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# Stark shift measurement of the $(6s)^2\,{}^1S_0 \rightarrow (6s6p)\,{}^3P_1$ ytterbium transition

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**Abstract.** The Stark shift of the $(6s)^2\,{}^1S_0 \rightarrow (6s6p)^3P_1$ transition in ytterbium was measured using a laser to excite an atomic beam first in a uniform electric field and subsequently in a field-free region. The laser frequency was scanned across the transition while fluorescence produced by the radiative decay of the excited state was detected. The frequency scan was calibrated using isotope and hyperfine splittings that have been measured previously. The Stark shift rate was found to be $-15.419 \pm 0.048$ kHz kV$^{-2}$ cm$^{-2}$ and the tensor polarizability of the $(6s6p)^3P_1$ state was determined to be $\alpha_2 = 5.81 \pm 0.13$ kHz kV$^{-2}$ cm$^{-2}$.

## 1. Introduction

Recent precision measurements of Stark shifts have made possible stringent tests of atomic theory and provided information about polarizabilities of atomic states that are needed for describing properties such as charge-exchange cross sections, van der Waals constants and dielectric constants [1–6]. This work reports the first determination of the Stark shift rate of the ytterbium $(6s)^2\,{}^1S_0 \rightarrow (6s6p)\,{}^3P_1$ transition and an improved value for the tensor polarizability of the $(6s6p)^3P_1$ state. Ytterbium is important for a wide variety of investigations including the study of laser cooling and the development of improved frequency standards [7–10]. It has a number of states that are readily populated by using CW lasers to excite the ground state. This has permitted the study of the hyperfine interaction of excited states [11–13]. Ytterbium is also ideal for studying isotope shifts since it has naturally occurring isotopes with atomic mass units 168 (0.13%), 170 (3.05%), 171 (14.3%), 172 (21.9%), 173 (16.12%), 174 (31.8%) and 176 (12.7%). The nuclear spin of the even isotopes is zero while isotopes 171 and 173 have spins of $\frac{1}{2}$ and $\frac{5}{2}$ respectively.

For isotopes having zero nuclear spin, an electric field $\tilde{E}$ shifts the energy of the $|JM_J\rangle$ state by an amount

$$\varepsilon = -\left\{\alpha_0 + \alpha_2 \frac{3M_J^2 - J(J+1)}{J(2J-1)}\right\}\frac{E^2}{2}. \tag{1}$$

Here, $J$ is the total angular momentum quantum number (excluding nuclear spin), and $M_J$ is its azimuthal component, $\alpha_0$ and $\alpha_2$ are the scalar and tensor polarizabilities. The electric field shifts the frequency for the transition between the $(6s)^2\,{}^1S_0$ and $(6s6p)\,{}^3P_1$ states by

$$\Delta\nu = KE^2 \tag{2}$$

where the Stark shift rate

$$K = -\tfrac{1}{2}\{\alpha_0({}^3P_1) - 2\alpha_2({}^3P_1) - \alpha_0({}^1S_0)\}. \tag{3}$$

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Here, $M_J$ has been set to zero since the laser was linearly polarized along the quantization axis, which was specified by the electric field, and therefore, only populated the $M_J = 0$ sublevel of the $^3P_1$ state.

For $^{171,173}$Yb, the hyperfine interaction must also be considered in the Hamiltonian. Each hyperfine level is labelled by $F$ where $F = J + I$ is the sum of the angular momentum $J$ and the nuclear spin $I$. The Stark shifts encountered in this experiment were much smaller than the hyperfine energy splittings occurring in $^{171,173}$Yb. The effect of an electric field on a hyperfine level having $F > 1/2$ is given by equation (1) where $J$ is replaced by $F$ and $M_F$ is substituted for $M_J$†. For the $F = 1/2$ level of the $^{171}$Yb $^3P_1$ state there is no tensor shift and the Stark shift rate for a transition to this level from the ground state is given by

$$K(^{171}\text{Yb}, F = 1/2) = -\tfrac{1}{2}\{\alpha_0(^3P_1) - \alpha_0(^1S_0)\}. \tag{4}$$

In this experiment, transitions to the $^3P_1$ state of the even isotopes were studied to determine the Stark shift rate $K$ given by equation (3). The tensor polarizability of the excited state was found by subtracting equation (4) from equation (3). Transitions to the hyperfine levels of the $^3P_1$ state in $^{171,173}$Yb, for which $F > 1/2$, were not studied since they yield no additional information and assumptions must be made about the relative populations of the $M_F$ sublevels, generated by the laser excitation of the ground state, in order to extract a value for $\alpha_2(^3P_1)$.

