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OBSERVATION OF THE $6\,^2P_{1/2}-7\,^2P_{1/2}$ M1 TRANSITION IN ATOMIC THALLIUM VAPOR*

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The $6\,^2P_{1/2}-7\,^2P_{1/2}$ (292.7 nm) M1 transition in Tl is observed and its matrix element $m = \langle 7\,^2P_{1/2}|\mu_z|6\,^2P_{1/2}\rangle$ is measured. Tl vapor is illuminated by a pulsed linearly polarized laser beam (λ = 292.7 nm). Interference between m and the Stark-induced $6\,^2P_{1/2}-7\,^2P_{1/2}$ E1 amplitude in finite electric field E results in circular polarization of 535 nm fluorescence proportional to m/E, which is detected. The result is $m = -(2.11 \pm 0.30) \times 10^{-5}\,|eh/2m_ec|$, in agreement with theory. The ultimate goal of this research is to detect parity violation in the neutral weak interaction by observation of a helicity dependence in the $6\,^2P_{1/2}-7\,^2P_{1/2}$ absorption when the laser light is circularly polarized.

We report observations of the M1 transition $6\,^2P_{1/2}-7\,^2P_{1/2}$ (292.7 nm) in atomic Tl vapor, carried out with a technique suggested by Bouchiat and Bouchiat [1–3]. Our result and that for the $6\,^2S_{1/2}-7\,^2S_{1/2}$ transition in cesium [4–6] are of interest because parity violation in neutral weak currents might imply the existence of observable circular dichroism in these and other forbidden M1 transitions [3]. The 292.7 nm transition in Tl is particularly interesting because the expected circular dichroism is almost one order of magnitude larger than that associated with the $6\,^2S_{1/2}-7\,^2S_{1/2}$ cesium transition. The measurement described here is a preliminary step toward detection of this effect.

In our experiment (see fig. 1) a flash-lamp-pumped dye laser tuned with 2 etalons produces 0.5 μs, 585.4 nm light pulses, rep. rate ~12/s (variable). These are fed into a temperature-controlled ADA doubling crystal which yields 292.7 nm pulses of bandwidth ~2 GHz, typical power 0.1 m joule/pulse, and linear polarization $\hat{\epsilon} = \hat{y}$ (see fig. 1 for coordinate system). If desired, $\hat{\epsilon} = \hat{z}$ can be produced with a half-wave plate; both linear polarizations are used in the measurements described. The laser beam passes through the observation cell along the x axis and is detected with a photodiode (RCA 935) checked for linearity.

The cell is a fused silica (Suprasil) cylinder 60 mm long by 18 mm o.d. containing a pair of plane-parallel

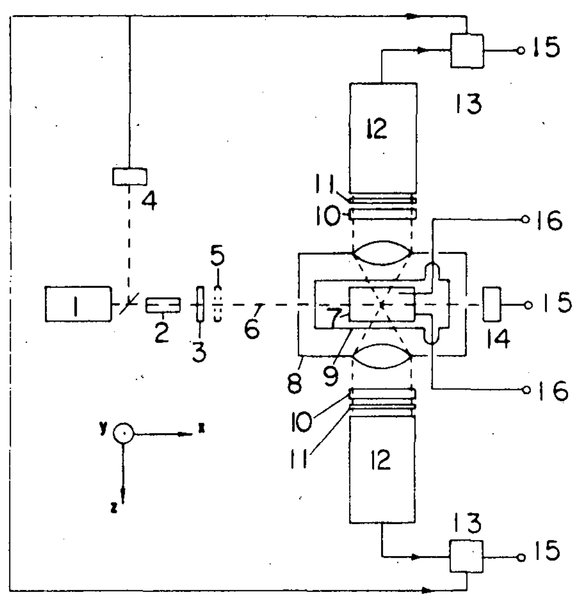

Fig. 1. Schematic diagram of apparatus: 1, pulsed dye laser; 2, doubling crystal; 3, visible blocking filter; 4, gating photodiode; 5, half-wave plate; 6, 292.7 nm laser beam; 7, electrodes, E into or out of page; 8, oven; 9, cell; 10, 535 nm interference filters; 11, circular pol. analyzers; 12, 8850 PMT's; 13, linear gates; 14, laser beam detector (photodiode); 15, to amplifiers, ADC, scalers; 16, automatic voltage polarity switch.

