Precision Spectroscopy of Hydrogen with a Lamb-Shift Polarimeter

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Abstract. A spinfilter, the most important component of a Lamb-shift polarimeter, is used to produce a beam of metastable hydrogen (deuterium) atoms in one hyperfine state (HFS)($\alpha 1$, $\alpha 2$ and together with the Sona transition $\beta 3$). As function of a magnetic field separated transitions between the $2S_{1/2}$ metastable Zeeman states seem to be observable as well as single transitions into the short-lived $2P_{1/2}$ and $2P_{3/2}$ states. The Breit-Rabi diagrams for these states and, therefore, the g factors can be measured with good precision. Furthermore, the hyperfine splittings and the Lamb shift can be observed as well. Application of this method to anti-hydrogen atoms is suggested.

Keywords: Lamb shift, Hyperfine Splitting, Spinfilter, Breit-Rabi Diagram, g-factor
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INTRODUCTION

In 1952 Rabi [1] suggested that the *Atomic Beam Resonance Method* [2] could be used to study also the excited states of atoms. This was realized in 1955 by Heberle et al. [3] with a modified setup for the metastable hydrogen state $2S_{1/2}$ in vanishing magnetic fields and in 1956 by Senitzky and Rabi [4] for the alkaline atoms. When Lamb and Retherford [5] measured the Lamb shift, they were not able to separate the different hyperfine levels of the $2S_{1/2}$, $2P_{1/2}$, and the $2P_{3/2}$ fine structure states completely. Since then, different methods have been applied to measure the hyperfine splittings and the Lamb shift of the excited states ($n = 2$) of the hydrogen atom near $B \sim 0$ G [6], [7], [8], [9]. However, the complete Breit-Rabi diagrams [10], i.e. the binding energies of the single Zeeman states with $n = 2$ as a function of the magnetic field, have not yet been measured. On the other hand, the binding energies and, therefore, the g-factors of the single Zeeman states, the Lamb shift and the hyperfine splittings, can be calculated as a function of the magnetic field with bound-state QED [12]. However, the accuracy of these calculations is limited by the uncertainties of a number of parameters. For example, the charge radius of the proton must be taken into account. With a fit to precision data these values could be determined.

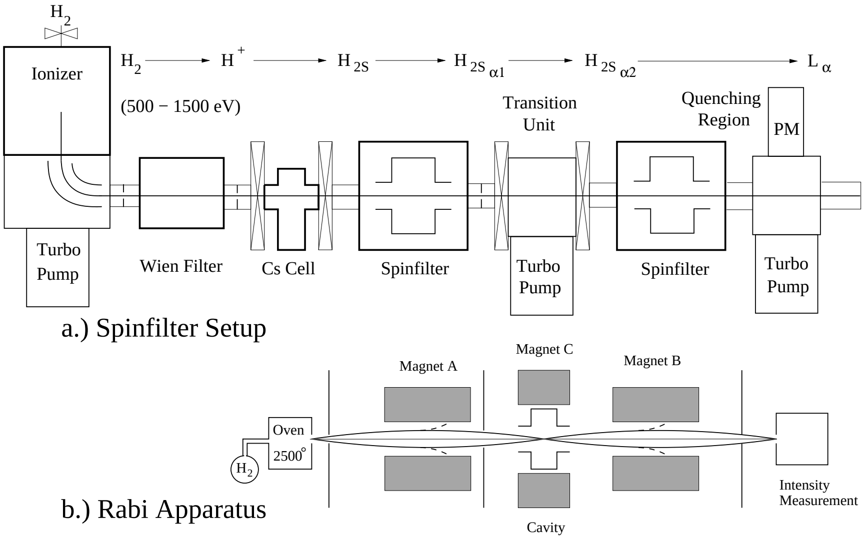

FIGURE 1. **a.)** The setup with two spinfilters for the measurement of the $2S_{1/2}$ Breit-Rabi diagram. **b.)** The analogous setup of the Rabi apparatus for the $1S_{1/2}$ HFS.

