Precision Spectroscopy of Hydrogen with a Lamb-shift Polarimeter

R. Engels[a]., K. Grigoryev[a,c], M. Mikirtychyants[a,c], H. Paetz gen. Schieck[b], G. Schug[a], A. Vasilyev[c], M. Westig[a,b], and H. Ströher[a]

For the Breit-Rabi diagram of the hydrogen states $2S_{1/2}, 2P_{1/2}$ and $2P_{3/2}$ (Fig. 1) experimental data of high precision exist only for weak magnetic fields about a few mG, which allow to check the results of advanced bound-state QED calculations. These experimental data stem from 2-photon laser-spectroscopy [1, 2] and the separated-oscillatory-field method [3]. At higher magnetic fields, the crossing of the β and the e states around 570 G were measured decades ago [4]. From the Breit-Rabi diagram the classical Lamb shift, the hyperfine splittings and, from the slope of the energy levels, the g-factors of those states can be determined. The calculation of these values by bound-state QED is on a very accurate level, so that the uncertainty now is dominated by effects like the charge distribution of the proton. With a very precise measured Breit-Rabi diagram a test of the bound-state QED seems possible, which is expected to contribute e.g. in the determination of the charge distribution in the proton.

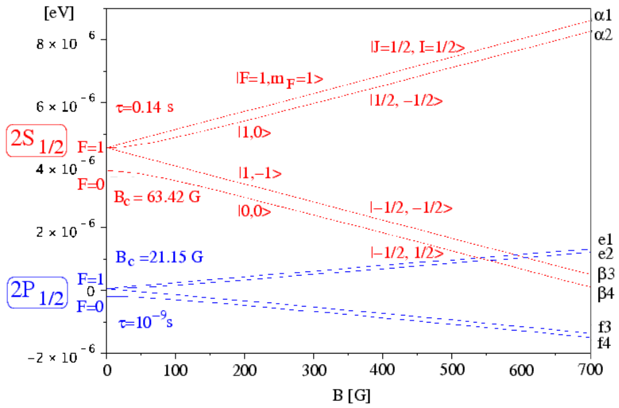

Fig. 1: The Breit-Rabi diagrams for the metastable $2S_{1/2}$ and the short-lived $2P_{1/2}$ hyperfine states.

A spinfilter, the most important component of a Lamb-shift Polarimeter [5], is able to produce a beam of metastable hydrogen (deuterium) atoms in only one hyperfine state ($\alpha1$, $\alpha2$ or $\beta3$). From these states, $M1$ transitions into the other hyperfine states can be induced at different transverse magnetic fields and the population of these states can be measured with a second spinfilter. Based on the expected error of $\Delta f = 10$ kHz for a single measurement, 100 measurements between 0 and 100 G should lead to a relative error of 10^{-6} for the g-factors. Increasing of the magnetic field range will decrease the size of the error substantially. But it has to be taken into account, that the g-factors will change for large magnetic field. In addition, the hyperfine splitting of the $2S_{1/2}$ state corresponds to the difference of the $\alpha1 \rightarrow \beta4$ and the $\alpha2 \rightarrow \beta3$ transition energies or the sum of the transitions energies $\alpha1 \rightarrow \alpha2$ and $\beta3 \rightarrow \beta4$ independent of the magnetic field strength. Therefore, it is possible to average the values, measured at different fields to obtain an error of the hyperfine splitting of less than 1 kHz. The error is dominated by the Heisenberg uncertainty relation $\Delta\nu \times \Delta t \sim 1$, which will broaden the half with of the resonance. This problem can be solved by exiting the slow hydrogen beam of an atomic beam source (ABS) by electron bombardment before the hyperfine states are separated with the spinfilter.

In a proof-of-principle measurement [6] $E1$ transitions into the single Zeeman states of the $2P_{1/2}$ state were induced with a Lecher TEM (transverse electromagnetic) transmission line. Because of the short lifetime (10^{-9}s) of the $2P_{1/2}$ state the atoms will decay immediately into the ground state and the produced Lyman-α photons are detected with a photomultiplier as a function of the radio frequency at a stable power level (see Fig. 2).

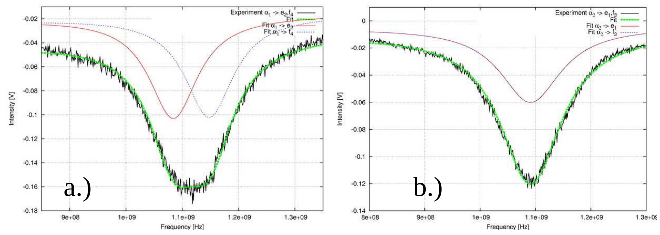

Fig. 2: The observed transitions $\alpha1 \rightarrow f4$ and $\alpha1 \rightarrow e2$ (a.) or $\alpha2 \rightarrow f3$ and $\alpha2 \rightarrow e1$ (b.) at a small vertical magnetic field ($B \sim 0.5$ G) in the transition region.

From the observed transitions at small magnetic fields the hyperfine splitting of the $2P_{1/2}$ state can be directly determined to 59.98 (2.03) MHz, which fits to the best known value of 59.22 (14) MHz [3]. A much better precision of $\Delta f_{hfs} < 10$ kHz can be obtained, because similar to the M1 transitions the combination of the transition $[(\alpha1 \rightarrow f4) - (\alpha2 \rightarrow f3) - (\alpha1 \rightarrow e1) + (\alpha2 \rightarrow e2)]$ corresponds to the hyperfine splitting f_{hfs} independent of the magnetic field at the interaction region. Another outcome of these measurements is a value of 1057.34 (1.11) MHz for the classical Lamb shift. This agrees with other measurements [2], but the error is at least two orders larger.

With this setup an error of $\Delta f = 100$ kHz for a single measurement is expected. This means, that the relative error of the g-factor for 100 measurements between 0 and 100 G will be around 10^{-5} and can be decreased further by increasing the magnetic field range. There exists a huge dipole magnet with 1.5 T magnetic field strength in the COSY test hall which may lead to a relative error of $\sim 10^{-8}$ for the g-factor of the $2P_{1/2}$ states. In addition, $E1$ transitions into the single Zeeman states of the $2P_{3/2}$ state can be induced with a modified TEM waveguide for radio frequencies around 10 GHz. The same method is applicable for deuterium, too. In this case, three Zeeman states ($\alpha1$, $\alpha2$ and $\alpha3$) are selected by the spinfilter. In general this method may be useful for antihydrogen, because during the recombination of the antiproton and the positron $\sim 30\%$ of the antihydrogen will populate the metastable $2S_{1/2}$ state.

Supported by JCHP - FFE

References:

[1] N. Kolachevsky et al.; Phys.Rev.Lett. **92** 033003 (2004).
[2] C. Schwob et al.; Phys.Rev.Lett. **82** 4960 (1999).
[3] S.R. Lundeen et al., Phys.Rev.Lett. **34** 377 (1975).
[4] W.E. Lamb and R.C. Retherford, Phys.Rev. **81** 222 (1951).
[5] R. Engels et al., Rev.Sci.Instr. **74**, 11 4607 (2003).
[6] M. Westig, diploma thesis, IKP (2008).

[a] Forschungszentrum Jülich, IKP, Jülich, Germany
[b] Universität zu Köln, IKP, Köln, Germany
[c] PNPI Gatchina, Gatchina, Russia