Measurement of the nonlinear Stark effect in the $2\,^2P_{1/2}$ state of hydrogen

K. J. Kollath and H. Kleinpoppen
Department of Physics, University of Stirling, Stirling FK9 4LA, Scotland
(Received 6 May 1974)

Level crossings between the substates $2\,^2P_{3/2}$, $m_j = -3/2$ and $2\,^2P_{1/2}$, $m_j = 1/2$ of atomic hydrogen have been observed for electric fields up to 250 kV/m. A nonlinear low-field Stark effect has been measured for the $2\,^2P_{1/2}$ state, in agreement with theoretical calculations which include Lamb shift and hyperfine structure.

I. INTRODUCTION

The splitting of the Balmer lines of hydrogen under the influence of an external electric field was first observed by Stark[1] and Lo Surdo[2] in 1913. For fields of the order 10^4 kV/m the result was the well-known linear Stark effect in hydrogen. More recently, attention has been focused on the low-field Stark effect, in which the perturbation energy due to the electric field is of the same order as the Lamb shift and the fine structure (FS). This low-field Stark effect in hydrogen had to be considered in the accurate determinations of the Lamb shift[3] and of the Rydberg constant.[4] The low-field Stark effect in the $n=2$ level in particular has been of interest in the investigation of the beam-foil excitation mechanism.[5]

In the present experiment, the low-field Stark effect in the level $n=2$ has been measured for electric fields in the range 0–250 kV/m. The level-crossing technique[6] has been applied to achieve the necessary energy resolution[7] and a nonlinear effect has been found for the $2\,^2P_{1/2}$ state.

II. THEORY

A linear dependence of the energy levels on the external electric field can only be obtained if the energy splitting of states with different orbital quantum numbers l is negligible compared to the Stark shift. This condition was fulfilled for Stark's experiments and also for the early calculations[8] which neglected the FS and reproduced the linear effect, in agreement with the experiments. When the FS as described by the Dirac equation was included in the theory,[9] the linear effect was found again for large electric fields. For fields causing Stark shifts comparable to the FS, there was a nonlinear region, and for very small electric fields a linear effect was again predicted for the degenerate states $2\,^2S_{1/2}$ and $2\,^2P_{1/2}$. The subsequent discovery of the Lamb shift showed that, in fact, no such degeneracy exists, and consequently a nonlinear behavior should be seen for all fields smaller than 300 kV/m, the field strength where the Stark shift equals the FS in the level $n=2$.

The first calculation of the low-field Stark effect of hydrogen including FS and Lamb shift was done by Lüders,[10] who solved the secular equations numerically. We have repeated the calculation for $n=2$, using the most recent values for the natural constants[11] and including the hyperfine structure (HFS). The 16×16 matrix of the basis states $|2ljFm_F\rangle$ for the operator $H_S = e\vec{E}\cdot\vec{r}$ splits into submatrices of the same m_F if the electric field is taken in z direction, which is also the quantization axis, so that m_F remains a good quantum number. The matrix is diagonalized numerically and the result is shown in Fig. 1. The HFS is too small to be resolved in the graph, but is of interest for the analysis of the level crossings. Each of the FS branches shown consists of four substates of which those with the same $|m_F|\neq 0$ are degenerate.

III. EXPERIMENT

The experimental method was to determine the level-crossing position, which is the magnetic field necessary to produce the degeneracy of the substates $2\,^2P_{3/2}$, $m_j=-\frac{3}{2}$ and $2\,^2P_{1/2}$, $m_j=\frac{1}{2}$. The crossing manifests itself as a change of the Ly-α resonance fluorescence intensity observed in a fixed direction.[12] When an electric field $\vec{E}$ is applied along the z axis, parallel to the magnetic field $\vec{B}$, the $2\,^2P_{1/2}$ state is shifted and the levels cross at a different magnetic field. The experimental data for the crossing positions as the electric field is varied may be compared with theoretical values $B_c(E)$ obtained by combining Zeeman- and Stark-effect calculations.