MEASUREMENT OF THE $2S_{1/2}$ HYPERFINE TRANSITIONS

With a spinfilter [13], the most important component of a Lamb-shift polarimeter [14], it is possible to produce an intense beam of hydrogen atoms in the ground state $1S_{1/2}$ and in single metastable HFS $\alpha 1$, $\alpha 2$ or $\beta 3$ of the $2S_{1/2}$ state only. This can be used to establish a setup similar to that of the *Atomic Beam Resonance Method* (Fig. 1). In our setup, the *analyzing magnets* of the Rabi apparatus are replaced by spinfilters. In an electron-impact ionizer H_2 molecules are dissociated and ionized. The energy of the produced protons is between 300 and 2000 eV, and a beam intensity up to 10 μA can be achieved. After deflection to a horizontal beam direction, a Wien filter is used to separate the protons from the other ions, which originate from the residual gas. The width of the proton-velocity distribution is minimized by two diaphragms at both ends of the Wien filter. By charge exchange with cesium vapour [15], metastable hydrogen atoms in the state $2S_{1/2}$ are produced from about 15% of the protons. In the first spinfilter all metastable atoms except those in one HFS are quenched into the ground state and only metastable atoms in the HFS $\alpha 1$ or $\alpha 2$ remain in the beam. In a homogeneous magnetic field, radio frequency (rf) transitions are induced with the electric field vector parallel to the velocity direction of the hydrogen atoms in order to avoid longitudinal Doppler shift and broadening. The direction of the magnetic field, produced by two Helmholtz-like coils ($B \leq 100$ G), can be aligned parallel or perpendicular to the velocity direction of the atoms. Thus, for a transverse magnetic field, the transitions $\alpha 1 \rightarrow \alpha 2$, $\alpha 1 \rightarrow \beta 4$, $\alpha 2 \rightarrow \alpha 1$ and $\alpha 2 \rightarrow \beta 3$ can be measured. Together with the Sona transition [16] behind the first spinfilter it is possible to exchange the population numbers of the HFS $\alpha 1$ and $\beta 3$. Therefore, the transition $\beta 3 \rightarrow \beta 4$ can be measured, too. In the setup, shown in figure 1, the first spinfilter is used to depopulate the HFS $\alpha 2$, $\beta 3$ and $\beta 4$, so that only metastable atoms in the HFS $\alpha 1$ are found in the beam. With the magnetic field in the transition unit perpendicular to the beam direction the rf is swept across the resonance to induce transitions from the HFS $\alpha 1$ to the HFS $\alpha 2$. A subsequent spinfilter is tuned to transmit only atoms in the state $\alpha 2$. After quenching the metastables into the ground state by the Stark effect, the intensity change is detected by counting the Lyman-α photons with a photomultiplier in the quenching region as a function of the rf to find the resonance frequency.

Estimated Results and Errors

Due to the long lifetime (0.14 s) of the metastable $2S_{1/2}$ state [17], the natural half-width of the resonance is about 1.1 Hz (4.6×10^{-15} eV). Because of the short time of the fast metastable atoms in the small interaction region and the Heisenberg uncertainty principle, a broadening of the resonance peak up to 40 MHz is expected to be the dominant source of the experimental error, which will be around $\Delta f = 10$ kHz for a count rate of more than 10^5 photons/s in the photomultiplier. The longitudinal Doppler effect is suppressed in first order, because the beam direction of the metastable atoms is perpendicular to the rf wave vector. Second order effects of the Doppler shift (caused, e.g., by misalignment of the beam axis) can be measured by rotating the rf wave vector. The Doppler broadening of the resonance peak will be small due to the velocity distribution of the incoming metastable atoms of about 1%. The transverse Doppler shift will be around 200 Hz for a beam energy of 1 keV and around 50 Hz for 500 eV and can be measured by varying the beam energy. With measured frequencies at 100 different magnetic fields up to 100 G a relative error of 10^{-6} of the slope of the energy levels and, therefore, of the g-factor seems to be feasible. With an upgrade of the magnetic field up to 1000 G and decreasing of the frequency errors down to $\Delta f = 1$ kHz a relative error of 10^{-8} may be possible. A strong advantage of this method as compared to other measurements is the possibility to measure the hyperfine splitting of the $2S_{1/2}$ state independent of the magnetic field. The combinations of the transition frequencies $(\alpha 1 \rightarrow \beta 4) - (\alpha 2 \rightarrow \beta 3)$ and $(\alpha 1 \rightarrow \alpha 2) + (\beta 3 \rightarrow \beta 4)$ result in the values of the $2S_{1/2}$ hyperfine splitting for every magnetic field.

