Measurement of the $6S \rightarrow 7S$ Transition Polarizability in Atomic Cesium and an Improved Test of the Standard Model

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The ratio of the off-diagonal hyperfine amplitude to the tensor transition polarizability ($M_{\rm hf}/\beta$) for the $6S \rightarrow 7S$ transition in cesium has been measured. The value of $\beta = 27.024(43)_{\rm expt}(67)_{\rm theor} a_0^3$ is then obtained using an accurate semiempirical value of $M_{\rm hf}$. This is combined with a previous measurement of parity nonconservation in atomic cesium and previous atomic structure calculations to determine the value of the weak charge. The uncertainties in the atomic structure calculations are updated (and reduced) in light of new experimental tests. The result $Q_W = -72.06(28)_{\rm expt}(34)_{\rm theor}$ differs from the prediction of the standard model of elementary particle physics by 2.5σ. [S0031-9007(99)08690-1]

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Electroweak experiments have now reached high precision in testing the standard model and in searching for new physics beyond it [1,2]. These experiments include measurements of parity nonconservation (PNC) in atoms as first proposed in Ref. [3]. Atomic PNC measurements are uniquely sensitive to a variety of new physics, such as the existence of additional Z bosons, because of the different energy scale and because they probe a different set of model-independent electron-quark coupling constants than those measured by high-energy experiments [2]. The most precise atomic PNC experiment [4] examines the mixing of S and P states in atomic cesium. Specifically, it compares the mixing due to the PNC neutral weak current interaction to the S-P mixing caused by an applied electric field ("Stark mixing"). In previous work [4], this measurement was combined with theoretical calculations of the structure of the cesium atom to obtain the weak charge Q_W, which characterizes the strength of the neutral weak interaction and can be compared to the value predicted by the standard model. The atomic structure calculations were used to obtain two pieces of information: the amount of Stark mixing and the relevant PNC electronic matrix elements. The 1.2% uncertainty in the determination of Q_W was dominated by the uncertainties in those two calculated quantities. In this paper we report a reduced uncertainty in Q_W that is obtained by (1) measuring the Stark mixing and (2) incorporating new experimental data into the evaluation of the uncertainty in the calculation of the PNC matrix elements. These new data indicate that the calculations are more accurate than was indicated by the less precise (and in some cases incorrect) data available at the time the calculations were published.

Theory.—The $6S$ ground state and $7S$ excited state of atomic cesium both have two hyperfine levels: $F = 3$ and $F = 4$. In the presence of a dc electric field $\vec{E}$, a magnetic field, and a standing-wave laser field with propagation vector $\vec{k}$ and polarization $\vec{\epsilon}$, the $\Delta F = \pm 1$ $6S \rightarrow 7S$ amplitudes, used in both Ref. [4] and the present work, are given by [5]

$$A_{6S\rightarrow 7S} = [i\beta(\vec{E} \times \vec{\epsilon}) + M1(\vec{k} \times \vec{\epsilon}) + E1_{\rm PNC}\vec{\epsilon}] \cdot \langle F' m_F' | \vec{\sigma} | F m_F \rangle , \quad (1)$$

where $M1 = M \pm M_{\rm hf}\delta_{FF'\pm 1}$ is the magnetic dipole amplitude (M is from relativistic and spin-orbit effects, $M_{\rm hf}$ is from the off-diagonal hyperfine interaction) and $\vec{\sigma}$ is the Pauli spin matrix. The tensor transition polarizability [3] β characterizes the size of the Stark mixing-induced electric dipole amplitude, and $E1_{\rm PNC}$ is the PNC matrix element given by

$$E1_{\rm PNC} \equiv \overline{\langle 7S |} \boldsymbol{D} \overline{| 6S \rangle} = \frac{Q_W}{N} k_{\rm PNC} . \quad (2)$$

