Stark Effect Investigations in the $5d\,6s\,(^3D)\,6p\;^2D_{3/2}$-State of Li I

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(Z. Naturforsch. **32 a**, 708 – 710 [1977]; received May 4, 1977)

The Stark effect of the $5d\,6s\,(^3D)\,6p\;^2D_{3/2}$-state of Lu I was investigated using the level crossing technique in combined magnetic and electric fields. From the broadening of the Hanle signal due to the shifts of the crossings in the electric field the Stark effect parameter $|\beta| = 6(2)$ kHz/(kV/cm)^2 was deduced. A theoretical study considering some of the mixing states is made.

1. Introduction

The electronic structure of the neutral Lutetium ($Z = 71$), the last element of the Lanthanides, is characterized by the filled $4f^{14}$ shell, which has contracted to the inside of the $5s^2 5p^6$ shells of the Xenon substructure and behaves like an inner shell. On the other hand the three outer electrons $5d\,6s^2$ form the ground state $5d\,6s^2\;^2D_{3/2}$. Their excitation is responsible for the optical spectrum. Because the one-electron energies E_{5d}, E_{6s} or E_{6p} of the outer electrons are quite similar to each other, there exist many competing configurations like $5d^2\,6s$ or $6s\,6p^2$, whose energy levels are close to each other. Therefore the interpretation of the spectrum is quite difficult and as a result the classification of many levels has changed during the years [1–3]. An extensive study of the spectrum was made by Camus [4, 5]. His classification and state vectors are used in this work.

It is important for the term analysis that apart from the energies and J-values of the levels one should get more information about other properties like g_J-values, hyperfine constants, mean lifetimes or Stark effect parameters. The g_J-values in first order are determined by the angular part of the wave functions and are mainly used to establish the coupling properties within a given configuration. The hyperfine constants, the lifetimes and the Stark effect parameters likewise reflect certain coupling properties. But they are also very sensitive to the radial part of the wave functions: the hyperfine constants because of the $\langle n\,l | r^{-3} | n\,l \rangle$-values are sensitive in the region near the origin $r = 0$, the mean lifetimes and Stark effect parameters because of the $\langle n\,l | r | n'\,l' \rangle$-values between different configurations are sensitive to the outer region $r \approx a_0$. The combination of all these parameters can be very useful for the identification of particular levels in complex spectra.

In this work the $5d\,6s\,(^3D)\,6p\;^2D_{3/2}$-State of Lu I was investigated using the level crossing technique. The influence of a constant electric field on the zero field crossings (Hanle effect) was used to determine the Stark effect parameter β of this state. A theoretical study was done in order to explain the experimental value.

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2. Experiments

For the experiments a conventional level-crossing apparatus (as shown in Fig. 1) was used. An atomic beam of Lutetium was produced by a tantalum oven, which was heated by electron bombardment to a temperature of about 1300 °K. The atomic beam was illuminated by the light of a hollow cathode, which was filled by metallic Lutetium and was run in an atmosphere of ca. 5 Torr of Neon. Typical discharge conditions were about 170 V and 1 A. The resonance light was observed as a function of a magnetic field, which was produced by two Helm-

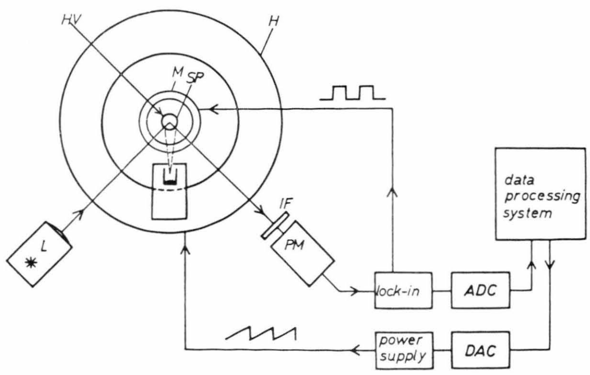

Fig. 1. Schematic diagram of apparatus: L Light source, H Helmholtz coils, SP Stark plates, HV High voltage, M Modulation coils, IF Interference filter.

holtz coils. An interference filter in front of the photomultiplier selected the line $\lambda = 451.8$ nm of the transition 5d6s(^{3}D)6p $^2D_{3/2}$ – 5d6s^2 $^2D_{3/2}$ (Figure 2). For the study of the Stark effect an electric field up to $E_z \approx 40$ kV/cm was applied by two metallic Stark plates with a distance $d \approx 1$ cm inside the interaction region. The electric field was parallel to the magnetic field.