MEASUREMENT OF THE $2P_{1/2}$ HYPERFINE TRANSITIONS

Lamb and Retherford [5] proposed in their famous paper to induce the transitions from the metastable HFS into the HFS of the short-lived $2P_{1/2}$ state ($\tau = 10^{-9}$ s) with variable rf and a stable power level at a constant magnetic field. But at that time this was not possible because of technical constraints. Today, however, rf generators for the 1 GHz range with a precision better than 1 Hz and stable amplitude are available. Inducing transitions at various frequencies and constant rf power can be achieved by the use of a Lecher (TEM) transmission line. The TEM waveguide of a constant characteristic impedance transports the rf through the vacuum and at the opposite end the amplitude can be controlled. Through holes in the conductors around the beam line the metastable atoms can reach the volume between the inner and the outer conductor of the TEM waveguide where the transitions are induced. With a proper design it is guaranteed that the electric rf field is homogeneous and its direction is parallel to the velocity vector of the hydrogen beam. In this case, the rf wave vector must be perpendicular to the atomic

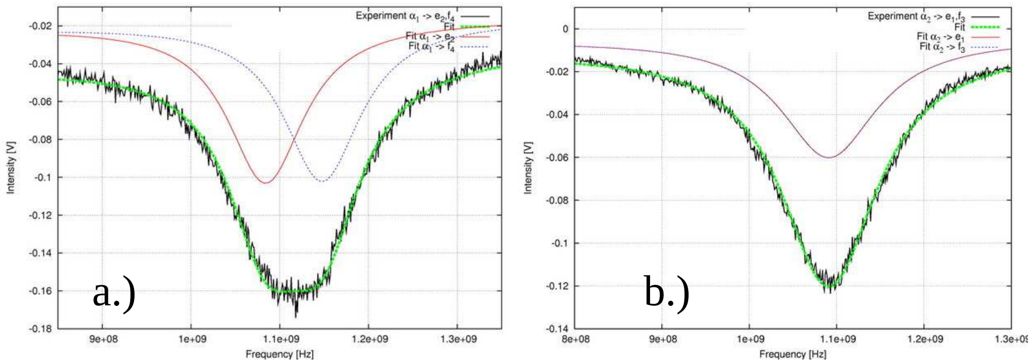

FIGURE 2. The observed transitions $\alpha 1 \rightarrow f4$ and $\alpha 1 \rightarrow e2$ (a.) or $\alpha 2 \rightarrow f3$ and $\alpha 2 \rightarrow e1$ (b.) at a small vertical magnetic field ($B \sim 0.5$ G) in the transition region.

beam and the Doppler effect can be suppressed in first order. Through a hole in the outer conductor the Lyman-α photons produced by the decay of the $2P_{1/2}$ states are detected in a photomultiplier.

First Results

In a first proof-of-principle measurement [18] metastable hydrogen atoms in the HFS $\alpha 1$ or $\alpha 2$ are selected in the spinfilter and reach the TEM waveguide (Fig. 2). For a small transverse magnetic field about 0.5 G the transitions $\alpha 1 \rightarrow f4$ and $\alpha 1 \rightarrow e2$ (a.) or $\alpha 2 \rightarrow f3$ and $\alpha 2 \rightarrow e1$ (b.) are observed. The frequency difference of the two resonances of the transitions $\alpha 1 \rightarrow f4$ and $\alpha 1 \rightarrow e2$ in Fig. 2 a.) corresponds to the hyperfine splitting energy of the $2P_{1/2}$ state. The preliminary result from a fit ist 59.98 (2.03) MHz, which agrees with the prior result of 59.22 (14) MHz [8]. The transition frequencies from the $2S_{1/2}$ into the $2P_{1/2}$ state together with the HFS of these states allow to calculate a value of the classical Lamb shift. As a first result a value of 1057.34(1.11) MHz could be determined.

