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

A. A. Vasilyev, I. M. Savukov, M. S. Safronova,* and H. G. Berry
Department of Physics, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, Indiana 46556
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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 and other previously measured transition rates to derive an accurate value of the vector transition polarizability β and, consequently, reevaluate 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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The parity-nonconserving (PNC) effects in cesium give rise to nonzero amplitude E_{PNC} for the $6s$-$7s$ transition forbidden by the parity-selection rules. In Ref. [1], the ratio $\mathrm{Im}(E_{\mathrm{PNC}})/\beta$ was measured with 0.3% accuracy. This measurement, together with the theoretical value of E_{PNC} amplitude and either experimental or theoretical value of β allows one to infer the value of the weak charge Q_W of the electroweak interaction as described, for example, in Refs. [2,3].

Bennett and Wieman's measurement [4] in 1999 of the ratio of the off-diagonal hyperfine amplitude M_{hf} to the vector polarizability β for the $6s$-$7s$ transition in cesium enabled them to evaluate Q_W with 0.6% uncertainty. In this evaluation they used a theoretical value for M_{hf} which has been verified in subsequent calculations [5,6]. 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 [7–10] that calculate the parity-nonconserving transition amplitude E_{PNC} of the cesium $6s$-$7s$ transition.

This recent interest suggested a careful study of all the measured parameters that go into such a test. The scalar and vector polarizabilities α and β can be calculated as sums involving the reduced matrix elements of the electric-dipole transitions from the $6s$ and $7s$ states (Refs. [2,11,12]); the expression for α is

$$\alpha=\frac{1}{6}\sum_n\left[\langle 7s\|D\|np_{1/2}\rangle\langle np_{1/2}\|D\|6s\rangle\left(\frac{1}{E_{7s}-E_{np_{1/2}}}+\frac{1}{E_{6s}-E_{np_{1/2}}}\right)-\langle 7s\|D\|np_{3/2}\rangle\langle np_{3/2}\|D\|6s\rangle\times\left(\frac{1}{E_{7s}-E_{np_{3/2}}}+\frac{1}{E_{6s}-E_{np_{3/2}}}\right)\right]. \quad (1)$$

In Eq. (1), 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 α and β calculated using this direct summation method comes from the uncertainty of the $6s$-$7p_{3/2}$ matrix element [12].

In this paper, we present measurements of $6s$-$7p$ transition rates. The sum needed for the vector polarizability has some severe cancellations; hence, we use the experimentally well-determined α/β ratio [13] and our measurement to determine β, and, consequently, reevaluate 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 [14]. The relative measurement relied on the known value 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 ($7p_{3/2}$) 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. The blue light is produced by direct second harmonic generation from a potassium niobate ($KNbO_3$) $5\times5\times5$ mm^3 crystal pumped with a Coherent 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 sec 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 $\approx$750 MHz at 65 °C. Each absorption measurement is analyzed to verify that the chosen scan parameters are followed for the whole scan. When a spectral jump occurs the resulting spectrum shows an obvious error and is eliminated from subsequent analysis.

The saturation effect can significantly influence the absorption measurements. To test the possible effects of saturation on our measurements we measure the absorption of the $6s$-$7p_{1/2}$ and $6s$-$7p_{3/2}$ transitions for several different laser intensities as shown in Fig. 1. The results rule out the effect of saturation on our absorption measurements. The dark current from the photodetector is measured at the be-

*Present address: Electron and Optical Physics Division, National Institute of Standards and Technology, Gaithersburg, MD 20899-8410.

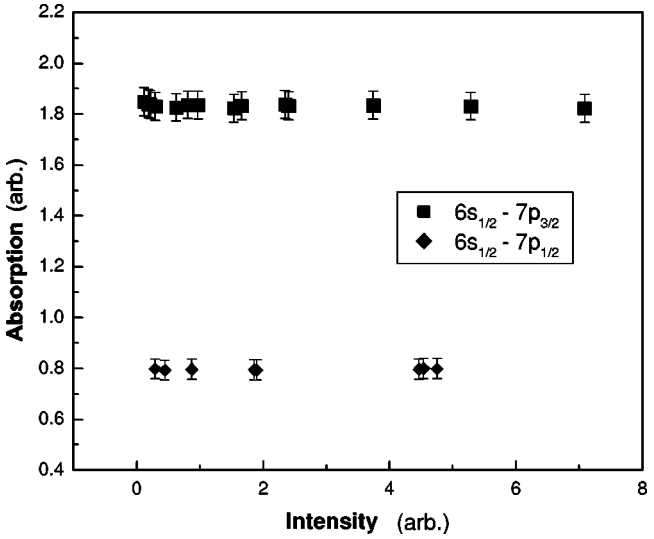

FIG. 1. Comparison of absorption rates for several laser intensities for the $6s$-$7p$ transitions at a fixed cesium cell temperature.

