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Publication Date
1978-11-01

Submitted to Physical Review Letters

LBL-8389
Preprint

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November 1978

Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

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Preliminary Observation of Parity Nonconservation in Atomic Thallium

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Abstract

Parity nonconservation is observed in the $6^2P_{1/2} - 7^2P_{1/2}$ transition in thallium. 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 Stark E1 amplitudes with M1 and parity-nonconserving E1 amplitudes $\mathcal{M}$, $\mathcal{E}_p$. Detection of this polarization yields the circular dichroism $\delta = +(5.2 \pm 2.4) \cdot 10^{-3}$, which agrees in sign and magnitude with theoretical estimates based on the Weinberg-Salam model.

1. Introduction

We report preliminary observations of parity nonconservation (PNC) in the $6^2P_{1/2} - 7^2P_{1/2}$ transition (292.7 nm) in atomic thallium (see Fig. 1). The transition is forbidden M1 with measured amplitude $M = (-2.1 \pm 0.3) \cdot 10^{-5} \left|\frac{e\hbar}{2m_e c}\right|$.[1] If parity is not conserved the $6^2P_{1/2}$ and $7^2P_{1/2}$ states are admixed with $^2S_{1/2}$ states. The transition amplitude then contains an additional E1 component E_p, and circular dichroism exists, defined by:

$$\delta = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{2\mathrm{Im}(E_p M^*)}{|M|^2 + |E_p|^2} \cong \frac{2\mathrm{Im}(E_p)}{M} \tag{1}$$

where $\sigma_\pm$ are the cross sections for absorption of 293 nm photons (UV) with ± helicity respectively. Theoretical estimates of δ based on the Weinberg-Salam (W-S) model[2] yield:[3,4]

$$\delta_{theo} = \frac{2\mathrm{Im}(E_{p,theo})}{M_{expt}} = (+2.3 \pm 0.9) \cdot 10^{-3} \tag{2}$$

for $\sin^2\theta_W = 0.25$, where θ_W is the Weinberg angle. The uncertainty in δ_{theo} arises from the uncertainties in M_{expt} (~ 15%), and $E_{p,theo}$ (~25%). The aim of this experiment is to measure δ.

Investigations of this type were first suggested by Bouchiat and Bouchiat,[5] and an experiment on Cs is being carried out by their group at Paris.[6] Also, optical rotation experiments on bismuth have been reported (but with contradictory results),[7,8,9] while PNC in high energy electron scattering, consistent with W-S model, has been observed at SLAC.[10]

2. Experimental Method

The simplest way to measure δ would be to illuminate $T\ell$ vapor in a field-free region with circularly polarized 293 nm light and observe the helicity dependence of the decay fluorescence (e.g. at 535 nm, see Fig. 1). Unfortunately this is impractical because of background effects. Instead, using a technique first suggested by Bouchiat and Bouchiat,[5] we apply an external field $\underset{\sim}{E}$ which Stark-mixes $^2P_{1/2}$ states with $^2S_{1/2}$ and $^2D_{3/2}$ states. The transition intensity, proportional to E^2, is thereby increased above the background; moreover interference between the Stark transition amplitudes and $\mathcal{M}, \mathcal{E}_p$ polarizes the $7^2P_{1/2}$ state, permitting measurement of $\mathcal{M}$ and δ.

Let the 293 nm photon beam be along x, and choose $\underset{\sim}{E} = E\hat{y}$, (see Fig. 1b). Ignoring terms of order $[\mathcal{M} \mp \mathcal{E}_p]^2$, the $7^2P_{1/2}$ polarization along z is:

$$P_z(F=1 \rightarrow F=1) \cong \frac{4\alpha - 2\beta}{3\alpha^2 + 2\beta^2} [\mathcal{M} \mp \mathcal{E}_p] \quad (3)$$

$$P_z(F=0 \rightarrow F=1) \cong \frac{-2}{\beta} [\mathcal{M} \mp \mathcal{E}_p] \quad (4)$$