The apparatus consisted of five aluminum vacuum tanks. The two tanks of direct interest are shown in Fig. 2. In the furnace a beam of H atoms is generated by thermal dissociation of molecular hydrogen passing through a tungsten pipe, heated by electron bombardment. The atoms travel through a differential pumping aperture into a small tank which fits into the 65-mm air gap between the pole faces of a 10-in. magnet. The beam is interrupted by a chopper before arriving at the magnet cen-

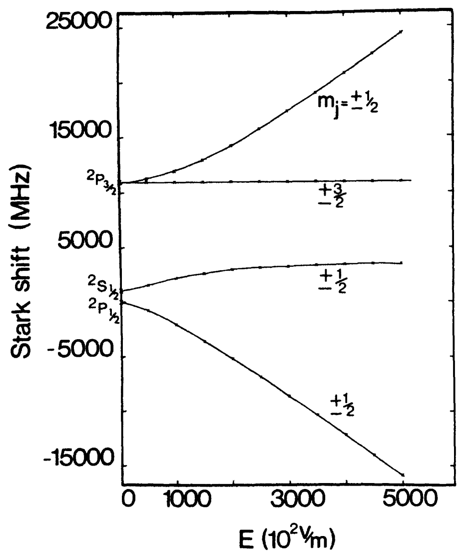

FIG. 1. Low-field Stark effect in the level $n=2$ of hydrogen. Each of the branches consists of four HFS states, of which those with the same $|m_F|\neq 0$ are degenerate.

ter. Here an electric field parallel to the magnetic field and perpendicular to the plane shown was provided by a parallel plate condenser. Within the condenser the atoms were exposed to Ly-α radiation produced by a microwave-powered discharge of hydrogen and helium. The discharge was separated from the vacuum tank by a MgF_2 window. The Ly-α output of the lamp was monitored by a NO ionization chamber through a filter of dry oxygen.

The scattered Ly-α light was observed by a channeltron photomultiplier (PM) through an oxygen filter. The PM was placed just outside the pole faces and was surrounded by a shield of magnetically soft iron to reduce the stray magnetic field. The single-photon PM pulses were amplified and registered in a double scaler, gated at the same frequency as the atomic beam was interrupted by the chopper. The angle between the incident light and the atomic beam was 40°, Doppler-shifting the absorption center away from the minimum of the strongly self-reversed Ly-α line. As shown in Fig. 2, the directions of the incident and observed light were at right angles in the plane perpendicular to the electric and magnetic fields. This geometry ensures resonance signals for $\Delta m=2$ level crossings with a Lorentzian absorption line shape and maximum amplitude.[13]

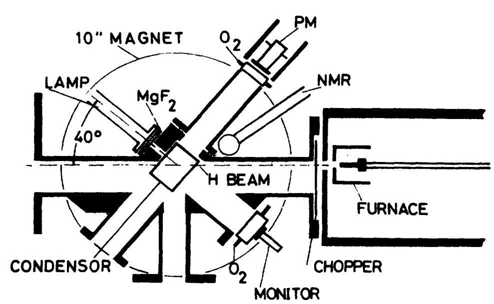

FIG. 2. Schematic diagram of the experimental setup, as explained in Sec. III.

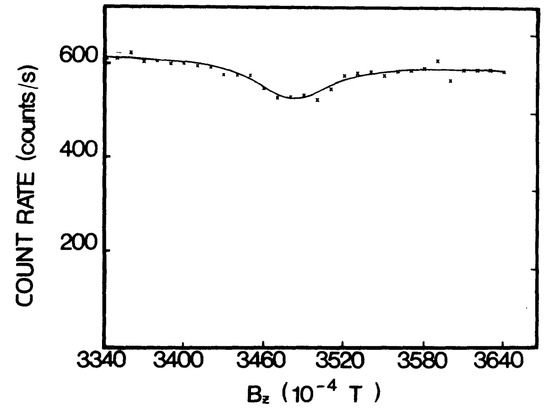

FIG. 3. Experimental Ly-α resonance fluorescence count rate close to a level crossing, vs magnetic field B_z for $E_z=29.6$ kV/m. Crosses, experimental values; solid line, least-squares fit.

In the experiment the count rate of Ly-α photons was determined at constant electric field for different magnetic field strengths. The magnetic field was stabilized at each value by a NMR system. The background count rate originating from the Ly-α lamp and from the beam source were subtracted. The remaining resonance fluorescence count rate was of the same order as each of the two backgrounds. A resonance signal is shown in Fig. 3. The resonance fluorescence count rate is plotted against the magnetic field B_z. Similar resonance curves have been obtained by variation of the electric field while the magnetic field was held constant.

The resonance signals were fitted with a least-squares computer program using a working line shape which includes the Lorentzian profile and a sloped background, given by

$$S(X)=\frac{A}{1+(Z-X)^2/B^2}+D(Z-X)+C\,.$$

The program determined the best values for the parameters A, B, C, D, and Z and their covariance matrix.