Here, $\overline{|nS\rangle}$ is an $|nS\rangle$ state into which the PNC Hamiltonian has mixed a small amount of $|nP\rangle$ states, $\boldsymbol{D}$ is the electric dipole operator, N is the number of neutrons, and $k_{\rm PNC}$ is the calculation of the sum of relevant matrix elements between S and P states given by

$$k_{\rm PNC} = \frac{N}{Q_W} \sum_n \left(\frac{\langle 7S|\vec{D}|nP\rangle\langle nP|H_{\rm PNC}|6S\rangle}{E_{6S} - E_{nP}} + \frac{\langle 7S|H_{\rm PNC}|nP\rangle\langle nP|\vec{D}|6S\rangle}{E_{7S} - E_{nP}} \right) . \quad (3)$$

Since $H_{\rm PNC} = G_F \gamma^5 Q_W \rho_N(r)/\sqrt{8}$, each of the terms in Eq. (3) is the product of a dipole matrix element times a γ^5 matrix element evaluated in the nucleus. Ninety-eight percent of the sum comes from the $6P_{1/2}$ and $7P_{1/2}$ states [6].

In Ref. [4], $\mathrm{Im}(E1_{\rm PNC})/\beta$ is measured. The value Q_W is obtained by multiplying this ratio by $\beta N/k_{\rm PNC}$. This paper concerns the improved determination of β and $k_{\rm PNC}$, and thus Q_W.

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To determine β, we measure $M_{\rm hf}/\beta$ and take advantage of the fact that $M_{\rm hf}$ can be accurately determined semiempirically [7]. The amplitude $M_{\rm hf}$ is due to the hyperfine interaction and thus can be expressed in terms of well-measured hyperfine splittings. In this experiment we observe the $6S \rightarrow 7S$ rate driven with a standing-wave laser beam with polarization $\vec{\epsilon} = \epsilon\hat{z}$ and a field geometry (E along $\hat{x}$) such that the transition rate is

$$|A_{6S\rightarrow 7S}|^2 = \beta^2 E^2 \epsilon^2 + (M \pm M_{\rm hf}\delta_{FF'\pm 1})^2 \epsilon^2, \quad (4)$$

where small interference terms have been omitted. The β-PNC and $M1$-PNC interference terms are negligible, and the β-$M1$ interference terms cancel almost identically ($<10^{-6}$) because of their $\hat{k}$ dependence and the standing-wave geometry of the experiment. We determine $M_{\rm hf}/\beta$ by measuring the total rate on the two $\Delta F = \pm 1$ hyperfine transitions with large E, where $|A_{6S\rightarrow 7S}|^2 \approx \beta^2 E^2$, and with $E = 0$, where $|A_{6S\rightarrow 7S}|^2 \approx (M \pm M_{\rm hf}\delta_{FF'\pm 1})^2$. We combine the ratios of the high and low E rates on both transitions to determine $M_{\rm hf}/\beta$.

A complication arises because the locations of the antinodes of the oscillating electric ($\varepsilon_{\rm ac}$) and magnetic ($b_{\rm ac}$) fields are separated by $\lambda/4$ in the standing wave. Because of this separation, photoionization (which is driven by $\varepsilon_{\rm ac}$) is larger for $7S$ atoms excited by $\varepsilon_{\rm ac}$ ($E1$ atoms) than it is for $7S$ atoms excited by $b_{\rm ac}$ ($M1$ atoms). The result is that the detection efficiency for $E1$ excitations is slightly smaller ($\sim$1% for typical intensities) than for $M1$ excitations. This difference gives a potential systematic error that is intensity dependent. The ratios of the signals, measured at a laser intensity I, for the $\Delta F = +1$ and $\Delta F = -1$ transitions, respectively, are then

$$R_I^{3\rightarrow 4} \equiv \left(\frac{M - M_{\rm hf}}{\beta E}\right)^2 (1 + \eta I) \quad (5a)$$

and

$$R_I^{4\rightarrow 3} \equiv \left(\frac{M + M_{\rm hf}}{\beta E}\right)^2 (1 + \eta I), \quad (5b)$$

where η is a parameter that describes the difference in the photoionization fraction.