$$P_z(F=0 \rightarrow F=0) = 0 \quad (5)$$

for each indicated hfs component of the transition. Here $\mp$ refer to $\pm$293nm photon helicities, and α, β are Stark amplitudes defined in refs. 1,3. Calculations yield $\alpha = +7.4 \cdot 10^{-8} E$, $\beta = 6.0 \cdot 10^{-8} E$ with uncertainties ~15% (atomic units, but E in V/cm). This gives $\alpha/\beta = 1.23$ in agreement with observations.[1]

In earlier measurements we detected P by observing the circular polarization P_c of 535 nm($7^2S_{1/2} \rightarrow 6^2P_{3/2}$) fluorescence.[1] However P_c is very small: $P_c \cong 0.08P$, because of cascade depolarization and resonance trapping. In the present experiment we detect P by pumping the $7^2P_{1/2}$ atoms to the $8^2S_{1/2}$ state with 2.18μ(IR) circularly polarized photons directed along z, and we observe the intensity of 323 nm($8^2S_{1/2} \rightarrow 6^2P_{3/2}$) fluorescence. Let I_+, I_- be the intensities for IR photons with $J_z = \pm 1$. Then we observe the asymmetry:

$$\Delta_o = \frac{I_- - I_+}{I_- + I_+} = 0.7P \qquad (6)$$

The dilution factor 0.7 is determined from measurements of M made during the PNC experiment. It agrees with a calibration experiment in which the 2.18μ beam was directed along −x to analyze the large polarization along that axis which arises from interference between α and β amplitudes in the 1→1 transition:

$$P_x(1\rightarrow 1) = \mp \frac{4\alpha\beta}{3\alpha^2+2\beta^2} = \mp 0.75 \qquad (7)$$

for ± UV helicities respectively.

Figure 2 is a schematic diagram of the apparatus. L1 and L2 are synchronized flash lamp pumped tunable pulsed dye lasers (pulse width .5μs, rep rate 19/s, energy/pulse ~ 7 mj., wavelength 585.4 nm.).[11] Light from L1 passes through an ADA doubling crystal where 292.7 nm photons are produced. The linear polarization is precisely defined by a Glan-air prism (LP) and circular polarization is produced by a crystalline quartz quarter-wave plate (UV $\lambda/4$) which rotates as shown in Fig. 2 to provide pulse-to-pulse alternation of photon helicity. The quarter wave plate is anti-reflection coated, and great care is taken with its alignment to avoid possible systematic errors. Light from L2 drives a Chromatix CMX4/IR optical parametric oscillator for production of linearly polarized IR photons. These are circularly polarized with either of 2 quartz quarter-wave plates (IR $\lambda/4$) which are alternately inserted in the IR beam. Thallium vapor at $T \simeq 1050°K$, density $n \sim 9 \cdot 10^{14}$ cm^{-3} is contained in the main cell, (Suprasil fused quartz) which has plane tantalum electrodes, separation 1 cm, to generate E. There are 2 interaction regions(1,2) at which the IR photons (with opposite J_z) intersect the UV beam. The 323 nm fluorescence signals I_1, I_2 from regions 1,2 are detected separately. The quantity $(I_1-I_2)/(I_1+I_2)$ is almost independent of intensity fluctuations but is directly proportional to P.

In practice we confine ourselves to observation of the 0-1, 0-0 lines at 300 V/cm in all PNC data, because $P_z(0 \to 1)$ is relatively large (eq'n 4), $P_z(0 \to 0)$ should be 0, and neither line is as susceptible to possible systematic errors as the $1 \to 1$ line. The choice of 300 V/cm is dictated by background, the major component of which is fluorescence from scattered 293 nm light. Lower values of E would not give larger measured asymmetries because of background dilution.

After traversing the main cell, the UV beam passes through a second fixed quarter wave plate (A) which restores linear polarization $\hat{\varepsilon}$.

