Measurement of the $6s – 7p$ transition probabilities in atomic cesium and a revised value for the weak charge $Q_W$

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We have measured the $6s – 7p_{1/2, 3/2}$ transition probabilities in atomic cesium using a direct absorption technique. We use our result plus other previously measured transition rates to derive an accurate value of the vector transition polarizability $\beta$ and, consequently, re-evaluate the weak charge $Q_W$. Our derived value $Q_W = -72.65(49)$ agrees with the prediction of the standard model to within one standard deviation.

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Bennett and Wieman’s measurement [1] in 1999 of the ratio of the off-diagonal hyperfine amplitude $M_{hf}$ to the vector polarizability $\beta$ for the $6s – 7s$ transition in cesium enabled them to evaluate the weak charge $Q_W$ of the electroweak interaction. In this evaluation they used a theoretical value for $M_{hf}$ which has been verified in subsequent calculations [2, 3]. Their $Q_W$ value differs from the prediction of the standard model by almost 2.5 standard deviations and has stimulated several recent theoretical papers [4, 5, 6, 7] which calculate the parity-nonconserving transition amplitude $E_{\text{PNC}}$ of the cesium $6s – 7s$ transition.

This recent interest suggested a careful study of all the measured parameters which go into such a test. The scalar and vector polarizabilities $\alpha$ and $\beta$ can be calculated as sums involving the reduced matrix elements of the electric-dipole transition rates from the $6s$ and $7s$ states (Refs. [6, 8, 9]):

$$\alpha = \frac{1}{6} \sum_n \left[ \frac{\langle 7s \parallel D \parallel np_{1/2} \rangle \langle np_{1/2} \parallel D \parallel 6s \rangle}{E_{7s} - E_{np_{1/2}}} + \frac{1}{E_{6s} - E_{np_{1/2}}} \right]$$

$$\beta = \frac{1}{6} \sum_n \left[ \frac{\langle 7s \parallel D \parallel np_{3/2} \rangle \langle np_{3/2} \parallel D \parallel 6s \rangle}{E_{7s} - E_{np_{3/2}}} + \frac{1}{E_{6s} - E_{np_{3/2}}} \right] + \frac{1}{2} \left[ \langle 7s \parallel D \parallel np_{3/2} \rangle \langle np_{3/2} \parallel D \parallel 6s \rangle \right]$$

In Eqs. (1,2), dominant contributions come from the $n = 6, 7$ terms. Therefore, the most important contributions come from the $6s – 6p, 7s – 6p, 6s – 7p,$ and $7p – 7s$ matrix elements. The dominant contribution to the uncertainties of $\alpha$ and $\beta$ calculated using this direct summation method comes from the uncertainty of $6s – 7p_{3/2}$ matrix element [6].

In this paper, we present new measurements of $6s – 7p$ transition rates. The sum needed for the vector polarizability has some severe cancellations; hence, we use the experimentally well-determined $\alpha/\beta$ ratio [1] and our new measurement to determine $\beta$, and, consequently, re-evaluate the weak charge $Q_W$.

The best previous measurement of the $6s – 7p$ transition rates was a photographic optical absorption measurement utilizing the hook method [2]. The relative measurement relied on the known values for the $6s – 6p_{3/2}$ transition. In order to measure the transition probability directly, we have made an absolute absorption measurement of laser light passing through a known number of cesium atoms for each transition.

An electrically heated and insulated cesium cell, at temperatures between room temperature and 90 °C provided a 5 cm long target for laser light close to the resonant wavelengths of 455 nm ($7p_{1/2}$) and 459 nm ($7p_{1/2}$). The cell temperature was measured with a multiprobe NIST calibrated K-type thermocouple thermometer with an accuracy of 0.1 °C degree. The needed blue light is produced by direct second harmonic generation (SHG) from a potassium niobate (KNaO$_3$) $5 \times 5 \times 5$ mm crystal pumped with a Coherent Model MBR-110 Titanium:Sapphire (Ti:Sapphire) ring laser.

To acquire each single absorption spectrum we scan the Ti:Sapphire laser over a frequency range of 15 GHz during a 50 seconds time interval. We observe two well-resolved absorption peaks during each scan, since the separation between the hyperfine states of the $6s$ ground state equals 9.19 GHz. The hyperfine structure of the $7p$ level is not resolved due to the much larger Doppler broadening of approximately 750 MHz at 65 °C. Further experimental details will be published later [13].
Since saturation might significantly influence the absorption measurements, we have measured the absorption for several different laser intensities, as shown in Figure 1. Similar results are also obtained for several different cell temperatures. We have made an average of seventy sets of data to obtain the transition probabilities for the 6s – 7p1/2 transition of 1.836(18) × 10⁶ s⁻¹ and for the 6s – 7p3/2 transition of 7.934(80) × 10⁵ s⁻¹. Adding other uncertainties (due to temperature measurements and Cs vapor pressure) to these values yields results accurate to 1.6%. The corresponding reduced matrix elements are compared with theory [16, 14, 13] and experiment [12] in Table I.

