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New Observation of Parity Nonconservation  
in Atomic Thallium

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Abstract

Refined observations of parity nonconservation in the  $6^2P_{1/2} - 7^2P_{1/2}$  transition in  $_{81}\text{Tl}^{203,205}$  are reported. Absorption of circularly polarized 293 nm photons by  $6^2P_{1/2}$  atoms in an E field results in polarization of the  $7^2P_{1/2}$  state, through interference of the Stark E1 amplitude with M1 and parity-nonconserving E1 amplitudes  $M$  and  $\mathcal{E}_p$ . Detection of this polarization yields the circular dichroism  $\delta = +(2.9 \pm \begin{smallmatrix} 1.0 \\ 0.9 \end{smallmatrix}) \times 10^{-3}$ , which agrees with theoretical estimates based on the Weinberg-Salam model, for  $\sin^2 \theta_W = 0.23$ . The present experiment is an improved version of an earlier one in which the result  $\delta = +(5.2 \pm 2.4) \times 10^{-3}$  was obtained.

We report new observations of parity nonconservation (PNC) in the  $6^2P_{1/2} - 7^2P_{1/2}$  transition in atomic thallium, (see Fig. 1). The transition amplitude is forbidden M1 with measured amplitude  $M = (-2.1 \pm 0.3) \times 10^{-5} \left| \frac{e\hbar}{2m_e c} \right|^1$ . Parity nonconservation causes the  $6^2P_{1/2}$  and  $7^2P_{1/2}$  states to be admixed with  $2S_{1/2}$  states; thus the transition amplitude contains an additional E1 component  $\mathcal{E}_p$ . This results in circular dichroism, defined by:

$$\delta = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{2\text{Im}(\mathcal{E}_p M^*)}{|M|^2 + |\mathcal{E}_p|^2} \approx \frac{2\text{Im}\mathcal{E}_p}{M} \quad (1)$$

where  $\sigma_{\pm}$  are the cross-sections for absorption of 293 nm photons, with  $\pm$  helicity, respectively. Theoretical estimates of  $\mathcal{E}_p$  based on the Weinberg-Salam (W-S) model<sup>2</sup> yield<sup>3,4,5</sup>

$$\begin{aligned} \delta_{\text{theo}} &= \frac{2\text{Im}(\mathcal{E}_{p,\text{theo}})}{M_{\text{expt}}} \\ &= (2.1 \pm 0.7) \times 10^{-3} \end{aligned} \quad (2)$$

for  $\sin^2 \theta_W = 0.23$ , where  $\theta_W$  is the Weinberg angle.

The aim of this experiment is to measure  $\delta$ . The dipole amplitudes  $\mathcal{E}_p$  and  $M$  are observed by their interference with a Stark E1 amplitude  $\beta E$  caused by a 215 V/cm electric field  $E$ , in the  $6P_{1/2, F=0} - 7^2P_{1/2, F=1}$  transition. This causes a polarization  $\Delta = -\frac{2M}{\beta E} (1 \pm \frac{\delta}{2})$  in the  $7^2P_{1/2, F=1}$  state. The latter is analyzed by selective excitation of  $m_F = +1$  or  $-1$  substates to the  $8^2S_{1/2}$  state with circularly polarized 2.18 $\mu$  light, followed by observation of  $8^2S_{1/2} - 6^2P_{3/2}$  fluorescence at 323 nm. (See Fig. 1.) In a preliminary version of the experiment<sup>6</sup> we obtained the result  $\delta = +(5.2 \pm 2.4) \times 10^{-3}$ . Although the basic method has remained unchanged,

numerous improvements in the apparatus have been made and we have also carried out a thorough investigation of possible sources of systematic error.

Apparatus improvements include use of a new thallium cell with better geometry, yielding higher signal and lower background; better detection efficiency; better laser stability and higher laser output power; use of a Pockels cell instead of a rotating quarter-wave plate to produce circularly polarized 293 nm light; automatic laser frequency control for 293 nm light; use of a faster on-line computer with a more sophisticated interface and running program; use of a mirror to reflect the 293 nm beam back through the main cell, which does not affect the genuine parity asymmetry but reduces the M1 asymmetry; and other miscellaneous improvements.

The main sources of possible systematic error (false parity asymmetry) are a) Imperfect UV circular polarization, and b) Stray electric fields in the interaction regions which do not reverse exactly in proportion to the main component of electric field employed for the Stark effect.<sup>7</sup> By means of a combination of auxiliary experiments carried out during each parity experimental run, we have measured precisely the contribution of these effects to the parity asymmetry, and have corrected for them with very small uncertainty. The auxiliary experiments involve asymmetry measurements with linearly polarized 293 nm light, and with circularly polarized 293 nm light and a magnetic field of  $\pm 5$  gauss along the 293 nm beam direction, each with and without the mirror. These will be described in detail in a forthcoming publication.