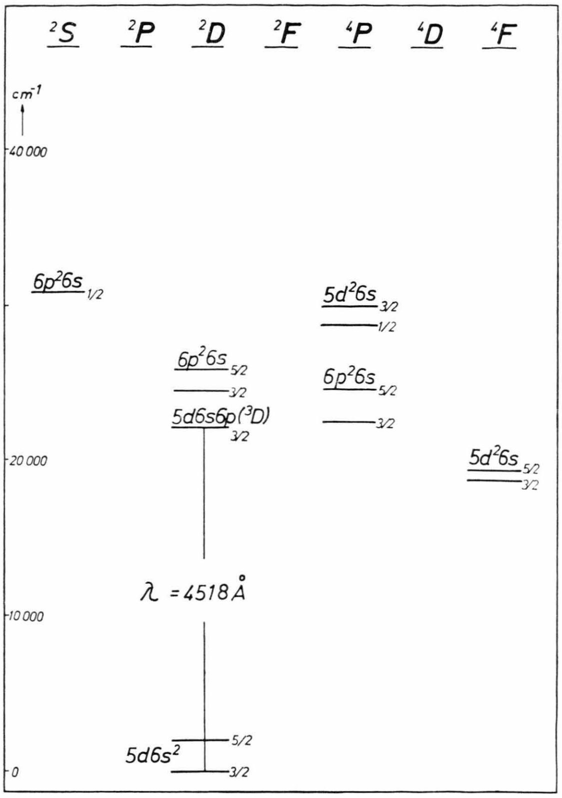

Fig. 2. Relevant energy levels of Lu I.

The effect of the electric field on a magnetic sublevel $(a\,J\,M)$ can be described by an effective hamiltonian

$$H = (\alpha + \beta\, J_z^2)\, E_z^2 \tag{1}$$

where α and β are the Stark effect parameters. E_z is the applied electric field. The Stark effect parameters are determined by the sum

$$\sum_{bJ'} \frac{|\langle a\,J \,\|\, D \,\|\, b\,J' \rangle|^2}{E_{aJ} - E_{bJ'}} \tag{2}$$

where $\langle a\,J \,\|\, D \,\|\, b\,J' \rangle$ are the reduced electric dipole matrix elements between $|a\,J\rangle$ and other states $|b\,J'\rangle$, which can be mixed to $|a\,J\rangle$ by the electric dipole operator $\vec{D} = -\sum e\,\vec{r}_i$. The denominator $(E_{aJ} - E_{bJ'})$ is the energy difference of the mixing states. Thus the influence of states $|b\,J'\rangle$, which are close to $|a\,J\rangle$, are obviously favoured. The second part $\beta\, J_z^2\, E_z^2$ of the effective hamiltonian shifts magnetic sublevels $|a\,J\,M\rangle$ with different $|M|$-values in a different way and therefore causes shifts of the level crossings of the sublevels with respect to their magnetic field position.

For levels with hyperfine splitting one can measure the shifts of the high field crossings or of the zero field crossings (Hanle effect). In our experiments the influence of the electric field on the Hanle effect was investigated. Because the signal of the Hanle effect usually is the sum of many zero-field crossings the shifts of these crossings due to smaller electric fields cause a decrease of the signal amplitude and an increase of the signal width. In the region where the Stark effect shifts $\beta\, M^2\, E_z^2$ become larger than the natural width $\Gamma = \tau^{-1}$ of the excited states, which determines the signal width of the crossings, the overlapping signals of the Hanle effect can be separated and new high field crossings appear. Because the Stark effect parameter β of the 5d6s(^{3}D)6p $^2D_{3/2}$-state is small and an increase of the electric field was prevented by discharges between the Stark plates and the oven, in our experiments only the decrease of the amplitude and the increase of the signal width was measured. Figure 3

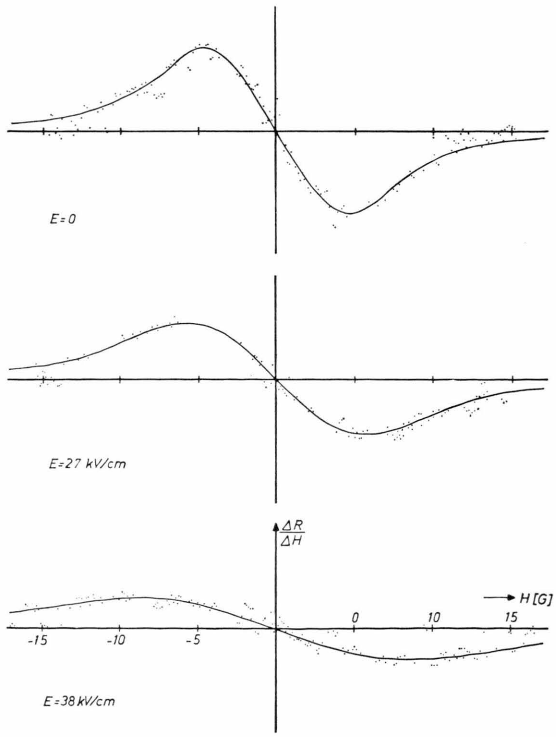

Fig. 3. Hanle effect signal for $E=0$, $E=27$ kV/cm and $E=38$ kV/cm.

