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Stark effect in He I in extremely high electric field

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In the spectral range between 480–630 nm the Stark effect of the transitions n^1Q–2^1S, n^1Q–2^1P and n^3Q–2^3P (n = 3–10, $Q = S, P, D, ...$) was studied in atomic helium using electric field up to 1500 kV/cm. For such an extremely high field the Stark splitting becomes greater than the simple structure of the atom. In consequence, anticrossings of the Stark components of the same magnetic quantum number occur. The experimental results have been compared with the theoretical shifts. The results of calculations show good agreement with observation not only for low field values, but also for those in high fields and in the case of level anticrossings.

Keywords: Stark effect, helium, electric field.

1. Introduction

At low electric field the Stark components of atomic lines are resolved and their individual positions can be precisely determined by photographic photometry. But in the case of high fields the identification of components with respect to the magnetic quantum number is extremely difficult, because the Stark splitting becomes greater than the simple structure of the atom and anticrossings of the Stark components occur. For such a case the computer technique becomes useful [1, 2]. Theoretical description should take into account the large number of interacting levels corresponding to different n numbers. In our computer program we considered electric field interaction between levels with n = 1–10.

2. Experiment

The experimental arrangement was similar to that used by Windholz and co-workers in numerous Stark effect investigations (see [3]). The spectra were taken from

a direction perpendicular to the electric field, using a stigmatic three prism spectrograph. The recordings of the spectra were made using photographic technique. The shifts of the Stark components were measured against unshifted lines, which were obtained by a second exposure without field. For this measurements a modified Abbe comparator coupled with a computer processing set was used.

3. Theory

The hamiltonian for a two-electron atomic system can be described in the form [4]:

$$H = H_0 + H_{\mathrm{mp}} + H_{\mathrm{spin}} + H_{\mathrm{rel}} \tag{1}$$

where H_0 is nonrelativistic, fixed-nucleus part, H_{rel} and H_{mp} correspond to electric fine structure (H_{mp} is mass polarization correction) and H_{spin} is magnetic fine structure contribution. Since H_0 is diagonal in L and S it is usual to use LS coupled basis states for calculations the eigenvalues of H. We denote these basis states by $|nLSJM\rangle$, in which n is some radial quantum number. The matrix elements of $H - H_0$ between states differing in n or L are small enough not to cause any shifts greater than 1 kHz in the eigenvalues of states with $L > 1$. Therefore we neglect that contribution. The nonzero matrix elements of H between basis states with the same n and L numbers are:

$$\langle n(L0)LM|H|n(L0)LM\rangle = E_{nL0} \tag{2}$$

$$\langle n(L1)L-1M|H|n(L1)L-1M\rangle = E_{nL1} - (L+1)h_{so} + \frac{2L+2}{2L-1}h_{ss} \tag{3}$$

$$\langle n(L1)LM|H|n(L1)LM\rangle = E_{nL1} - h_{so} - 2h_{ss} \tag{4}$$

$$\langle n(L1)L+1M|H|n(L1)L+1M\rangle = E_{nL1} + Lh_{so} + \frac{2L}{2L+3}h_{ss} \tag{5}$$

$$\langle n(L1)LM|H|n(L0)LM\rangle = \langle n(L0)LM|H|n(L1)LM\rangle = \sqrt{L(L+1)}\,h_{\mathrm{off}} \tag{6}$$

Therefore, to describe the $1snl$ configuration we need values of five radial integrals: E_{nLS} ($S = 0, 1$), h_{so}, h_{ss}, h_{off}. The values of these integrals can be find in a semiempirical way in the framework of Slater–Condon theory where electric and magnetic fine structure integrals are evaluated so, as to fit the observed energy levels. The h_{off} parameter responsible for the mixing of singlet and triplet states can be eliminated from the calculation by the use of Heisenberg approximation:

$$h_{\mathrm{off}} = 3h_{so} \tag{7}$$

valid for hydrogen-like wave functions. Then, the remaining four parameters can be determined from experimental energy levels of states $1snl\ ^1L$ and ^3L from [5]. Such a method was used in papers [6, 7], where values of radial integrals were tabulated for $n = 2$–8. We adopted results of this calculation in our analysis. For $n = 9$ and 10 the fine structure parameters were found by us using all available experimental data for helium energy levels from [8]. In some cases, because of the lack of data, we neglected splittings of triplets levels and the values for positions of the center-of-gravity were used. Hamiltonian of the atom in external electric field consists of two parts:

$$H' = H + H_{\mathrm{el}} \tag{8}$$

where the field-dependent part is:

$$H_{\mathrm{el}} = -\mathbf{d} \cdot \mathbf{E} = ezE_z \tag{9}$$

The matrix elements of H_{el} are given by:

$$\langle nLSJM \left| ezE_z \right| n'L'S'J'M' \rangle =$$

$$= eE_z \partial_{SS'} \partial_{MM'} \sum_{M_L,\, M_S} C^{LSJ}_{M_L M_S M}\, C^{L'S'J'}_{M_L M_S M}\, C^{L'1L}_{M_L 0 M_L} (2L+1)^{-1/2} \langle nL||r||n'L' \rangle \tag{10}$$

where $C^{j_1 j_2 j_3}_{m_1 m_2 m_3}$ are Clebsch–Gordon coefficients.

The reduced matrix elements $\langle nL||r||n'L' \rangle$ for S–P and P–D transitions can be determined from the calculated oscillator strengths [9]:

$$\left| \langle nL||r||n'L' \rangle \right|^2 = \frac{3(2L+1)}{2\left| E^{\mathrm{ion}}_{n'L+1S} - E^{\mathrm{ion}}_{nLS} \right|} \left| f^{n'L+1S}_{nLS} \right| \tag{11}$$

where E^{ion}_{nLS} is an ionisation energy. For ionisation energies we used the experimental values from [5]. However for the case $n = 6$ we found large discrepancy between experimental and theoretical values. For the level 6^1P we used theoretical value 3035.78 cm^{-1} [9] instead of experimental one 3055.77 cm^{-1}[5]. Our calculations show that experimental value is wrong. The sign of the matrix elements was chosen as the same as for hydrogen-like functions.

For other transitions we used the hydrogen-like functions. Then the reduced matrix elements are given by [10]:

$$\langle nL-1||r||n'L' \rangle = \sqrt{L}\, R^{n'l-1}_{nl} \tag{12}$$

$$\langle nL+1||r||n'L' \rangle = \sqrt{L+1}\, R^{n'l+1}_{nl} \tag{13}$$

where

$$R_{nl}^{n'l\pm1} = \int_0^\infty R_{nl} R_{n'l\pm1} r^3 \mathrm{d}r \tag{14}$$

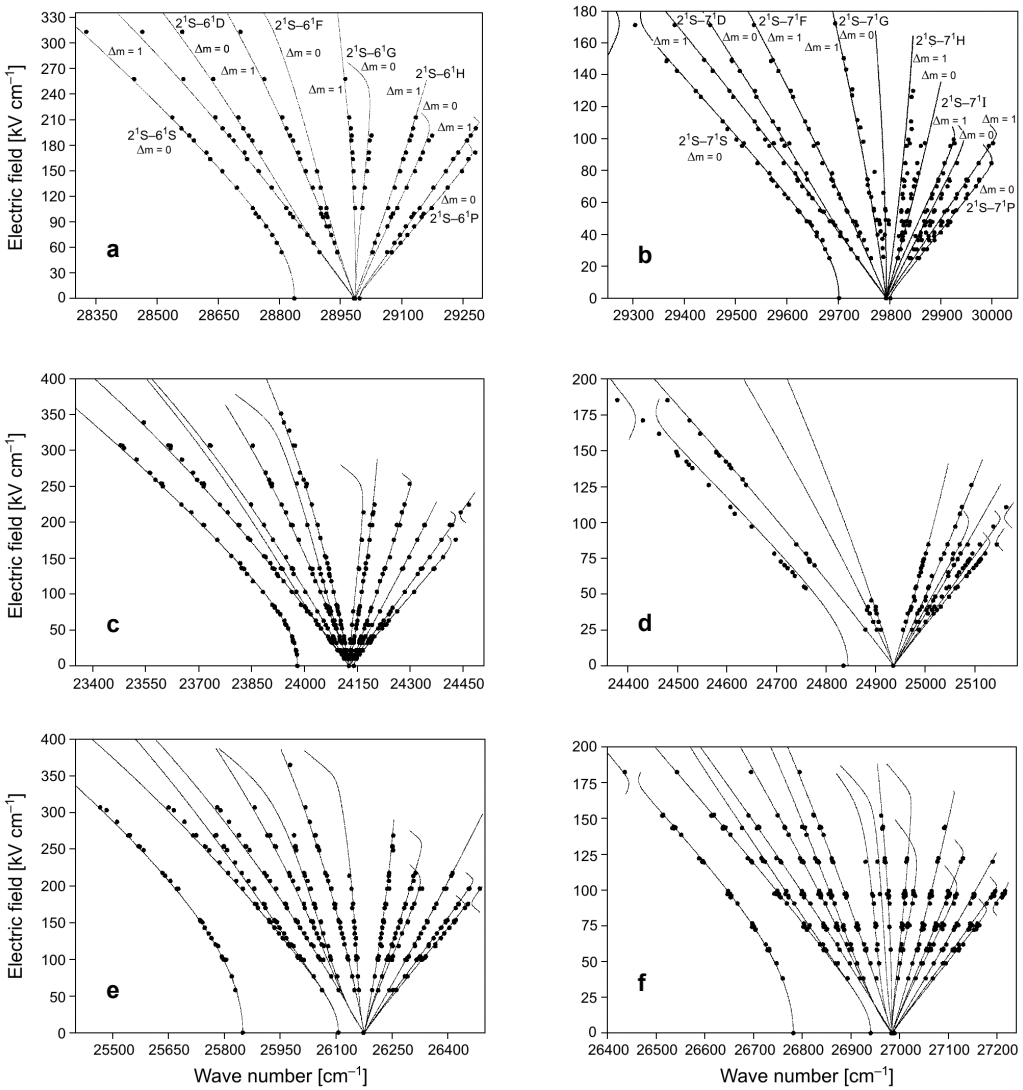

Figure. Stark effect for transitions ($Q = S, P, D, F, ...$): 6^1Q–2^1S_0 (**a**), 7^1Q–2^1S_0 (**b**), 6^1Q–2^1P (**c**), 7^1Q–2^1P (**d**), 6^3Q–2^3P (**e**), 7^3Q–2^3P (**f**). The solid lines correspond to theoretical predictions, black dots represent experimental results.

Radial integrals for $n = n'$ take very simple form:

$$R_{nl}^{nl-1} = R_{nl-1}^{nl} = \frac{3}{2} n \sqrt{n^2 - l^2} \tag{15}$$

and for $n \neq n'$:

$$R_{nl}^{n'l-1} = \frac{(-1)^{n'-1}}{4(2l-1)!} \sqrt{\frac{(n+l)!\,(n'+l+1)!}{(n-l-1)!\,(n'-l)!}}\, \frac{(4nn')^{l+1}(n-n')^{n+n'-2l-2}}{(n+n')^{n+n'}} \times$$
$$\times \left\{ F\left(-n_r, -n_r', 2l, -\frac{4nn'}{(n-n')^2}\right) - \left(\frac{n-n'}{n+n'}\right)^2 F\left(-n_r, -2, -n_r', 2l, -\frac{4nn'}{(n-n')^2}\right) \right\} \tag{16}$$

where $n_r = n - l - 1$, $n'_r = n' - l$ and $F(\alpha, \beta, \chi, \delta)$ are hypergeometric functions. In that way we have all matrix elements to build the H' hamiltonian matrix for each value of the electric field and each value of the magnetic quantum number M. The matrix is build from several large parts corresponding to different n numbers. Each of them, in turn, consists of two submatrices corresponding to singlet and triplet states, respectively, connected by off-diagonal matrix elements h_{off}.

4. Results

Some of our computer simulations for transitions n^1Q–2^1S, n^1Q–2^1P and n^3Q–2^3P ($Q = S, P, D, \ldots$) for $n = 6, 7$ compared with experimental data are presented in the Figure. The agreement between theory and experiment is satisfactory.

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