DISCUSSION

The dominant error in the first measurement was the inhomogeneity of the magnetic field and the uncertainty in the definition of the field direction. For example, an inhomogeneity of $\Delta B = 0.5$ G corresponds to an error of $\Delta f = 1$ MHz for the resonance frequency. A new setup with a set of Helmholtz coils to produce an inhomogeneity of $\Delta B/B = 10^{-4}$ and a much better shielding against external stray fields is in preparation. In addition, an error of $\Delta f = 100$ kHz is produced by the instability of the rf power of 3%. With available hardware this instability can be reduced to 0.002% or less. Because of the Heisenberg uncertainty relation $\Delta t \times \Delta W \sim h$ and the short transit time of the metastable atoms through the interaction region of $\Delta t = 4.4 \times 10^{-7}$ s (at 1 keV beam energy) the resonance half width will be increased from 100 to 109 MHz for the measurements of the transitions into the $2P_{1/2}$ states. For the transitions within the $2S_{1/2}$ states this effect will dominate the broadening to about 40 MHz. In addition, other effects like the velocity distribution of the incoming metastable hydrogen beam and the inhomogeneity of the magnetic field will influence the shape of the resonance peak. A large count rate of 10^7 photons/s in the multiplier allows very precise measurements of this shape. Several upgrades like a more efficient Lyman-α detection system and a larger proton beam after the ionizer will increase this number to 10^9 photons/s. Nevertheless, this deformation of the peak will result in an error of about $\Delta f = 100$ kHz. Instead of directly induced transitions it is possible to use the *separated-oscillatory-field* technique used by Ramsey and others [8] to overcome the large half-width of the resonance peak and to decrease the error. Until now no influence of the different Doppler shifts (see section 2.1) is observed. Other effects like the Stark shift caused by electric fields and the motional Stark effect can be neglected so far. An error of $\Delta f = 100$ kHz for a single measurement will lead to a relative error of 10^{-5} and after an upgrade 10^{-7} for the g-factors of the $2P_{1/2}$ states. Like the hyperfine splitting of the $2S_{1/2}$ state the hyperfine splitting of the $2P_{1/2}$ state can be measured by a combination of different transitions independent of the magnetic field ($f_{HFS_{(2P_{1/2})}} = (\alpha 1 \rightarrow f4) - (\alpha 2 \rightarrow f3) - (\alpha 1 \rightarrow e1) + (\alpha 2 \rightarrow e2)$). Therefore, it is possible to perform a large number of independent measurements at different magnetic fields and to average these results to decrease the error from 140 kHz [8] down zu 10 kHz. With a modified TEM waveguide, transitions from the $2S_{1/2}$ HFS into the $2P_{3/2}$ HFS can be induced and the hyperfine splitting of the $2P_{3/2}$ state can be measured. Those transitions are around 10 GHz. For deuterium the spinfilter allows to separate three metastable states $\alpha 1$, $\alpha 2$ and $\alpha 3$ which correspond to the three different nuclear spin substates with I=+1,0,-1. Therefore, a higher number of transitions can be measured and the results can be compared with hydrogen within the D_{21} theory. A spinfilter can be designed for other atoms, too. For example, a spinfilter for ^{3}He is in preparation. Before cold antihydrogen cannot be produced for 2-photon laser-spectroscopy experiments this method can also be applied to antihydrogen beams. During the recombination of the antiproton and the positron 30% of the produced antihydrogen atoms end up in the $2S_{1/2}$ metastable state. With a much better Lyman-α detection system 10 antihydrogen atoms per s will produce a count rate of 1 photon/s in the photomultplier.

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