and Fig. 4 show the experimental results for the increase of the signal width, from which the value $|\beta| = 6(2)$ kHz/(kV/cm)^2 was deduced.

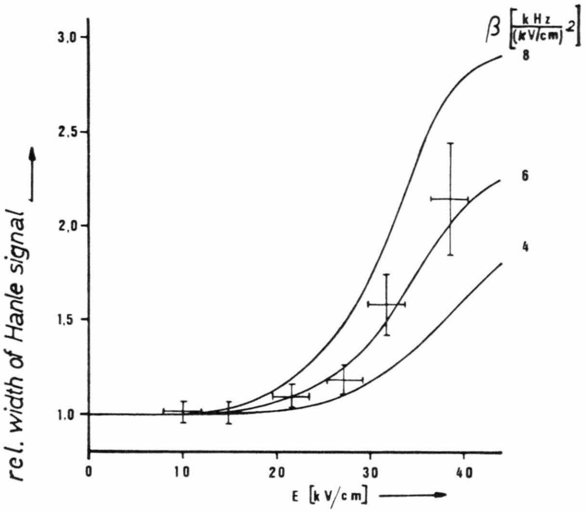

Fig. 4. Width of Hanle signal in dependence of the electric field strength.

3. Discussion

The first step in the calculation of the Stark effect parameters usually is the limitation of the infinite sum (2) to the contribution of those mixing states $|bJ'\rangle$ which have a small energy difference to $|aJ\rangle$ and/or have large dipole matrix elements with $|aJ\rangle$. In the case of the 5d6s(^{3}D)6p $^2D_{3/2}$-state it is obvious to look for the contribution of those states with even parity which have a small energy difference to the 5d6s(^{3}D)6p $^2D_{3/2}$-state. The ^{4}F-states of the 5d^{2}6s-configuration and the ^{2}D- and ^{4}P-states of the 6s6p^2-configuration (if indeed this classification is correct) with energy differences between $300-3000\ \mathrm{cm}^{-1}$ should give the main contribution to the Stark effect of the 5d6s(^{3}D)6p $^2D_{3/2}$-state. The next step is the construction of the wave functions in some arbitrarily chosen coupling scheme. For the 5d6s(^{3}D)6p $^2D_{3/2}$-state we used the following wave functions of Camus:

$$|5d6s(^3D)6p\,^2D_{3/2}\rangle = 0.76\ |(^3D)\,^2D_{3/2}\rangle + 0.453\,|(^1D)\,^2D_{3/2}\rangle - 0.288\,|(^3D)\,^4P_{3/2}\rangle - 0.131\,|(^3D)\,^4D_{3/2}\rangle - 0.271\,|(^3D)\,^4F_{3/2}\rangle\,. \quad (3)$$

The state vectors of the mixing ^{4}P- and ^{2}D-states of the 6s6p^2-configuration and the ^{4}F-states of the 5d^{2}6s-configuration were unknown to us. For their evaluation we used the parametric potential method of Klapisch [6]. Unfortunately these calculations were quite sensitive to small changes in the parameters and the energy fits for many levels were rather poor (which may be due to incorrect classifications). Therefore these results could only be regarded as rough approximations.

The last step in the evaluation of the Stark parameter is the calculation of the radial integrals of the mixing states. If one concentrates on the levels of the 6s6p^2- and 6s5d^2-configuration, the Stark effect of the 5d6s(^{3}D)6p $^2D_{3/2}$-state is determined by the radial integral $\langle 5d|r|6p\rangle$. The parametric potential method for the integral yielded $\langle 5d|r|6p\rangle = 1.9\,a_0$.

Taking into account all these uncertainties, the theoretical value of the Stark parameter β of the 5d6s(^{3}D)6p $^2D_{3/2}$-state can only be said to be in the order of some kHz/(kV/cm)^2. It is obvious that one needs more experimental values of the Stark effect parameters from other states of the same configuration 5d6s6p. Experiments in the 5d6s(^{1}D)6p $^2F_{5/2}$-state are in progress.

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