First, we calculate the value of α using the formula of Eq. (4). In Table I we list the values of electric-dipole matrix elements used in this calculation (present, Refs. [11, 10, 17]), together with the uncertainty of each matrix element and its contribution to the uncertainty in the value of α. We also list the contributions to the value of α from the terms with n > 7 and from the term αα, which compensates for the excitations from the core to the valence shell violating Pauli principle; these very small contributions are taken from Ref. [10]. As we see from Table I, the uncertainty in α is dominated by the uncertainty in the value of the 7p3/2 – 6s matrix element. Therefore, our more accurate measurement of the 7p3/2 – 6s matrix element allows a significant decrease of the uncertainty in the value of α (and correspondingly β) obtained by this method.

In more detail, dominant contributions to the scalar and vector polarizabilities α and β come from matrix elements of terms with n = 6 and n = 7, while n = 8 and n = 9 contributions are relatively small but significant. The contributions from the terms with n > 9 are very small (less than 0.4% according to [10]). Therefore, the values of only eight matrix elements are needed to be known to high accuracy to produce accurate values of α and β: 6p1/2 – 6s, 6p3/2 – 6s, 7p1/2 – 6s, 7p3/2 – 6s, 6p1/2 – 7s, 6p3/2 – 7s, 7p1/2 – 7s, and 7p3/2 – 7s. The values of the 6p – 6s matrix elements were measured to better than 0.15% precision in Ref. [16]. The values of the 7p – 7s matrix elements were derived in Ref. [10] from the experimental value of the Stark shift from Ref. [8] with 0.15% precision. These experimental values are in excellent agreement with all high-precision theoretical calculations [11, 14, 15]. The electric-dipole matrix elements for 7p1/2 – 6s and 7p3/2 – 6s transitions are measured in this work with 0.8% accuracy. The previous measurement of the 7p3/2 – 6s matrix element from [12] has 1.7% uncertainty which gave the dominant contribution to the uncertainties of the recommended values of α and β in Ref. [10]. The 7p1/2 – 6s and 7p3/2 – 6s matrix elements are also difficult to calculate accurately (see, for example, Ref. [10] for discussion). The matrix elements for the 7s – 6p transitions are derived from the measurement of the 7s lifetime conducted in Ref. [13]. The ratio of the reduced matrix elements for 7s – 6p1/2 and 7s – 6p3/2 transitions is taken to be R = 1.528 ± 0.004 based on theoretical calculations [10, 14, 13]. The uncertainty of the ratio does not significantly affect the uncertainties of the reduced matrix elements. We used the theoretical values for matrix elements with n = 8, 9 (the values of 6s – 8p matrix elements are taken from Ref. [10]) and the experimental values of energies from [14] in evaluating formula of Eq. (4). We obtain the final value for the scalar transition polarizability α = 269.7(1.1) a.u.. Table I shows that 98.5% of this value comes from the experimentally derived contributions (n = 6, 7).

The parity-nonconserving effects in cesium give rise to a non-zero amplitude 

\[ \beta \]

for the 6s – 7s transition forbidden by parity-selection rules. In Ref. [20], the nuclear spin-independent average Im(E_{\text{PNC}})/\beta was measured to be \(-1.5935(56)\) mV/cm. This value was combined in Ref. [3] with a measurement of \(\beta = 27.024(43)_{\text{expt}}(67)_{\text{theor}} a_0^2\), conducted in the same work, and with an average of theoretical calculations [3, 21].

TABLE I: A comparison of theoretical and experimental reduced electric-dipole matrix elements (a.u.) for 7p1/2 – 6s and 7p3/2 – 6s transitions in cesium. In Ref. [2], 6s – 7p oscillator strength were normalized to the value of 6s – 6p3/2 oscillator strength. We have re-normalized those values to the most recently measured value of 6s – 6p3/2 oscillator strength from Ref. [16].