tantalum electrodes (separation 6 mm) for generating a uniform field E along y. The cell is connected to a vacuum system through remotely actuated quartz valves and is enclosed in a resistance-heated stainless

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steel oven. Approximately 30 mg of 99.9999% pure Tl metal (natural abundance) is contained in a separately heated cell side-arm. Most of the data were taken at an oven temperature T_1 = 950 K and a side-arm temperature T_2 = 880 K, corresponding to Tl vapor density [7] of $1.5-2 \times 10^{14}$ cm^{-3}. The cell-oven unit is enclosed in a vacuum tank (press. ~30 torr) to minimize oven corrosion and diffusion of atmospheric gas through cell walls at high operating temperatures.

The detection system consists of 25 mm dia. f – 1 quartz lenses mounted in the oven, 535 nm interference filters (2 nm FWHM, 60% peak transmission), Polaroid left-circular polarization analysers (CPA's) and RCA 8850 photomultipliers placed along $\pm z$. Photomultiplier and photodiode outputs are amplified, processed by an analog-to-digital converter and scalers and recorded on tape. We chose to observe 535 nm radiation ($7\,^2S_{1/2} \to 6\,^2P_{3/2}$) because, although the spontaneous emission rates for the 535 nm and 377.6 nm ($7\,^2S_{1/2} \to 6\,^2P_{1/2}$) transitions are comparable [8] for an isolated Tl atom, 377.6 nm photons are resonantly trapped, depolarized, and converted to 535 nm photons at the high Tl densities required. Our observations of 377.6 nm trapping as a function of temperature are in agreement with theoretical estimates [9, 10].

In field $\boldsymbol{E} = \pm E\hat{j}$, atomic Tl $6\,^2P_{1/2}$, $7\,^2P_{1/2}$ states are mixed with $n\,^2S_{1/2}$, $n\,^2D_{3/2}$ states by the Stark effect, and stimulated E1 absorptions $6\,^2P_{1/2} \to 7\,^2P_{1/2}$ can occur with amplitudes proportional to E. Let the Hamiltonian describing the interaction of atom and incoming radiation be written $H' = +|e|\,\hat{\boldsymbol{\epsilon}}\cdot\boldsymbol{r} + [\hat{\boldsymbol{x}} \times \boldsymbol{\mu}]\cdot\hat{\boldsymbol{\epsilon}}$ where $\hat{\boldsymbol{\epsilon}}$ is a polarization unit vector and $\boldsymbol{\mu}$ is the magnetic moment operator. For $\hat{\boldsymbol{\epsilon}} \parallel \boldsymbol{E}$, E1 hfs transitions $F = 0 \to F' = 0$ and $F = 1 \to F' = 1$ ($\Delta m_F = 0$) are observable, while for $\hat{\boldsymbol{\epsilon}} \perp \boldsymbol{E}$, E1 transitions $F = 0 \to F' = 1$, $F = 1 \to F' = 1, 0$ ($\Delta m_F = \pm 1$) can be seen [11]. Interference between the M1 amplitude $m = \langle 7\,^2P_{1/2}|\mu_z|6\,^2P_{1/2}\rangle$ (or the corresponding $\Delta m_F = \pm 1$ amplitudes) and the E1 amplitude results in a z component of polarization of the $7\,^2P_{1/2}$ state for $F' = 1$ and consequent circular polarization of 535 nm fluorescence. The latter changes sign when $\boldsymbol{E}$ is reversed.

The expected intensities

$$I = \sum_{m_F, m_F'} |\langle 7P, F'm_F'|H'|6P, Fm_F\rangle|^2$$

and 7P polarizations

$$P = I^{-1} \sum_{m_F, m_F'} m_F' |\langle 7P, F'm_F'|H'|6P, Fm_F\rangle|^2$$

are given in tables 1 and 2 in terms of second order Stark matrix elements α and β for laser polarizations $\parallel$ and $\perp$, respectively, to the static field E. The latter are calculated from Dirac wave-functions for Tl generated numerically from a modified Tietz potential. These wave-functions have been used to calculate bound state energies, oscillator strengths and hfs splittings for comparison with experimental values. The good agreement implies an accuracy of 10% in the following calculated values in atomic units, E in volts/cm:

$$\alpha = 7.49 \times 10^{-8} E, \tag{1}$$

$$\beta = 6.00 \times 10^{-8} E, \tag{2}$$

$$(\beta/\alpha)_{\text{theory}} = 0.80. \tag{3}$$

Observations of intensities of the various hfs components were made without CPA's. The results are shown in fig. 2 and summarized in column 5 of table 1. In each case $I \propto E^2$ since for the large E fields used, m^2 is negligible. The intensity ratios of observed $\parallel$ and $\perp$ components yield $(\beta/\alpha)_{\text{exp't}} = 0.84$ in reasonable agreement with (3).

Unfortunately there exists a non-resonant background fluorescence which varies approximately as the square of the density and is about as large as the resonant $F = 1 \to F' = 1$ Stark signal at $E = 30$ V/cm at normal operating conditions. It varies linearly with laser power, and is thought to arise from transitions $h\nu$ + Tl (6P) + Tl (6P) → Tl (6P) + Tl (7P).

Circular polarization measurements to determine m were carried out at various values of E. Data were taken on- and off-resonance for + and – values of E with $\pm z$ detector channels. E was reversed after each laser pulse. We define

$$n(\pm E) = N_{+z}^{\text{on res}}(\pm E) - N_{+z}^{\text{off res}}(\pm E),$$

and

$$n'(\pm E) = N_{-z}^{\text{on res}}(\pm E) - N_{-z}^{\text{off res}}(\pm E)$$

for the total number of counts in a given run for $\pm z$ counters, respectively. An experimental asymmetry is defined by:

$$\Delta = \frac{1}{2}\left\{\frac{n'(+E) - n(+E)}{n'(+E) + n(+E)} - \frac{n'(-E) - n(-E)}{n'(-E) + n(-E)}\right\}. \tag{4}$$

