# Measurement of Stark Amplitudes $\alpha, \beta$ in the $6^2P_{1/2} \rightarrow 7^2P_{1/2}$ Transition in Atomic Thallium

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We report measurements of the Stark-amplitude coefficients $\alpha, \beta$ for the transition $6P_{1/2} \rightarrow 7P_{1/2}$ (293 nm) in $^{205}$Tl in an external electric field $E$. $\alpha$ is determined by measurement of absorption of 293-nm light at the $F=1 \rightarrow F=1$ resonance in a cell with known electric field and interaction length, and calibrated density. $\beta$ is determined from the ratio $\beta^2/\alpha^2$ of intensities of $F=0 \rightarrow F=1$ and $F=0 \rightarrow F=0$ lines in fluorescence. We obtain $\alpha = (1.31 \pm 0.06) \times 10^{-5} \mu_0$ cm/V, $\beta = (1.09 \pm 0.05) \times 10^{-5} \mu_0$ cm/V (where $\mu_0$ is the electron Bohr magneton). These results indicate substantial shielding by core electrons.

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The $6^2P_{1/2} \rightarrow 7^2P_{1/2}$ transition (293 nm) in atomic thallium has been studied extensively in our laboratory because of its connection to parity nonconservation (PNC).[1-4] The transition is nominally forbidden $M1$ (with amplitude $M$). However, because of PNC there is also an electric dipole component $\mathcal{E}_P$, and in the presence of an external electric field **E** a Stark-induced $E1$ component exists in addition. The amplitude coefficients for the latter are $\alpha$ and $\beta$ for **E** parallel and perpendicular, respectively, to the linear polarization $\hat{\epsilon}$ of the absorbed photon.

In the one-electron central-field approximation, these quantities are given in the lowest order by

$$\alpha = \frac{e^2}{9} \sum_{nS} R_{7P,nS} R_{6P,nS} \left[ \frac{1}{E_7 - E_{nS}} + \frac{1}{E_6 - E_{nS}} \right] + \frac{2e^2}{9} \sum_{nD_{3/2}} R_{7P,nD} R_{6P,nD} \left[ \frac{1}{E_7 - E_{nD}} + \frac{1}{E_6 - E_{nD}} \right], \quad (1)$$

and

$$\beta = \frac{e^2}{9} \sum_{nS} R_{7P,nS} R_{6P,nS} \left[ \frac{1}{E_6 - E_{ns}} - \frac{1}{E_7 - E_{ns}} \right] + \frac{e^2}{9} \sum_{nD_{3/2}} R_{7P,nD} R_{6P,nD} \left[ \frac{1}{E_7 - E_{nD}} - \frac{1}{E_6 - E_{nD}} \right], \quad (2)$$

where $E_6 = E(6^2P_{1/2})$, $E_7 = E(7^2P_{1/2})$, and $R_{7P,nS} = \langle 7^2P_{1/2} | r | n^2S_{1/2} \rangle$, etc. As presently defined, $\alpha$ and $\beta$ each have dimensions (length$^3$).[5]

In a previous experiment, interference between the PNC and Stark $E1$ amplitudes was observed and the quantity

$$\mathrm{Im}(E_P/\beta) = -1.73 \pm 0.26 \pm 0.07 \text{ mV/cm} \quad (3)$$

was determined.[3,4] To extract $E_P$, one must determine $\beta$, but until now $\beta$ was not known experimentally, and only rather naive estimates of it were available.[6,7] We here report direct measurements of $\alpha$ and $\beta$.

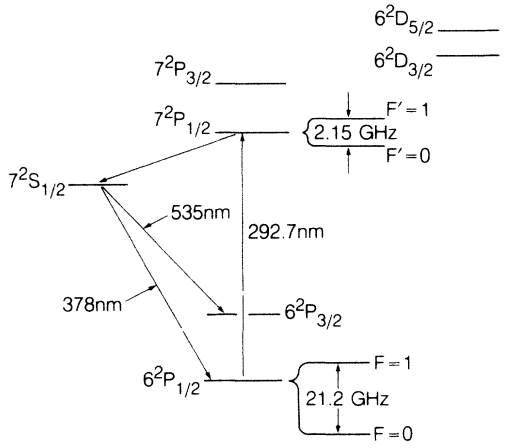


FIG. 1. Low-lying energy levels of Tl (not to scale). The hyperfine components of the $6^2P_{1/2}$ and $7^2P_{1/2}$ states are shown.