ginning and at the end for each scan, and accounted for in the data analysis. The measured transmitted intensity $I(\lambda)$ can be described by Beer's law,

$$I(\lambda)=I_0 e^{-\alpha(\lambda)L}, \tag{2}$$

where I_0 is incident intensity, $\alpha(\lambda)$ is the absorption coefficient and L is the length of the absorption cell. In order to improve the signal-to-noise ratios the absorption measurements are made under conditions that cannot be treated as optical-thin conditions [$\alpha(\lambda)L \ll 1$]. Thus, the absorption coefficient at the resonance wavelength is calculated in two steps. First, we calculate values of $\ln[I(\lambda)]$. Second, the Gaussian profile is fitted in $\ln[I(\lambda)]$. Then we use fitting parameters (the area of the Gaussian profile and its half-width) to calculate a value for the absorption coefficient at the resonance wavelength. The typical accuracy of a single absorption coefficient measurement derived from the fitting procedure is equal to or better than 0.4%. The line profile $g(\nu)$ and the cesium vapor pressure are needed for accurate calculation of the transition probability from the absorption measurements. The Doppler width is more than 400 times larger than natural linewidth and hence the Doppler broadening is the dominant mechanism which determines the line profile in our measurements. The linewidths of the $6s$-$7p_{1/2}$ and $6s$-$7p_{3/2}$ transitions are slightly broader than the Doppler width, due to the hyperfine structure of $7p$ levels. We take this fact into account when calculating the transition rates. The corresponding linewidths are calculated by using known hyperfine structure of the Cs $7p$ levels [15]. The equilibrium vapor pressure is calculated from the Taylor and Langmuir formulas [16]. Taylor and Langmuir quote an uncertainty of 1% for their formulas. These equations are thought to represent the best vapor pressure values for cesium [17–19], and are cited routinely to this day in the cesium spectroscopic literature. Possible errors in the cesium atom vapor pressure have been addressed comprehensively by Rafac [19]. The temperature measurement accuracy of 0.1 °C leads to 0.5% uncertainty in the cesium vapor density. Further experimental details will be published later [20].

TABLE I. A comparison of theoretical and experimental reduced electric-dipole matrix elements (a.u.) for $7p_{1/2}$-$6s$ and $7p_{3/2}$-$6s$ transitions in cesium. In Ref. [14], $6s$-$7p$ oscillator strengths were normalized to the value of $6s$-$6p_{3/2}$ oscillator strength. We have renormalized those values to the most recently measured value of $6s$-$6p_{3/2}$ oscillator strength from Ref. [23].

Ref.	$7p_{1/2}$-$6s$	$7p_{3/2}$-$6s$
Theory [12]	0.279	0.576
Theory [21]	0.275	0.583
Theory [22]	0.280	0.576
Expt. [14]	0.2825(20)	0.5795(100)
This work	0.2757(20)	0.5856(50)

We have made an average of 70 sets of data to obtain the transition probabilities for the $6s$-$7p_{1/2}$ transition of $1.836(18)\times10^6\,\mathrm{s}^{-1}$ and for the $6s$-$7p_{3/2}$ transition of $7.934(80)\times10^5\,\mathrm{s}^{-1}$. Adding uncertainties due to the single absorption coefficient measurement, temperature measurements and Cs vapor pressure to these values yields results accurate to 1.6%. The corresponding reduced matrix elements are compared with theory [12,21,22] and experiment [14] in Table I.

First, we calculate the value of α using the formula of Eq. (1). In Table II, we list the values of electric-dipole matrix elements used in this calculation (present, Refs. [12,23,24]) 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 α_{vc} that compensates for the excitations from the core to the valence shell violating the Pauli principle; these very small contributions are taken from Ref. [12]. As we see from Table II, the uncertainty in α is dominated by the uncertainty in the value of the $7p_{3/2}$-$6s$ matrix element. Therefore, our more accurate measurement of the $7p_{3/2}$-$6s$ 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 Ref. [12]). Therefore, the values of only eight matrix elements are needed to be known to high accuracy to produce accurate values of α and β: $6p_{1/2}$-$6s$, $6p_{3/2}$-$6s$, $7p_{1/2}$-$6s$, $7p_{3/2}$-$6s$, $6p_{1/2}$-$7s$, $6p_{3/2}$-$7s$, $7p_{1/2}$-$7s$, and $7p_{3/2}$-$7s$. The values of the $6p$-$6s$ matrix elements were measured to better than 0.15% precision in Ref. [23]. The values of the $7p$-$7s$ matrix elements were derived in Ref. [12] from the experimental value of the Stark shift from Ref. [25] with 0.15% precision. These experimental values are in excellent agreement with all high-precision theoretical calculations [12,21,22]. The electric-dipole matrix elements for $7p_{1/2}$-$6s$ and $7p_{3/2}$-$6s$ transitions are measured in this work with 0.8% accuracy. The previous measurement of the

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

n	$\lvert d\rvert$	$\delta d(\%)$	$\delta\alpha$	$\lvert d\rvert$	$\delta d(\%)$	$\delta\alpha$	α
		$7s$-$np_{1/2}$			$np_{1/2}$-$6s$		
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 [c]	3.0	0.01	−0.48
9	0.347	6.0	0.00	0.043	10.0	0.01	−0.08
		$7s$-$np_{3/2}$			$np_{3/2}$-$6s$		
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 [c]	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. $\alpha_{>9}$							−0.90(45) [c]
Theor. α_{vc}							0.2(1) [c]
α_{total}							−269.7(1.1)

[a]Reference [24].
[b]Reference [23].
[c]Reference [12].
[d]This work.