Experiment.—The apparatus used in the present experiment is very similar to that in Refs. [4,8]. A collimated beam of cesium is optically pumped into either the $F = 3$ or $F = 4$ hyperfine level of the $6S_{1/2}$ ground state. The beam of atoms then travels roughly along the $\hat{z}$ axis into a region with mutually orthogonal dc electric (along $\hat{x}$) and magnetic (along $\hat{z}$) fields and intersects a 540-nm standing-wave laser field (along $\hat{y}$) at right angles. The laser field is produced by a tunable dye laser that is frequency locked to a finesse $\simeq 10^5$ Fabry-Perot etalon. The etalon is, in turn, locked to a stable reference cavity. The light going to the reference cavity is double passed through an acousto-optic modulator (AOM), so the frequency of the laser light interacting with the atomic beam is $\nu_{\rm laser} = \nu_{\rm ref} - 2\nu_{\rm AOM}$. Thus, we can change the frequency of the dye laser in a very controlled manner by changing the frequency of the AOM. The dye laser drives the $6S \rightarrow 7S$ transition. Approximately half of the atoms excited to the $7S$ state relax to the previously depleted hyperfine ground state ($F = 3$ or $F = 4$). Further downstream, the atoms in the repopulated hyperfine level scatter photons from a diode laser probe beam tuned to an appropriate $6S_{1/2}$-$6P_{3/2}$ cycling transition. We collect the scattered photons on a large-area photodiode, and its photocurrent is proportional to the number of atoms making the $6S \rightarrow 7S$ transition.

To measure the ratio $R_I^{3\rightarrow 4}$ (or $R_I^{4\rightarrow 3}$), we scan the laser over the $6S \rightarrow 7S$ $\Delta F = +1$ (or $\Delta F = -1$) transition in 0.3-MHz steps. After each step we integrate the photocurrent for 16.67 ms and store that data point on disk. We alternate between scans with $E = 707.63(68)$ V/cm and $E = 0$ V/cm.

There is a 540-nm-laser-frequency-independent background signal from atoms in the wrong hyperfine state that is $\sim$100 times larger than the desired $M1$ signal for $E = 0$ V/cm. We measure this background before and after each data point by detuning the laser $\sim$50 MHz from line center and measuring the photocurrent. These background points are measured alternately above and below the line center to cancel any linear frequency dependence of the background. We subtract the average background from the data points to leave only the contribution from atoms making the $6S \rightarrow 7S$ transition. The sum of all the data points (the area under the spectral line) is proportional to the total transition rate.

We looked for but did not observe any frequency dependence to the background. Also, all likely mechanisms, such as molecular transitions or light scattering off the mirrors, should have very broad spectral features and, hence, will be eliminated by the background subtraction. The uncertainty in our results due to possible frequency dependent backgrounds is less than 0.05%.

Sample background-subtracted scans are shown in Fig. 1. The two line shapes are asymmetric and slightly offset from one another because of their differing sensitivity to ac Stark shifts as discussed in Ref. [9]. The different line shapes do not affect our measurement of the total transition rate because the atoms' total transition amplitude is unchanged, even though the resonant frequency of each atom is shifted according to the local $\varepsilon_{\rm ac}$ field. Therefore, by integrating the areas under the entire broadened lines we can determine the desired relative ratios $R_I^{3\rightarrow 4}$ and $R_I^{4\rightarrow 3}$.

Results.—The detection efficiency and signal-to-noise ratio are significantly higher for $R^{3\rightarrow 4}$; we measure that ratio at five different intensities from 0.6 to 2.8 kW and determine η to 1.5 parts in 10^3 using a least squares fit. We find the ratios $R_0^{3\rightarrow 4} = 2.4636(8) \times 10^{-3}$ and $R_0^{4\rightarrow 3} = 1.1357(6) \times 10^{-3}$ where the two uncertainties have a common contribution from the extrapolation to