## 2. Description of the method

The apparatus is illustrated in figure 1. It has been described in detail elsewhere and is therefore only briefly discussed [4, 5]. An atomic beam of ytterbium was generated using an oven and a series of slits producing a beam having a divergence of $\sim 2$ mrad. Laser light at a wavelength of 555.6 nm was supplied by a ring dye laser (Coherent 699) that was pumped by an argon-ion laser. The laser excited the atomic beam first in a uniform electric field and subsequently in a field-free region. The laser beams orthogonally intersected the atomic beam to eliminate first-order Doppler shifts.

The electric field was generated by two stainless steel plates having a thickness of 1.3 cm (0.5 in) and a diameter of 7.6 cm (3 in). The spacing was determined to be $1.0163 \pm 0.0003$ cm using machinist blocks with thicknesses specified with an uncertainty of less than $2.5 \times 10^{-5}$ cm. Plate voltages of 0–50 kV were continuously monitored using a precision voltage divider that reduced the voltage by a factor of 5000 with an accuracy of 0.01%. The reduced voltage was measured by a voltmeter having an uncertainty of less than 0.002%.

The laser frequency was tuned across the transition while fluorescence produced by the radiative decay of the excited state back to the ground state was detected by two photomultipliers (PM1 and PM2). The signals were sent to lock-in amplifiers that were externally triggered by a signal generator at a rate of 256 Hz. A sample spectrum observed in the field-free region is shown in figure 2. No non-linearity in the scan of the laser frequency was observed, although the laser scan speed was found to vary slightly from scan to scan. The frequency was therefore calibrated as follows. First, the centre position of each peak was determined by fitting a Gaussian function to the data. The frequency intervals separating the various isotopes have been determined by Clark *et al* [11] and were used to calibrate the frequency of each laser scan with an uncertainty of less than one part in 4000.

† The second-order perturbative correction given by $(\alpha_2 E^2/2)^2/h\Delta E_F$ where $\Delta E_F$ is the difference in hyperfine level energies, was less than 0.1 MHz.

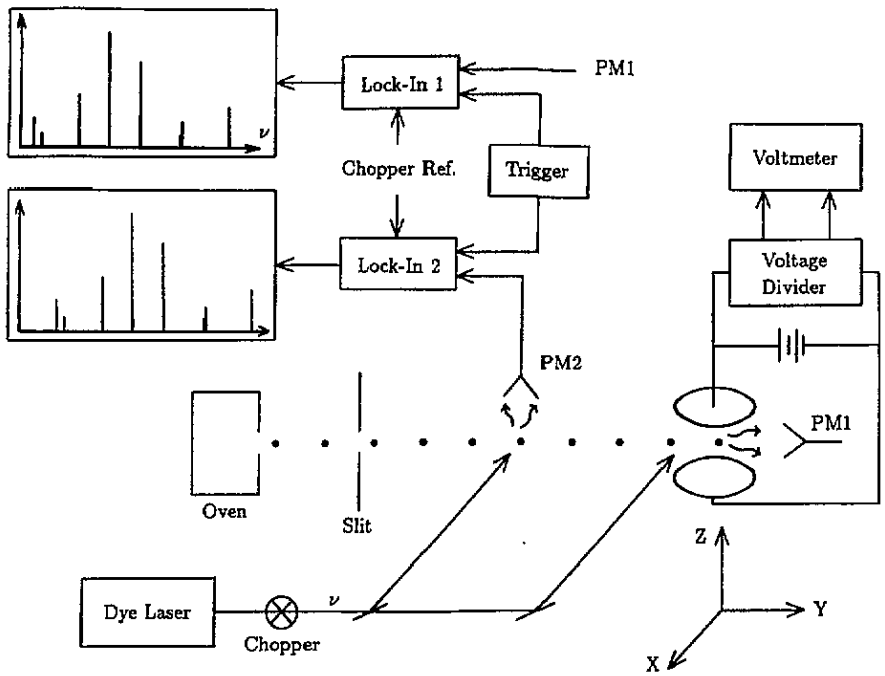


**Figure 1.** The apparatus. (Details are described in the text.)

The average frequency interval represented by a single data point was 0.1855 MHz. The frequency shifts between the peaks observed in the field and field-free regions were then found.