$7p_{3/2}$-$6s$ matrix element from Ref. [14] has 1.7% uncertainty, which gave the dominant contribution to the uncertainties of the recommended values of α and β in Ref. [12]. The $7p_{1/2}$-$6s$ and $7p_{3/2}$-$6s$ matrix elements are also difficult to calculate accurately (see, for example, Ref. [12] for discussion). The matrix elements for the $7s$-$6p$ transitions are derived from the measurement of the $7s$ lifetime conducted in Ref. [24]. The ratio of the reduced matrix elements for $7s$-$6p_{3/2}$ and $7s$-$6p_{1/2}$ transitions is taken to be $R=1.528\pm0.004$ based on theoretical calculations [12,21,22]. 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. [12]) and the experimental values of energies from Ref. [26] in evaluating the formula of Eq. (1). We obtain the final value for the scalar transition polarizability $\alpha=-269.7(1.1)$ a.u. Table II shows that 98.5% of this value comes from the experimentally derived contributions ($n=6,7$). Below, we use this value of α to reevaluate the weak charge Q_W.

In Ref. [1], the nuclear spin-independent average $\mathrm{Im}(E_{\mathrm{PNC}})/\beta$ was measured to be $-1.5935(56)$ mV/cm. This value was combined in Ref. [4] with a measurement of $\beta=27.024(43)_{\mathrm{expt}}(67)_{\mathrm{theor}}\ a_0^3$, conducted in the same work, and with an average of theoretical calculations [2,3] $E_{\mathrm{PNC}}=0.9065(36)\times10^{-11}ie a_0 Q_W/N$, where N is the number of neutrons and a_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_{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. [2,3] with experiment. The resulting value of the weak charge $Q_W=-72.06(28)_{\mathrm{expt}}(34)_{\mathrm{theor}}$ [4] was found to differ from the value predicted by the standard model $Q_W^{\mathrm{SM}}=-73.09(3)$ from Ref. [27] by 2.3σ. Using our experimental result and the analysis given above to determine α, plus the measurement by Cho *et al.* [13] of the α/β ratio, we derive the almost completely experimentally determined value $\beta=27.22(11)a_0^3$. We use this result to determine the value of weak charge $Q_W=-72.58(49)$, which differs by only 1.1σ from the one predicted by the standard model [27]. However, the theoretical calculations of E_{PNC} have been improved recently to include Breit [7–10,28] and vacuum-polarization corrections to the PNC amplitude [9]. The revised value of the PNC amplitude, given in Ref. [9], which is the average of three most accurate calculations [2,3,8] and includes contributions from Breit and vacuum-polarization corrections [7,9] is $E_{\mathrm{PNC}}=0.9057(37)\times10^{-11}ie a_0 Q_W/N$. Combining this value with experiment [1] and our result for β we obtain our final value for the weak charge

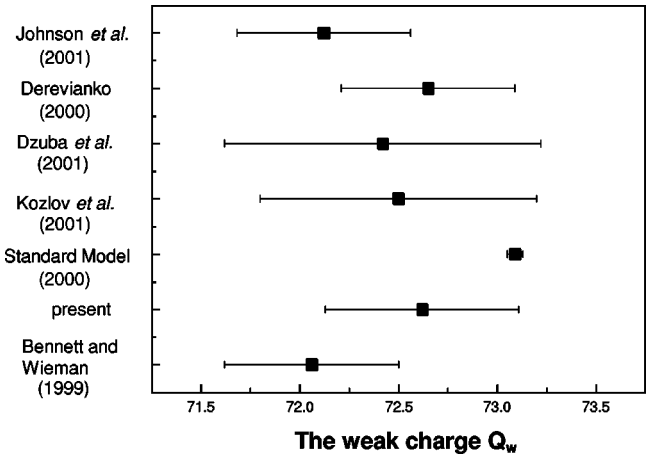

FIG. 2. Comparison of recent determinations of $|Q_W|$.

$$Q_W = -72.65(49),$$

which is in agreement with the value predicted by the standard model [27] to 1σ. In Fig. 2, we compare these results with recent calculations for the weak charge Q_W. The discrepancies between the values of Q_W from Refs. [7–10] result from the differences in the values of PNC amplitude used to obtain the value of the weak charge. The differences between the value of E_{PNC} in Refs. [7–10] are due to different treatments of the Breit interaction, omission of the vacuum-polarization correction in Refs. [7,8,10] and use of the different values for the main part of the PNC amplitude in different works.

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 polarizability α based almost completely on experimentally determined atomic parameters. Including a previous accurate experimental determination of the α/β ratio yields a value for the vector polarizability β 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 [4] and also with recent atomic calculations [7–10] in Fig. 2. Future improvements in this method of estimating Q_W can come from better calculations (or experimental measurements) of the $7s$-$6p$ transition rates.

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