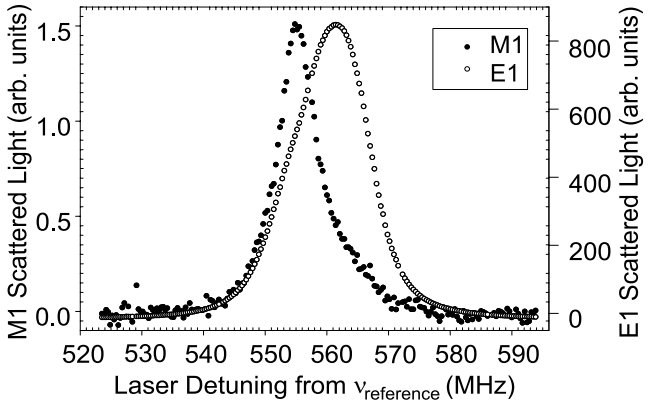

FIG. 1. Sample data comparing scans with and without an applied electric field. Open circles are with $E = 707$ V/cm and the scale on the right. Closed circles are with $E = 0$ V/cm and the scale on the left. The two lines are offset from one another and have different widths because of the different sensitivities to ac Stark shifts for the $M1$ and $E1$ transitions.

zero intensity. Combining these results using Eq. (5) we find $M_{\rm hf}/\beta = -5.6195(91)$ V/cm [10]. From Ref. [7] we take $M_{\rm hf} = -151.86(38)$ (V/cm)a_0^3, which is based on measured hyperfine splittings with a $0.3 \pm 0.3\%$ theory correction due to many body effects. This gives

$$\beta = 27.024(43)_{\rm expt}(67)_{\rm theor} a_0^3 . \quad (6)$$

This value is in excellent agreement with the semiempirical values $\beta = 27.17(35)a_0^3$ [7] and $\beta = 27.15(13)a_0^3$ [11] and the calculated value $\beta = 27.00a_0^3$ [12].

Using our measured values for β and $\mathrm{Im}(E1_{\rm PNC})/\beta$, and the calculated value of $k_{\rm PNC}$, we can now extract Q_W. The key issue is the uncertainty in the value of $k_{\rm PNC}$. The authors of Refs. [6,12–14] discuss this issue at considerable length. Here we only summarize the conclusion of both groups that the most reliable measure is to use the same *ab initio* calculations of the electronic structure that are used to find $k_{\rm PNC}$ to calculate dipole matrix elements and hyperfine splittings for the $6S_{1/2}$, $7S_{1/2}$, $6P_{1/2}$, and $7P_{1/2}$ states. The differences between these calculated values and the experimental determinations provide a reliable quantitative indication of the uncertainties in the calculations of $k_{\rm PNC}$. The authors considered how well these errors in the hyperfine splittings and dipole matrix elements reflect errors in $k_{\rm PNC}$ by rescaling their calculations in a variety of ways and comparing the relative sensitivities of the different quantities. They found that $k_{\rm PNC}$ has comparable or smaller sensitivity than the other quantities [15]. From comparing calculated and measured quantities, both groups arrived at uncertainties of about 1% for their value of $k_{\rm PNC}$. Since the time that Refs. [6,12–14] were published, there have been a number of new and more precise measurements of the quantities of interest. In all cases, the new measurements show better agreement with the calculations than earlier measurements and also show that the largest previous disagreements were likely due to experimental errors.

In Table I we have collected the results of the most precise measurements of relevant quantities in cesium. We list the quantities measured, the primary aspect of the electronic wave functions that is being tested in each comparison, and the difference between theory and experiment. Particularly notable are the top three lines of the table, which show that the agreement has dramatically improved from the 1%–2% disagreements of the older experiments. In addition to the data in this table, there have been new experiments that revealed errors in earlier lifetime measurements in sodium and lithium. These new data eliminate what had appeared to be troubling 1% errors in equivalent calculations for those atoms.

The standard deviation of the fractional differences between theory and experiment in Table I is 4.0×10^{-3}. We believe this to be the most valid number to use to represent the 68% confidence level for $k_{\rm PNC}$. Using the average of $k_{\rm PNC} = 0.905 \times 10^{-11} iea_0$ [12] and $k_{\rm PNC} = 0.908 \times 10^{-11} iea_0$ [13], this gives a value of $k_{\rm PNC} = 0.9065(36) \times 10^{-11} iea_0$

When combined with our new value for β and the experimental PNC measurement, this gives

$$Q_W = -72.06(28)_{\rm expt}(34)_{\rm theor} . \quad (7)$$

The standard model value including radiative corrections is $Q_W = -73.20(13)$ [16]. Adding the uncertainties in quadrature, these values differ by 2.5σ.