For $E \gg 1$ V/cm, the Stark $E1$ contribution to the 293-nm transition greatly dominates over $M$ and $E_P$, and the latter amplitudes may be neglected for present purposes. The transition probabilities per unit time $W$ of the various hyperfine components of the $6^2P_{1/2} \rightarrow 7^2P_{1/2}$ transition (see Fig. 1) are proportional to the values in the following tabulation, where the nuclear spin of $^{205}$Tl is $\frac{1}{2}$:

| $F \rightarrow F'$ | $W$ |
|---|---|
| $0 \rightarrow 0$ $(\hat{\epsilon} \parallel \mathbf{E})$ | $\alpha^2E^2$ |
| $0 \rightarrow 1$ $(\hat{\epsilon} \perp \mathbf{E})$ | $\beta^2E^2$ |
| $1 \rightarrow 0$ $(\hat{\epsilon} \perp \mathbf{E})$ | $\beta^2E^2$ |
| $1 \rightarrow 1$ $(\hat{\epsilon} \parallel \mathbf{E})$ | $3\alpha^2E^2$ |
| $1 \rightarrow 1$ $(\hat{\epsilon} \perp \mathbf{E})$ | $2\beta^2E^2$ |

In the present experiment we determine $\alpha$ by measuring the absorption of a linearly polarized laser beam tuned to the $F=1 \rightarrow F'=1$ resonance, when this beam is passed through a cell containing $^{205}$Tl vapor at known temperature in a known electric field $\mathbf{E} \| \hat{\epsilon}$ over a region of known length $l$ (see Fig. 2). The intensity of the emerging beam, $I$, may be expressed in terms of that of the entering beam, $I_0$, by $I = I_0 \exp(-\mu l)$ where

$$\mu = \frac{(2\pi)^2}{\hbar c}\frac{n}{4}3\alpha^2 E^2\left(\frac{mc^2}{2\pi kT}\right)^{1/2} \exp[-(m\lambda_0^2/2kT)(\nu-\nu_0)^2]. \quad (4)$$

Here $n$ is the density of $6^2P_{1/2}$ atoms, $m$ is the mass of a $^{205}$Tl atom, $T$ is the effective vapor temperature, $\lambda_0 = 292.7$ nm, and $\nu$ and $\nu_0$ are the photon and resonance frequencies, respectively. Equation (4) is valid provided the laser bandwidth is much less than the Doppler width, a condition very well satisfied here. [A correction to (4) for finite laser bandwidth is less than 0.5% and may be neglected.] To determine $n$ we measure absorption of another laser beam tuned to the $6^2P_{3/2}(F=1) \rightarrow 7^2S_{1/2}(F'=0)$ allowed $E1$ transition (535 nm) in the same cell under identical conditions. For sufficiently weak intensities (such that stimulated-emission effects may be neglected), this absorption is described by $I' = I_0' \exp(-\mu' l')$, where $l'$ is the cell length, and

$$\mu' = \frac{nA\lambda'^3}{32\pi}e^{-\Delta E/kT}\left(\frac{m}{2\pi kT}\right)^{1/2} \exp[-(m\lambda'^2/2kT)(\nu-\nu')^2]. \quad (5)$$

Here, $\lambda' = 535$ nm, $A = (7.11 \pm 0.16)\times 10^7$ sec$^{-1}$ is the precisely determined[8] coefficient for spontaneous emission in $7^2S_{1/2} \rightarrow 6^2P_{3/2}$, $e^{-\Delta E/kT}$ is a Boltzmann factor accounting for $E(6^2P_{3/2}) - E(6^2P_{1/2}) = \Delta E = 7793$ cm$^{-1}$, and $\nu'$ is the resonance frequency. In the ratio of absorption coefficients $\mu/\mu'$, factors of $n$ and of $T^{-1/2}$ cancel, and the exponential factors involving $\nu-\nu'$ or $\nu-\nu_0$ may be set equal to unity on resonance. However, $T$ must still be known because of the Boltzmann factor. Once $\alpha$ is found $\beta$ is determined by measurement of the ratio of intensities $\beta^2/\alpha^2$ in decay fluorescence at 535 nm for the $6P_{1/2} \rightarrow 7P_{1/2}$ $0 \rightarrow 1$ and $0 \rightarrow 0$ resonances.