The data on which our present result is based were taken in 11 separate runs (~400 hours total). Approximately  $8.7 \times 10^6$  laser pulses were devoted to the  $6^2P_{1/2}, F = 0 - 7^2P_{1/2}, F = 1$  (0-1) transition with the mirror, and  $5.2 \times 10^6$  pulses to the 0-1 transition without the mirror. These were interspersed in groups of 2048 and 1024 pulses respectively. An additional  $6 \times 10^6$  pulses were devoted to background and systematic measurements. Observations of the M1 and parity asymmetries were carried out simultaneously. Data were also obtained for the 0-0 transition, which should not and does not display parity violation.

The results are summarized in Table 1. Column 2 gives the average M1 asymmetry observed for each run. It fluctuates because of variable dilutions from background, variable small admixtures of 0-0 signal, and imperfections in  $2.18\mu$  polarization. Since these dilutions affect the parity and M-1 polarizations equally, we arbitrarily normalize the parity asymmetries  $\Delta_p$  to an M1 asymmetry  $\Delta_M$  for no mirror of  $9.0 \times 10^{-3}$  (column 3). The uncertainties for  $\Delta_p$  are in each case compounded from the statistical uncertainties in the data and in the systematic corrections. The weighted averages of the normalized parity asymmetries with and without the mirror are:

$$\text{Mirror} \quad \Delta_{p,1} = (1.46 \pm 0.45 \pm 0.11) \times 10^{-5} \quad (3)$$

$$\text{No mirror} \quad \Delta_{p,2} = (1.58 \pm 0.58 \pm .06) \times 10^{-5} \quad (4)$$

The first uncertainty in equations (3) and (4) is statistical, the second is a non-statistical uncertainty in the corrections. Results (3) and (4) are consistent and their weighted average is:

$$\Delta_p(0-1) = (1.51 \pm 0.36 \pm 0.09) \times 10^{-5} \quad (5)$$

To obtain  $\delta = 2\text{Im } \mathcal{E}_p / M$  we take the ratio  $2 \Delta_p(0-1) / \Delta_{M'}$ , where  $\Delta_{M'} = K \times 9.0 \times 10^{-3}$ . The factor K corrects for reflections from the rear of the main cell, which reduces  $\Delta_M$  but not  $\Delta_p$ . We estimate  $K = 1.17$ , but it might be somewhat less which leads to skewness in the systematic uncertainty of our final result. The latter is:

$$\delta = +(2.9 \pm 0.7 \pm \frac{0.3}{0.2}) \times 10^{-3} \quad (6)$$

which is consistent with  $\delta_{\text{theo}}$  (see equation 2). Our result may be expressed in terms of the weak charge  $Q_W$ , defined in the Weinberg-Salam model as

$$Q_W = Z(1 - 4 \sin^2 \theta) - N = -123.$$

for  $\sin^2 \theta_W = 0.23$ . We find:

$$Q_{W,\text{expt}} = -155 \pm 68. \quad (7)$$

The quantity  $\delta_{\text{theo}}$  may be modified slightly by changes in the Stark amplitude. We write:

$$\delta_{\text{theo}} = \frac{2\text{Im}(\mathcal{E}_p)_{\text{theo}}}{M_{\text{expt}}} = - \frac{4I_m(\mathcal{E}_p)_{\text{theo}}}{\Delta_M^0 \beta E} \quad (8)$$

where  $E$  is the electric field,  $\Delta_M^0$  is the MI asymmetry corrected for background, imperfect polarization, and imperfect analyzing power, and  $\beta$ , the Stark amplitude for the 0-1 transition, takes the form:

$$\beta = \frac{e^2}{9} \sum_{\text{ns}} R_{7p,\text{ns}} R_{6p,\text{ns}} \left( \frac{1}{E_6 - E_{\text{ns}}} - \frac{1}{E_7 - E_{\text{ns}}} \right) + \frac{e^2}{9} \sum_{\text{nD}_{3/2}} R_{7p,\text{nD}} R_{6p,\text{nD}} \left( \frac{1}{E_7 - E_{\text{nD}}} - \frac{1}{E_6 - E_{\text{nD}}} \right) \quad (9)$$

Here  $E_6 = E(6^2P_{1/2})$ ,  $E_7 = E(7^2P_{1/2})$ , etc. and

$R_{7p,\text{ns}} = \langle 7^2P_{1/2} | r | n^2S_{1/2} \rangle$ , etc. The quantity  $\beta$  is strongly dominated by