Since the UV helicity reverses with each pulse, $\hat{\epsilon}$ is alternately parallel to $\hat{y}$ and to $\hat{z}$. The linearly polarized UV passes into a second cell with Stark field $E' \parallel E$. When $\hat{\epsilon} \parallel \hat{y}$ ($\hat{z}$) only the 0-0 (0-1) line is observed. This provides an effective means for tuning L1 to either desired resonance ($\Delta\nu$ = 2.13 Ghz) in the main cell. In practice our resolution is sufficient to give less than 10% contamination of either (0-0, 0-1) line by the other.

3. Observational Procedure and PNC Data

The UV helicity alternates with each pulse, E is reversed after every second pulse, and the IR circular polarization changes sign after each set of 128 pulses. We define

$$\Delta_{1,2} = \frac{I_1 - I_2}{I_1 + I_2} \quad \text{(regions 1,2)}$$

$$\Delta' = 1/2[\Delta_{1,2}(E>0) - \Delta_{1,2}(E<0)] \quad \text{(E reversal)}$$

$$\Delta = 1/2[\Delta'(IR+) - \Delta'(IR-)] \quad \text{(IR CP reversal)}$$

The average of observed asymmetries for opposite UV helicities (Δ_m) yields M, while 1/2 of the difference (Δ_p) yields E_p. The 0-1 line is observed for 25600 pulses, then an equal amount of data are taken for the 0-0 line. The entire procedure is executed repeatedly for a run.

Table 1 summarizes our results. Roughly equal amounts of data were taken with the IR beam entering region 1 first ("IR 1" in Table 1) and entering region 2 first ("IR 2"). Also, approximately equal amounts were taken for the UV $\lambda/4$ assembly as shown in Fig. 2 ("UV+") and rotated 180° about an axis normal to the page ("UV−"). A detailed description of the experiment and data to be published separately shows that imperfect circular polarization resulting from dichroism, optical activity, or Fresnel reflections in UV $\lambda/4$ can give a false Δ_p arising from M, but this is approximately the same in magnitude and sign for $\Delta_p(0\text{-}0)$ and $\Delta_p(0\text{-}1)$, given our observation conditions. Thus we use $\Delta_D = \Delta_p\,(0\text{-}1) - \Delta_p\,(0\text{-}0)$ to determine δ. Detailed statistical analysis shows that fluctuations of $\Delta_D = \Delta_p\,(0\text{-}1) - \Delta_p(0\text{-}0)$ are smaller than individual fluctuations of $\Delta_p(0\text{-}1)$ or $\Delta_p(0\text{-}0)$. Evidently there exist systematic drifts of $\Delta_p(0\text{-}0)$ and $\Delta_p(0\text{-}1)$ which are positively correlated and have a time scale of hours, but these do not appear in Δ_D.

To obtain $\delta/2 = \frac{\operatorname{Im} E_P}{M}$ we take the ratio $\frac{\Delta_D}{\Delta_m}$, where $\Delta M' = 1.17\ \Delta M$ and the factor 1.17 corrects for an estimated 8% reflection from the rear window of the main cell, which should diminish Δ_m but not Δ_D. We thus find

$$\delta_{expt} = +(5.2 \pm 2.4) \cdot 10^{-3} \qquad (8)$$

This result is consistent in sign and magnitude with δ_{theo} (eq'n 2) given the uncertainty in the latter. From δ_{expt} and $E_{P,theo} = (1.93\ i) \cdot 10^{-10}\ Q_W \left|\frac{e\hbar}{2m_e c}\right|$,[3] where $Q_W = (1-4\sin^2\theta_W)Z-N$, we obtain $Q_W \cong -280 \pm 140$.

Experimental improvements now underway should permit a more precise determination of δ.