The 293-nm photons are generated by a laser system described elsewhere.[4,9] These are delivered in 8-nsec pulses, repetition rate 17 Hz, with bandwidth $\sim 160$ MHz, and typical pulse energies of 2 mJ/pulse. The photon linear polarization is fixed by a Pockels cell. The absorption cell is a fused-silica cylinder of length $l' = 25$ cm, outside diameter 2.2 cm, with flat end windows slightly canted to avoid unwanted reflections. It contains a pair of parallel, flat, polished stainless-steel electrodes of length $l = 23$ cm, width 1.5 cm, separation $0.497 \pm 0.001$ cm, connected to the outside by wires and feedthroughs. Appended to the bottom of the cell is a narrow stem (Tl reservoir), and the cell is connected to an ion pump by a tube (sealed at the cell by a remotely actuated fused-silica ball valve). The main part of the cell and the stem are separately enclosed and heated by stainless-steel ovens. The entire apparatus is mounted in a rough vacuum tank.

The $E^2$ dependence of the absorption coefficient has been verified carefully, but for measurements actually used to determine $\alpha$, the field was $E = 1700$ V/cm. Numerical solution of Laplace's equation by the relaxation method for the electrode-cell-oven geometry reveals that corrections for electrode end and width effects are less than 0.2 and negligible. The main and stem oven temperatures were measured by four Chromel-Alumel thermocouples, all referenced to 0 °C. To determine the small temperature gradients along the main oven which arise from beam end holes, small ports for stem, fluorescence detector, feedthroughs, etc., we made preliminary temperature determinations with a movable axial thermocouple. Typical main oven temperatures were $T = 1030$ K. The partially absorbed 293-nm beam was detected by an ITT model FW114A photodiode. A similar photodiode was used to detect the beam reflected from the vacuum-tank entrance window, to normalize laser intensity. Both photodiodes were connected to preamplifiers, linear amplifiers, pulse stretchers, an analog-to-digital converter, and a computer that controlled the experiment and recorded and analyzed the data. Absorption was measured on and off resonance, and with $E$ on and off, in order to correct for background effects. The laser was tuned automatically to the center of the $1 \rightarrow 1$ line by means of a feedback loop referenced to the fluorescent signal at 535 nm.

Measurements of the 293- and 535-nm absorptions were carried out on the same days and with identical cell conditions. For the temperatures chosen $\mu l \sim 6\times 10^{-4}$, $\mu' l' \sim 1$. The precision of the $\mu$ measurement was limited by statistical uncertainty ($\Delta\mu/\mu = 1.7\%$). The cell and stem temperatures were sufficiently constant that the internal consistency of all determinations of $\mu'$ was within 0.2%; thus the precision of the measurement of $n$ was limited by the uncertainty in $A$ (2.25%). Great care was taken to avoid saturation effects in the case of $\mu'$, by keeping the (cw) 535-nm beam intensity very low, and by studying $\mu'$ vs $I_0'$ over a range of several orders of magnitude in the latter quantity. The observed line shape of the 535-nm absorption was in excellent agreement with Eq. (5) (see Fig. 3).