$R_{7p_{1/2}, 6D_{3/2}}$  and  $R_{7p_{1/2}, 7s_{1/2}}$  and is rather insensitive to the precise



values of other radial integrals. In ref. 3,  $R_{7p_{1/2}, 6D_{3/2}}$ ,  $R_{7p_{1/2}, 7s_{1/2}}$  were computed from atomic wave-functions generated from solutions to the Dirac equation for a single valence electron in a modified Tietz potential. However, we have since determined by experiment that  $A(7^2P_{1/2} - 7^2S_{1/2}) = (2.15 \pm 0.1) \times 10^7 \text{ s}^{-1}$ , which implies that  $|R_{7p_{1/2}, 7s_{1/2}}|$  is about 15% larger than the value given in ref. 3. Also, other calculations which include atomic core polarization<sup>8</sup> suggest that a similar increase is appropriate for  $R_{6D_{3/2}, 7p_{1/2}}$ . The result of these changes is a decrease in  $\beta$  of approximately 25%. However, since the major contribution to  $\mathcal{E}_p$  comes from  $R_{6p_{1/2}, 7s_{1/2}}$ , the changes in  $R_{7p_{1/2}, 7s_{1/2}}$  and  $R_{6D_{3/2}, 7p_{1/2}}$  do not have much effect on  $\mathcal{E}_p$ . The net result, from equation (8), is an increase of  $\delta_{\text{theo}}$  to about  $2.6 \times 10^{-3}$  for  $\sin^2 \theta_W = 0.23$ . We intend to measure  $A(6^2D_{3/2} - 7^2P_{1/2})$  in the near future.

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TABLE I.

RUN	Observed M1 Asymmetry $\Delta_M$ (NO MIRROR)	Corrected Parity Asymmetries Normalized to $\Delta_M = 9.0 \times 10^{-3}$	
		$\Delta_{P_1}$ (MIRROR)	$\Delta_{P_2}$ NO MIRROR
1	$6.40 \times 10^{-3}$	$0.92 \pm 2.01 \times 10^{-5}$	$-0.25 \pm 3.29 \times 10^{-5}$
2	$7.26 \times 10^{-3}$	$2.69 \pm 2.03 \times 10^{-5}$	$0.22 \pm 2.57 \times 10^{-5}$
3	$6.94 \times 10^{-3}$	$-0.65 \pm 2.87 \times 10^{-5}$	$6.14 \pm 4.84 \times 10^{-5}$
4	$7.04 \times 10^{-3}$	$-0.17 \pm 1.55 \times 10^{-5}$	$4.49 \pm 2.39 \times 10^{-5}$
5	$6.90 \times 10^{-3}$	$3.48 \pm 1.90 \times 10^{-5}$	$1.20 \pm 3.39 \times 10^{-5}$
6	$7.54 \times 10^{-3}$	$-1.64 \pm 2.06 \times 10^{-5}$	$-3.49 \pm 4.03 \times 10^{-5}$
7	$7.15 \times 10^{-3}$	$0.94 \pm 1.13 \times 10^{-5}$	$0.78 \pm 2.04 \times 10^{-5}$
8	$7.24 \times 10^{-3}$	$2.11 \pm 0.86 \times 10^{-5}$	$2.37 \pm 1.14 \times 10^{-5}$
9	$6.31 \times 10^{-3}$	$-0.32 \pm 2.35 \times 10^{-5}$	$-0.90 \pm 3.62 \times 10^{-5}$
10	$6.73 \times 10^{-3}$	$2.52 \pm 2.18 \times 10^{-5}$	$-1.58 \pm 2.92 \times 10^{-5}$
11	$6.81 \times 10^{-3}$	$3.70 \pm 1.48 \times 10^{-5}$	$2.27 \pm 2.02 \times 10^{-5}$

WEIGHTED AVERAGES: \*  $1.46 \pm 0.45 \times 10^{-5}$        $1.58 \pm 0.58 \times 10^{-5}$

\* Averages computed from binning of above data into 450 separate groups. Prior to correction of parity data for stray electric field and polarization effects,  $\Delta_{P_1} = +0.93 \times 10^{-5}$ ,  $\Delta_{P_2} = +1.18 \times 10^{-5}$ .

Figure Caption

- FIG. 1. (a) Low-lying energy levels of Tl (not to scale).  
(b) Coordinate system, orientation of photon beams, and electric field direction.  
(c) Schematic diagram indicating production and analysis of  $7^2P_{1/2}$  polarization in the 0-1 transition. The transition amplitudes to the  $m_F = \pm 1$  levels of  $7^2P_{1/2}$  are indicated. The polarization is analyzed by circularly polarized 2.18- $\mu\text{m}$  radiation ( $7^2P_{1/2} - 8^2S_{1/2}$  transition). The  $8^2S_{1/2}$  hfs is not resolved.