Acknowledgments

We thank Drs. M. Bouchiat, D. Neuffer, and M. Prior for helpful discussions, Miss P. Drell for much useful assistance, and Prof. D. Shirley for administrative support. We are much indebted to glassblower D. Anderberg and machinist G. Seiji for truly excellent workmanship. Three of us (R. Conti, P. Bucksbaum and S. Chu) were supported at various times during this research by National Science Foundation Fellowhips. This work was done under the auspices of the Chemical Sciences Division, Office of Basic Energy Sciences, Department of Energy.

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Table 1. Summary of PNC Data

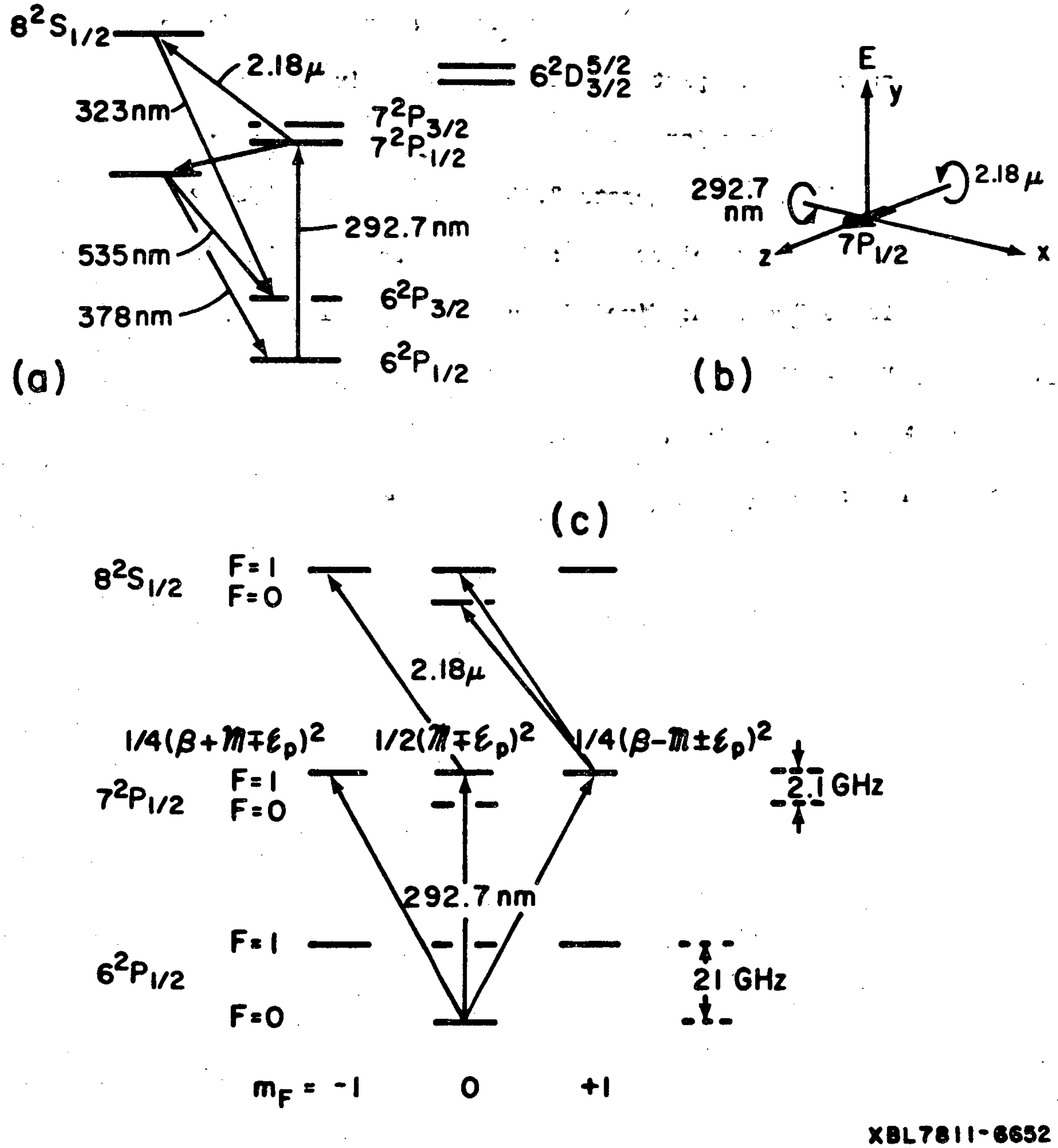
Condition	No. of Pulses	$\Delta_m^{(a)}$ $\times 10^{-7}$	$\bar{\Delta}_{0-1}^{(b)}$ $\times 10^{-7}$	$\bar{\Delta}_{0-0}^{(b)}$ $\times 10^{-7}$	$\bar{\Delta}_D = \overline{\Delta_{0-1} - \Delta_{0-0}}^{(b),(c)}$ $\times 10^{-7}$
UV +, IR 1	3.66×10^6 (54 hours)	46350	-76 ± 113	185 ± 134	-265 ± 171
UV −, IR 1	3.37×10^6 (49 hours)	44890	$(-)64 \pm 189$	$(+)11 \pm 135$	$(-)101 \pm 164$
UV +, IR 2	$3.99 \cdot 10^6$ (58 hours)	−43860	$(+)151 \pm 113$	$(+)181 \pm 95$	$(-) 54 \pm 128$
UV −, IR 2	$3.58 \cdot 10^6$ (52 hours)	−41640	-324 ± 154	-41 ± 131	-279 ± 158
E = 300 V/cm, all data.					$\bar{\Delta}_D = -169 \pm 74$