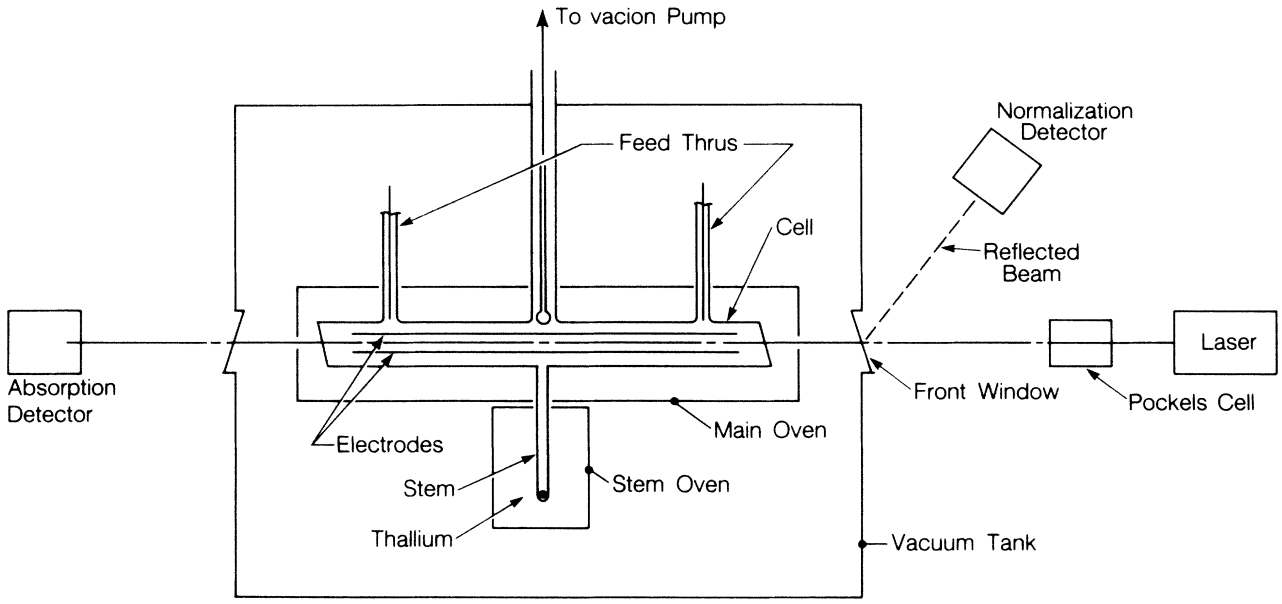


FIG. 2. Schematic diagram of experimental apparatus.

In order to test the system we also observed absorption in the transition $6^2P_{3/2} \rightarrow 7^2D_{5/2}$ (291.8 nm) by scanning a weak cw monochromatic laser beam through this resonance. From a formula similar to (5) plus knowledge of $n$ and $T$, and taking into account the partial resolution of hyperfine-structure components in this case we obtain the result

$$A(7^2D_{5/2} \rightarrow 6^2P_{3/2}) = (4.51 \pm 0.21) \times 10^7 \text{ sec}^{-1}. \quad (6)$$

This agrees with a previous determination[10]:

$$A(7^2D_{5/2} \rightarrow 6^2P_{3/2}) = (4.2 \pm 0.5) \times 10^7 \text{ sec}^{-1}.$$

Our main results are as follows. First,

$$\alpha = (1.31 \pm 0.06) \times 10^{-5} \mu_0 \text{ cm/V} = (247 \pm 12) a_0^3. \quad (7)$$

The combination, in quadrature, of the uncertainties in $A$ (2.25%), in $\mu$ (1.7%), in $E$ ($\sim 1\%$), and in a correction for nonuniformity of $T$ ($\sim 1\%$) as well as other miscellaneous small uncertainties yields a total fractional uncertainty in $\alpha$ of 5% (95% confidence). Next, from comparison of the $0 \rightarrow 0 (\mathbf{E} \| \hat{\epsilon})$ and $0 \rightarrow 1 (\mathbf{E} \perp \hat{\epsilon})$ fluorescence signals, we obtain