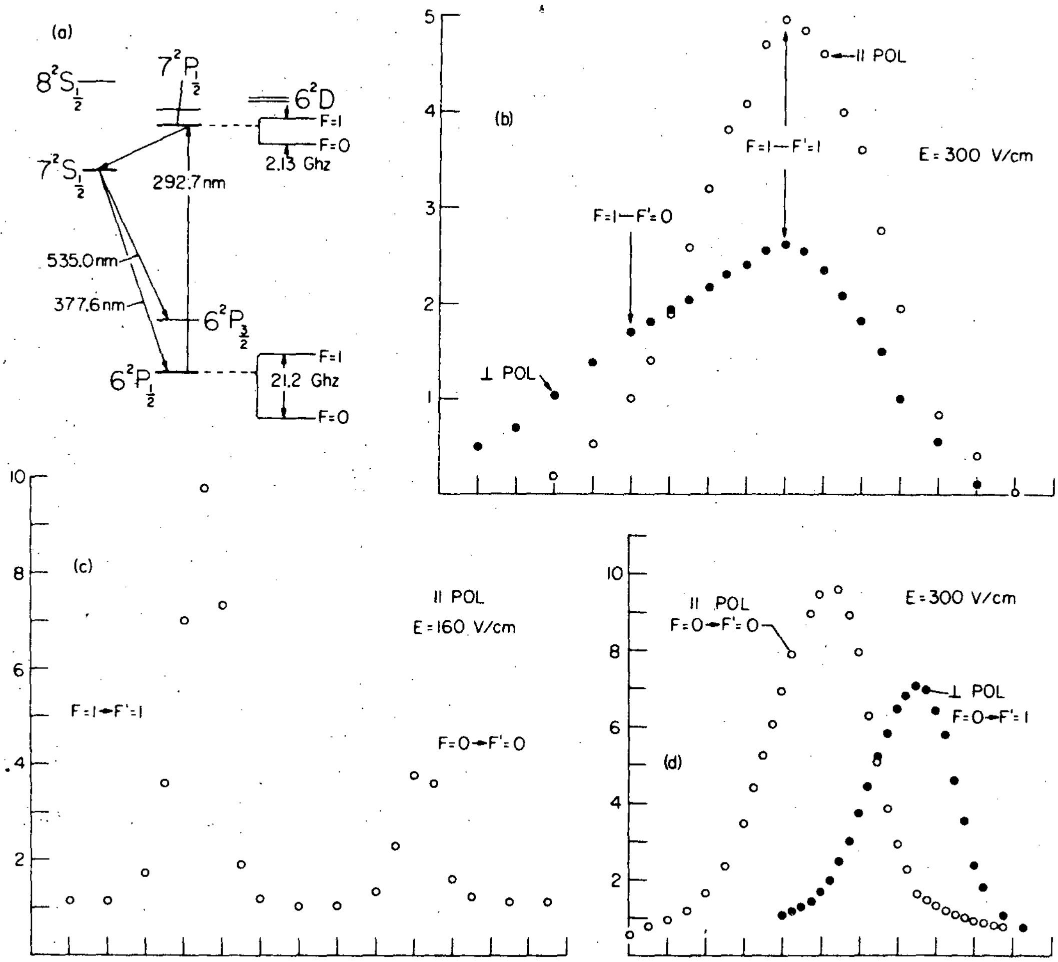

Fig. 2(a). Relevant energy levels of Tl, not to scale. (b), (c), (d): Experimental resonance curves for Stark-induced $6\,^2P_{1/2} - 7\,^2P_{1/2}$ E1 transitions. Open circles: Parallel polarization ($\hat{\epsilon} \parallel E$); Full circles: Perpendicular polarization ($\hat{\epsilon} \perp E$). Abscissas are etalon dial settings, linear scale; ordinates are signals, arbitrary units. Data of 2(b) taken with single etalon ($\Delta\nu_{laser} \approx 5$ GHz).

Table 1
Intensities of hyperfine components

$\hat{\epsilon}$	Transition	Theor. intensity I	Theor. rel. intensity for large E $(\beta/\alpha)_{theory} = 0.80$	Observed rel. intensity (see fig. 2)
$\hat{\epsilon} \parallel E$	$1 \to 1$	$3\alpha^2 + 2m^2$	3	3
	$0 \to 0$	α^2	1	1
$\hat{\epsilon} \perp \hat{E}$	$1 \to 1$ $1 \to 0$	$2\beta^2 + 2m^2$ $\beta^2 + m^2$	Only partially resolved: 1.92	2.1
	$0 \to 1$	$\beta^2 + m^2$	0.64	0.70

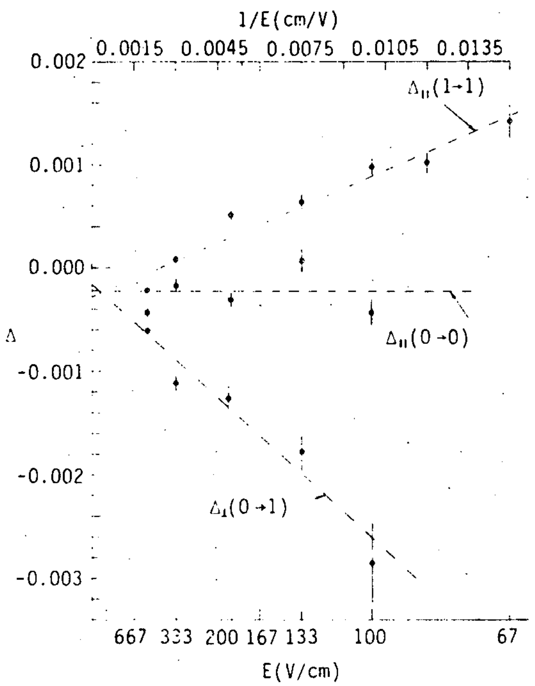

Fig. 3. Circular polarization asymmetries Δ resulting from interference of M1 and static-E-field-induced Stark amplitudes for laser polarization parallel to E: ($F = 1 - F' = 1$, $F = 0 - F' = 0$) and for laser polarization perpendicular to E: ($F = 0 - F' = 1$). The dashed lines are least squares fits to data points. The error bars represent probable errors in the means.

The results are shown in fig. 3 where Δ is plotted versus E^{-1} for $1 \to 1$, $0 \to 0$, and $0 \to 1$ transitions. Each data point corresponds to $\sim 4 \times 10^4$ laser pulses and between 10^7 and 3×10^8 photo-electrons. As expected, each Δ varies linearly with E^{-1}. Also, the observed ratio $\Delta_{\parallel}(1 \to 1)/\Delta_{\perp}(0 \to 1)$ is in agreement with the predicted values of table 2 based on $\beta/\alpha = 0.84$ and a hfs interaction correction of 15%.