All quoted uncertainties are standard errors in the mean.

a) Uncorrected M1 asymmetry. The statistical uncertainty in $\bar{\Delta}_m$ in any given run is $\sim 150 \times 10^{-7}$. The much larger variations shown are due to changes from run to run in signal to background ratio and slight variation in 2.18 μ circular polarization.

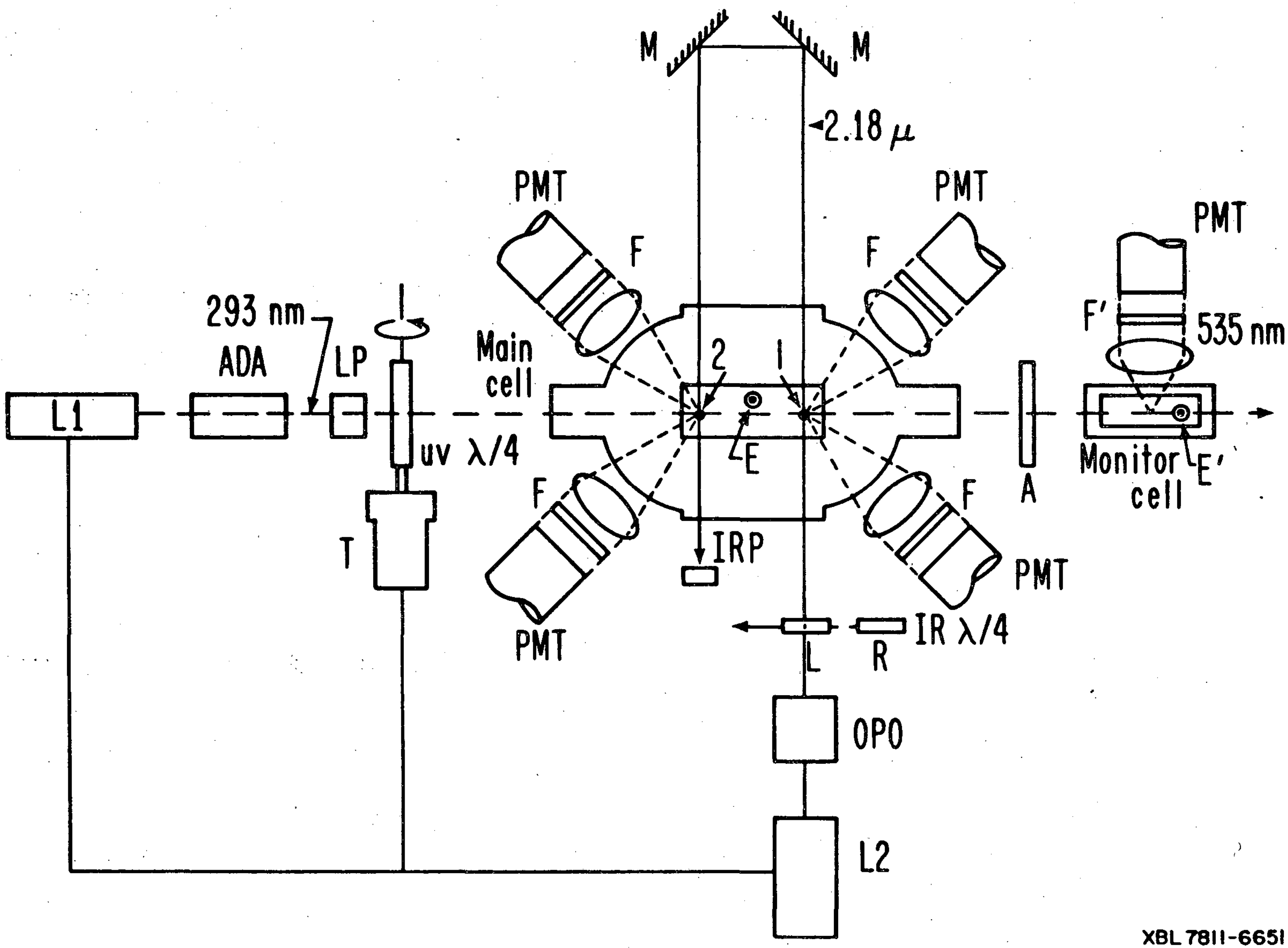
b) PNC asymmetries, normalized to $|\bar{\Delta}_m| = 55000 \cdot 10^{-7}$. The signs with parentheses indicate adjustment of sign to correct for changes in condition (column 1).

c) Δ_D is corrected (~ 6%) for the contamination of 0-0 line by 0-1 line. The apparent discrepancy between Δ_D and $\bar{\Delta}_{0-1} - \bar{\Delta}_{0-0}$ arises because we divide the data into 