Assuming that this difference is not due to an experimental error or a statistical fluctuation, it suggests several possibilities. The first possibility is that the calculated value of the γ^5 matrix element is in error by the requisite 1.58%. In light of Table I, such an error would require a wave function with a somewhat peculiar and insidious shape. Although none of the measured quantities depends on the shape of the wave function in a manner identical to that of γ^5, the different comparisons in Table I do probe the value of the wave function in all regions: short, intermediate, and long distances. The largest single difference of the 16 comparisons is only 0.79%, and the standard deviation is only 0.40%. The second possibility is that there are contributions or corrections to atomic PNC within the standard model that have been overlooked. We see no justification for either of these two possibilities, but they clearly need to be explored further. The first offers a formidable but not overwhelming challenge to both theoretical and experimental atomic physicists.

The final possibility is that this discrepancy is indicating the presence of some new physics not contained in the standard model. Physics that would be characterized by the S parameter [17] is not a likely candidate because the size of the contribution needed [$S = -1.4(6)$] would be in conflict with other data [1]. However, there are other types of new physics, such as an additional Z boson, that would be consistent with all other current data.

TABLE I. Fractional differences ($\times 10^3$) between measured and calculated values of quantities relevant for testing PNC calculations in atomic cesium. We only list the most precise experiments. The second column lists the most relevant aspects of the wave functions that are being tested. $\langle 1/r^3\rangle_{nP}$ is the average of $1/r^3$ over the wave function of the electronic state nP. Where the experiment has improved or changed significantly since the publication of Ref. [12], the difference from the old experiment is listed in brackets.

Quantity measured	Calculation tested	Difference ($\times 10^3$) Dzuba *et al.*[a,b]	Blundell *et al.*[c]	σ_{expt}
$6S \rightarrow 7S$ dc Stark shift[d]	$\langle 7P\|\|\boldsymbol{D}\ddagger S\rangle$	−3.4[19]	−0.7[22]	1.0[4]
$6P_{1/2}$ lifetime[e]	$\langle 6S\|\|\boldsymbol{D}\ddagger P_{1/2}\rangle$	−4.2[−8]	4.3[1]	1.0[43]
$6P_{3/2}$ lifetime[e]	$\langle 6S\|\|\boldsymbol{D}\ddagger P_{3/2}\rangle$	−2.6[−41]	7.9[−31]	2.3[22]
α[f]	$\langle 7S\|\|\boldsymbol{D}\ddagger P_{1/2}\rangle$, and $\langle 7S\|\|\boldsymbol{D}\ddagger P_{3/2}\rangle$	⋯	−1.4	3.2
β[g]	same as α	⋯	−0.8	3.0
$6S$ hfs[h]	$\psi_{6S}(r=0)$	1.8	−3.1	⋯
$7S$ hfs[i]	$\psi_{7S}(r=0)$	−6.0	−3.4	0.2
$6P_{1/2}$ hfs[j]	$\langle 1/r^3\rangle_{6P}$	−6.1	2.6	0.2
$7P_{1/2}$ hfs[k]	$\langle 1/r^3\rangle_{7P}$	−7.1	−1.5	0.5

[a]The value for k_{PNC} of Dzuba *et al.* is obtained using "energy rescaling" so we have used the corresponding "rescaled" values in the table for consistency. Blundell *et al.* do not rescale k_{PNC} and so we use their pure *ab inito* values in the table. [b]Refs. [13,14]. [c]Refs. [6,12]. [d]Ref. [8]. [e]Ref. [18]. [f]Using present work's value of β and α/β from Ref. [19]. [g]Present work. [h]Defined. [i]Ref. [20]. [j]Ref. [21]. [k]Ref. [22].

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