All of the data of fig. 3 were taken at $T_1 = 950$ K, $T_2 = 880$ K. We also investigated the temperature dependence of $\Delta_{\parallel}(1 \to 1)$ and $\Delta_{\parallel}(0 \to 0)$ over an order-of-magnitude range in Tl density. The results are consistent with those of fig. 3 except that as expected we observe some depolarization of 535 nm radiation due to resonance trapping at the highest temperatures. The asymmetries Δ all vanish when data are taken without CPA's. The small residual negative values of all three Δ's appears to be an experimental artifact and is not fully understood.

Amplitude m is obtained from the slope of $\Delta(1 \to 1)$ or $\Delta(0 \to 1)$ versus E^{-1} in fig. 3 and α or β after correction for dilution of polarization by cascading ($7\,^2P_{1/2} \to 7\,^2S_{1/2} \to 6\,^2P_{3/2}$); trapping, depolarization, and conversion of 377.6 nm photons; and finite solid angle effects. We obtain

$$m = \langle 7\,^2P_{1/2} | \mu_z | 6\,^2P_{1/2} \rangle = -(2.11 \pm 0.30) \times 10^{-5} |e\hbar/2m_e c| . \qquad (5)$$

Table 2
Polarizations and asymmetries

$\hat{\epsilon}$	Transition	Theor. polarization $P(7\,^2P_{1/2})$	Theor. polarization for large E, $(\beta/\alpha)_{expt} = 0.84$	Observed asymmetry (see fig. 3)
$\hat{\epsilon} \parallel E$	$1 \to 1$	$\frac{4m\alpha}{3\alpha^2 + 2m^2}$	$\frac{4}{3}\frac{m}{\alpha} = P_{\parallel}$	$\Delta_{\parallel}(1 \to 1)$
	$0 \to 0$	0	0	0
$\hat{\epsilon} \perp E$	$1 \to 1$	$-\frac{m\beta}{\beta^2 + m^2}$	Only partially resolved	–
	$1 \to 0$	0		
	$0 \to 1$	$-\frac{2m'\beta}{\beta^2 + m'^2}$	$-\frac{2m'}{\beta} = -2.07\,P_{\parallel}$	$\Delta_{\perp}(0 \to 1) = -2.1\,\Delta_{\parallel}(1 \to 1)$
		$m' = 1.15\,m$ due to hfs interaction correction		

The uncertainty in (5) arises from approximately equal uncertainties in theory (Stark effect) and in the slopes of fig. 3. Eq. (5) is to be compared with the theoretical result, obtained by Neuffer, of $m = -1.96 \times 10^{-5} |eh/2m_e c|$. The latter contains a relativistic contribution of $-1.76 \times 10^{-5} |eh/2m_e c|$, the remainder being due to interconfiguration interaction. Result (5) can be expressed as an A-coefficient:

$$A(7\,^2P_{1/2} \to 6\,^2P_{1/2}) = 1.4 \times 10^{-6}\ s^{-1}, \qquad (6)$$

or an oscillator strength:

$$f(6\,^2P_{1/2} \to 7\,^2P_{1/2}) = 1.8 \times 10^{-15}. \qquad (7)$$

If parity is violated in neutral weak currents, circular dichroism δ is expected in the $6\,^2P_{1/2} \to 7\,^2P_{1/2}$ transition. A calculation [12] based on the Weinberg model assuming $\sin \theta_\omega = \frac{1}{2}$ yields $\delta \sim 3 \times 10^{-3}$. Improvements in apparatus now underway should permit us to measure δ.

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[11] $I(^{203}Tl) = I(^{205}Tl) = \frac{1}{2}$; $\Delta\nu(6\,^2P_{1/2}, ^{203}Tl) = 21.1$ GHz; $\Delta\nu(6\,^2P_{1/2}, ^{205}Tl) = 21.3$ GHz; $\Delta\nu(7\,^2P_{1/2}, Tl) = 2.13$ GHz: A Flusberg, T. Mossberg and S.R. Hartmann, to be published.
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