$$\beta/\alpha = 0.83 \pm 0.01 \quad (95\% \text{ confidence}), \quad (8)$$

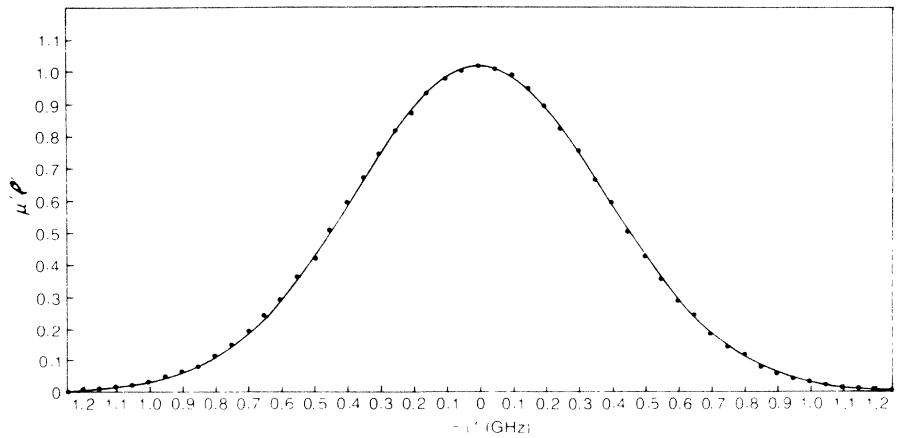


FIG. 3. Absorption curve for the transition $6^2P_{3/2}(F=1) \rightarrow 7^2S_{1/2}(F=0)$, 535 nm. The quantity $\mu' l'$ is plotted. Points: experimental data taken at effective vapor temperature $T = 1030$ K. Solid curve: $\mu' l'$ calculated from Eq. (5) for $T = 1030$ K and normalized to agree with experimental point at $\nu = \nu'$.

TABLE I. Theoretical values of $\mathrm{Im}\,\mathscr{E}_P$ calculated in various potential models (Ref. 7). No many-body corrections included.

| Potential type | $\mathrm{Im}\,\mathscr{E}_P$ $(10^{-10}Q_W\mu_0)$ |
|---|---|
| Tietz | 2.11 |
| Green | 1.88 |
| Norcross | 2.03 |
| PNC Hartree-Fock | 2.16 |

which agrees with earlier measurements.[1] We also measured $\beta$ directly by absorption in the $1 \rightarrow 1$ line for $\hat{\epsilon} \perp \mathbf{E}$ and obtained $\beta/\alpha = 0.83 \pm 0.08$. Combining (7) and (8) we have

$$\beta = (1.09 \pm 0.05) \times 10^{-5} \mu_0 \text{ cm/V} = (198 \pm 10) a_0^3. \quad (9)$$

This may be compared with the naive theoretical estimate[6,7]

$$\beta_0 = 1.64 \times 10^{-5} \mu_0 \text{ cm/V} = 309 a_0^3. \quad (10)$$

The substantial discrepancy between (9) and (10) indicates that the valence electron is shielded from the external electric field to an appreciable extent by core electrons.

From (10) and (3) we obtain

$$\mathrm{Im}\,\mathscr{E}_P = (-1.88 \pm 0.36) \times 10^{-8} \mu_0 = (1.67 \pm 0.32) \times 10^{-10} Q_W \mu_0, \quad (11)$$

where $Q_W = Z(1 - 4\sin^2\theta_W) - N = -112.7$ is the weak charge for $^{205}$Tl in the standard SU(2) $\otimes$ U(1) electroweak model. Here $\theta_W$ is Weinberg's angle[11] and $\sin^2\theta_W = 0.215$, while $Z = 81$ and $N = 124$ are proton and neutron numbers, respectively. Result (11) may be compared to various theoretical estimates of $\mathscr{E}_P$ given in Ref. 7 (see Table I). See also the work of Das *et al.*[12] Because of the large discrepancy between (9) and (10) it is evident that substantial theoretical work remains to be done on many-body effects in the 293-nm transition amplitude. We understand that considerable efforts are currently being directed at this problem.[13-15]

Finally, $M$ was originally measured[1] by interference with the Stark $E1$ amplitudes $\alpha$, $\beta$, and its value calculated from the naive theoretical estimates of the latter quantities. Now that $\alpha$, $\beta$ are known experimentally we may revise the value of $M$:

$$M = -(1.35 \pm 0.13) \times 10^{-5} \mu_0. \quad (12)$$

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