IV. RESULTS

The values for the center Z of different resonance signals taken at the same electric field were

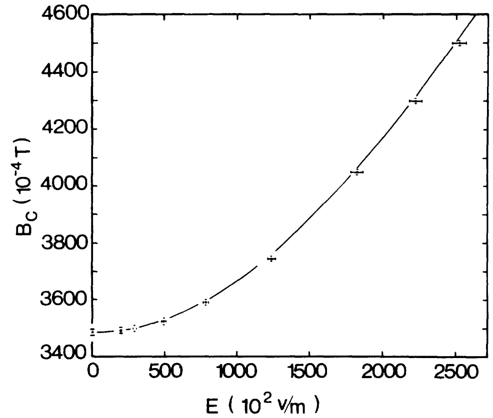

FIG. 4. Magnetic field B_c necessary to achieve the crossing (10^{-4} T≡1 G), vs electric field strength. Solid line, calculations; points, experimental results. The error bars include the statistical errors and estimates for systematic uncertainties.

averaged and their rms deviation calculated according to their statistical weights $1/\sigma^2$, where σ^2 is the variance of Z obtained from the fit. The results are shown in Fig. 4. The experimental points have two error bars. The vertical bar includes the rms error and an estimate for the systematic error introduced by possible asymmetric variations of the lamp intensity over the resonance signal. The horizontal bar indicates the uncertainties in the determination of the electric field strength, possible misalignment between electric and magnetic fields, and the effect of motional electric fields.

The solid line represents the theoretical values $B_c(E)$. If the HFS is included, each FS level splits into two levels and the crossing becomes a group of four closely spaced HFS crossings. The positions of these crossings have been calculated as functions of the electric field by combining the matrix elements for an external magnetic field[14] with the elements for the external electric field. Of the four HFS crossings, only two fulfill the condition $\Delta m = 2$ for observation, and these are separated by about 16×10^{-4} T. Because of the radiative width of the states, the two HFS crossings are not resolved but form only one broadened resonance curve with a full width at half-maximum of 67×10^{-4} T.[15] The values $B_c(E)$ shown by the solid line in Fig. 4 refer to the center between the two HFS crossings.

The experimental results show clearly a nonlinear low-field Stark effect for hydrogen. Within the present uncertainties, experiment and calculations are in agreement. It is planned to reduce the uncertainties by further investigations.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support given to the project in its initial phase by Professor H. Krüger, Physikalisches Institut der Universität Tübingen.

[1]J. Stark, Abh. Dtsch. Akad. Wiss. Berl. 47, 932 (1913).
[2]A. Lo Surdo, Mem. R. Accad. Naz. Lincei Cl. Sci. Fis. Mat. Nat. 22, 665 (1913).
[3]R. T. Robiscoe, Phys. Rev. 168, 4 (1968).
[4]J. A. Blackman and G. W. Series, J. Phys. B 6, 1090 (1973).
[5]H. J. Andrä, Phys. Rev. A 2, 2200 (1970) and A. Gaupp, H. J. Andrä, and J. Macek, Phys. Rev. Lett. 32, 268 (1974).
[6]B. Budick, S. Marcus, and R. Novick, Phys. Rev. 140, A1041 (1965).
[7]The only measurement with comparable energy resolution was done by Andrä (Ref. 5). In this experiment the differential Stark effect between the states $2\,^2P_{1/2}$ and $2\,^2S_{1/2}$ was determined for fields of 10–40 kV/m using beam-foil excitation and detection of the Ly-α beat frequencies.
[8]E. Schrödinger, Ann. Phys. (Leipz.) 80, 457 (1926).
[9]V. Rojanski, Phys. Rev. 33, 1 (1929) and R. Schlapp, Proc. R. Soc. Lond. A 119, 313 (1928).
[10]G. Lüders, Z. Naturforsch. 5a, 608 (1950).
[11]B. N. Taylor, W. H. Parker, and D. N. Langenberg, Rev. Mod. Phys. 41, 375 (1969).
[12]J. C. Baird, J. Brandenberger, K. I. Gondaira, and H. Metcalf, Phys. Rev. A 5, 564 (1972).
[13]M. E. Rose and R. L. Carovillano, Phys. Rev. 122, 1185 (1961).
[14]S. J. Brodsky and R. G. Parsons, Phys. Rev. 163, 134 (1967).
[15]L. C. Himmel and P. R. Fontana, Phys. Rev. 162, 23 (1967).