

trap starting with an initial temperature of 1 K which corresponds to an average velocity of 150 m/s. The average velocity change per excitation is 3.3 m/s. Cooling could thus be done in about 10 s with only 1 nW of resonant radiation at Lyman-α available from our source at its early stage.

A continuous coherent Lyman-α source opens also a possibility for high-resolution spectroscopy with only a few antihydrogen atoms [40]. Consider the excitation scheme shown in Fig. 2. Radiation at Lyman-α excites a single atom in a magnetic trap from the $1\ ^2S_{1/2}$ ground state to the $2\ ^2P_{3/2}$ excited state. The $2\ ^2P_{3/2}$ has a very short natural lifetime of 1.6 ns. Thus intense resonance fluorescence can be emitted by the decay of the $2\ ^2P_{3/2}$ state back into the ground state. Excitation on the strong Lyman-α transition is alternated with irradiation of the atom by ultraviolet light at 243 nm. Simultaneous Doppler-free absorption of two photons leaves the atom in the $2\ ^2S_{1/2}$ state. This state is metastable and decays by two-photon emission to the ground state with a natural lifetime of 122 ms. Observation of resonance fluorescence at Lyman-α in the following cycle is used to determine whether the weak two-photon excitation into the metastable state was successful or not. The absence of resonance fluorescence indicates that the atom has been excited ("shelved") into the metastable state. In that case the atom can be "reset" into the ground state by applying a microwave field to couple the long-lived $2\ ^2S_{1/2}$ state with the rapidly decaying $2\ ^2P_{3/2}$ state. The fraction of cycles with no resonance scattering represents the probability of the two-photon excitation. An absorption spectrum is obtained by stepwise scanning the 243 nm laser frequency while measuring the probability of excitation.

Shelving spectroscopy thus involves many decisions whether the antihydrogen atom has been excited to the metastable $2\ ^2S_{1/2}$ state or not. These decisions have to be made somewhat quicker than the natural lifetime of the metastable state and are based on the observation or the non-observation of fluorescent light at Lyman-α. The detection efficiency for fluorescent light from an antihydrogen sample in a magnetic trap with superconducting coils is probably rather

low. Shelving spectroscopy requires thus far more power at Lyman-α than laser cooling.

To conclude, the photon flux from our source for continuous Lyman-α radiation at its early stage is promising for laser cooling of antihydrogen in a magnetic trap. It is expected that the yield can be increased by several orders of magnitude. It would also be very interesting to replace one of the continuous beams in the FWM scheme by a pulse-amplified beam with a long duration, say µs to ms. Combining the advantages of narrow bandwidth and high intensity, such a hybrid Lyman-α source could be ideal for laser cooling, Zeeman slowing, and shelving spectroscopy of antihydrogen.

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