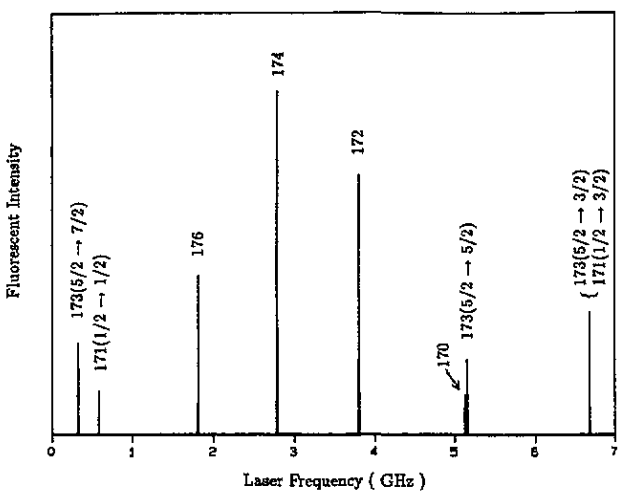


**Figure 2.** The ytterbium spectrum. The laser frequency was scanned across the $(6s)^2\,{}^1S_0 \rightarrow (6s6p)\,{}^3P_1$ transition exciting the various isotopes. These data were taken in the field-free region.

## 3. Results and conclusions

Nearly 500 wavelength scans were taken at several different electric fields. No difference in the Stark shifts experienced by the various even isotopes was observed. Their average frequency shift is plotted against the square of the electric field in figure 3. A least-squares fit of the function $y = KE^2 + y_0$ to the data yielded

$$K = -15.419 \pm 0.048 \text{ kHz kV}^{-2} \text{ cm}^{-2}.$$

The frequency shift at zero field $y_0$ was 5.33 MHz. This offset is believed to arise from a small difference of the intersection angle of the laser and atomic beams in the field and field-free regions. A similar offset was observed in an experiment that measured the Stark shift of a transition in barium [5]. The offset changed by up to 1 MHz whenever the oven was realigned after being cleaned and reloaded with ytterbium metal. However, the Stark shift rate $K$ was always found to be independent of the oven alignment.

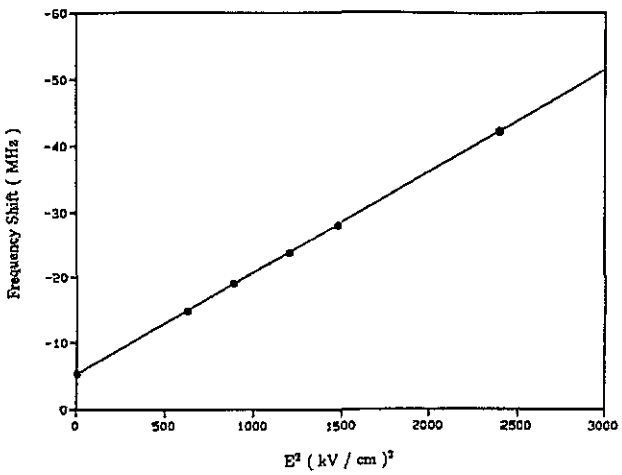


**Figure 3.** The frequency shift against electric field squared. The average frequency shift observed at each voltage is plotted. The standard deviation of the frequency shifts about their average value was less than that indicated by the size of the data points.

The tensor polarizability was found to be

$$\alpha_2 = 5.81 \pm 0.13 \text{ kHz kV}^{-2} \text{ cm}^{-2}.$$

The accuracies of the results for $K$ and $\alpha_2$ were limited by statistical variation of the data caused by jitter of the dye laser frequency. The 2% relative uncertainty in $\alpha_2$ was larger than that for $K$ since the tensor Stark shift, $\alpha_2 E^2/2$ was only about one third of the total Stark shift. Furthermore, figure 2 shows that the transitions in $^{172,174,176}$Yb, that determine $K$, have a higher signal-to-noise ratio than the transition to the $F = 1/2$ level of the $^3P_1$ state of $^{171}$Yb which was used to find $\alpha_2$. The result for $\alpha_2$ agreed with the value of $5.99 \pm 0.34$ kHz kV$^{-2}$ cm$^{-2}$ found in an optical double resonance experiment [14] and $6.04 \pm 0.21$ kHz kV$^{-2}$ cm$^{-2}$ obtained using quantum beats spectroscopy [15]. The scalar polarizability of the $^3P_1$ state can be found using $\alpha_0(^1S_0)$ which has been calculated using Hartree–Fock theory to be $66.1 \pm 6.6$ kHz kV$^{-2}$ cm$^{-2}$ [16]. Substituting this result, along with our results for $K$ and $\alpha_2$, into equation (3) gave $\alpha_0(^3P_1) = 108.6 \pm 6.6$ kHz kV$^{-2}$ cm$^{-2}$.

In conclusion, this experiment reports the measurement of the Stark shift rate for the $(6s)^2\,^1S_0 \rightarrow (6s6p)\,^3P_1$ transition with an accuracy of 0.3%. An improved value for the

tensor polarizability of the $^3P_1$ state was also obtained illustrating the usefulness of the experimental method.

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