32 small groups, calculate $\Delta_{0-1} - \Delta_{0-0}$ for each group, and take the weighted average to find $\bar{\Delta}_D$.



$8^2S_{1/2}$
2.18μ
$6^2D^{5/2}_{3/2}$
323nm
$7^2P_{3/2}$
$7^2P_{1/2}$
292.7nm
535nm
378nm
$6^2P_{3/2}$
$6^2P_{1/2}$
(a)
E
y
292.7 nm
2.18μ
z
$7P_{1/2}$
x
(b)
(c)
$8^2S_{1/2}$
F=1
F=0
2.18μ
$1/4(\beta+\mathcal{M}\mp\mathcal{E}_p)^2$
$1/2(\mathcal{M}\mp\mathcal{E}_p)^2$
$1/4(\beta-\mathcal{M}\pm\mathcal{E}_p)^2$
$7^2P_{1/2}$
F=1
F=0
2.1 GHz
292.7 nm
$6^2P_{1/2}$
F=1
F=0
21 GHz
m_F = -1
0
+1
XBL7811-6652

Fig. 1



M
M
2.18 μ
PMT
PMT
PMT
F
F
F'
535 nm
293 nm
ADA
LP
Main cell
2
1
L1
uv λ/4
E
Monitor cell
E'
A
F
F
T
IRP
PMT
PMT
IR λ/4
L
R
OPO
L2
XBL 7811-6651

Fig. 2

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.