| Ref. | 7p1/2 – 6s | 7p3/2 – 6s |
|------|------------|------------|
| Theory [10] | 0.279 | 0.576 |
| Theory [14] | 0.275 | 0.583 |
| Theory [15] | 0.280 | 0.576 |
| Expt. [12] | 0.2825(20) | 0.5795(100) |
| This work | 0.2757(20) | 0.5856(50) |
\[ E_{\text{PNC}} = 0.9065(36) \times 10^{-11} e\alpha_0 Q_W/N, \] where \( N \) is the number of neutrons and \( \alpha_0 \) is the Bohr radius, to give the value of the weak charge \( Q_W \). We note that the accuracy of the theoretical calculation of \( E_{\text{PNC}} \) was taken in Ref. [4] to be 0.4% based on the comparison of the theoretical calculations of various atomic properties conducted by the authors of Refs. [6, 21] with experiment. The resulting value of the weak charge \( Q_W = -72.06(28) \exp(34)_{\text{theor}} \) was found to differ from the value predicted by the standard model \( Q_{\text{SM}} = -73.09(3) \) from [22] by 2.3\sigma. Using our experimental result and the analysis given above to determine \( \alpha \), plus the measurement by Cho et al [1] of the \( \alpha/\beta \) ratio, we derive the almost completely experimentally determined value \( \beta = 27.22(11) \alpha_0^2 \). We use this result to determine the value of weak charge \( Q_W = -72.58(49) \), which differs by only 1.1\sigma from the one predicted by the standard model [22]. However, the theoretical calculations of \( E_{\text{PNC}} \) have been improved recently to include Breit and vacuum-polarization corrections to the PNC amplitude [4, 6, 7] in Figure 2. Future improvements in this method of estimating \( Q_W \) can come from better calculations (or experimental measurements) of the 7s \(- 6p \) transition rates and also from Tanner’s measurement in progress (private communication) of the ratio of the 6s \(- 7p \) transition rates.

In conclusion, we have measured the probabilities of the 6s \(- 7p_{1/2,3/2} \) transitions in atomic cesium using a direct absorption technique. We then indicate a straightforward method to determine the scalar transition polarization \( \alpha \) based almost completely on experimentally determined atomic parameters. Including a previous accurate experimental determination of the \( \alpha/\beta \) ratio yields a value for the vector polarization \( \beta \) and for the weak charge \( Q_W \).

Our derived value for \( Q_W \) agrees with the value predicted by the standard model to within one standard deviation. We compared the result with that of Bennett and Wieman [1] and also with recent atomic calculations [5, 11, 12, 13] in Figure 3. Future improvements in this method of estimating \( Q_W \) can come from better calculations (or experimental measurements) of the 7s \(- 6p \) transition rates and also from Tanner’s measurement in progress (private communication) of the ratio of the 6s \(- 7p \) transition rates.

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\[ Q_W = -72.65(49), \]

which is in agreement with the value predicted by the standard model [22] to 1\sigma. In Figure 3, we compare these results with recent calculations for the weak charge \( Q_W \).

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TABLE II: Contributions to the scalar $6s - 7s$ transition polarizability $\alpha$ in Cs and their uncertainties in a.u.

| $n$ | $d$ | $\delta d(\%)$ | $\delta \alpha$ | $d$ | $\delta d(\%)$ | $\delta \alpha$ | $\alpha$ |
|-----|-----|----------------|-----------------|-----|----------------|-----------------|--------|
| 6   | $-4.236^a$ | 0.5 | 0.16 | $-4.489^b$ | 0.1 | 0.05 | 32.32 |
| 7   | $10.308^c$ | 0.1 | 0.06 | $-0.276^d$ | 0.8 | 0.28 | 36.97 |
| 8   | $-0.915$ | 2.0 | 0.01 | $0.081^e$ | 3.0 | 0.01 | 0.48 |
| 9   | $-0.347$ | 6.0 | 0.00 | $0.043$ | 10.0 | 0.01 | 0.08 |

| $n$ | $d$ | $\delta d(\%)$ | $\delta \alpha$ | $d$ | $\delta d(\%)$ | $\delta \alpha$ | $\alpha$ |
|-----|-----|----------------|-----------------|-----|----------------|-----------------|--------|
| 6   | $6.473^a$ | 0.5 | 0.46 | $-6.324^b$ | 0.1 | 0.11 | 92.47 |
| 7   | $-14.320^c$ | 0.1 | 0.16 | $-0.586^d$ | 0.8 | 0.78 | 103.90 |
| 8   | $1.622$ | 2.0 | 0.05 | $0.218^e$ | 3.0 | 0.07 | 2.28 |
| 9   | $0.678$ | 6.0 | 0.03 | $0.127$ | 10.0 | 0.05 | 0.46 |

| Expt. $\alpha_{6,7}$ | $265.66(98)$ |
| Theor. $\alpha_{8,9}$ | $3.3(1)$ |
| Theor. $\alpha_{9\gamma}$ | $0.90(45)^c$ |
| Theor. $\alpha_{vc}$ | $-0.2(1)^e$ |
| $\alpha_{\text{total}}$ | $269.7(1.1)$ |

$^a$Ref. [17]
$^b$Ref. [18]
$^c$Ref. [19]
$^d$This work

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