The understanding of the accuracy of \textit{ab initio} calculations in cesium is vital for the analysis of the Cs parity nonconservation (PNC) experiment \cite{1}. In 1999, motivated by a number of recent high-precision experiments, Bennett and Wieman \cite{2} reanalyzed the agreement of theoretical calculations and experimental data for a number of Cs atomic properties and reduced the previous theoretical uncertainty in the PNC amplitude by a factor of two. Utilizing measurements of the tensor transition polarizability, \( \beta \), reported in the same work, they demonstrated a \( 2.5\sigma \) discrepancy between the value of the weak charge \( Q_W \) predicted by the Standard Model and that derived from the Cs PNC experiment. Although several papers (for example, \cite{3,4,5,6,7,8,9}), have addressed this disagreement since 1999, the issue of the accuracy of \textit{ab initio} calculations in Cs continues to be of interest.

In this work, we investigate the radiative properties of Cs \( 6p - nd \) transitions. Although these do not bear directly on PNC experiments done to date, they have been the subject of careful experimental investigation, and thus provide benchmarks for precise comparison of theory and experiment. In particular, there exist two independent measurements of the lifetimes of the \( 5d \) states \cite{10,11}, which do not agree within their stated uncertainties. There also exist several experimental determinations of the \( 6p - 6s \) Stark shifts which allow to infer the values of polarizabilities of the \( 6p \) states \cite{12,13,14}. Here we show that \textit{ab initio} theory can check the mutual consistency of \( 5d \) lifetime and \( 6p \) polarizability data, with an accuracy of about \( 1\% \). We find the lifetime and polarizability results to be inconsistent at this level. Our calculations agree with the experimental values of \( 6p \) polarizabilities, but deviate from both determinations of the \( 5d \) lifetimes. We suggest that further experiments are desirable in order to clarify this issue. In addition, understanding of the accuracy of the \( 5d \) state properties in Cs is germane to the ongoing PNC experiment in iso-electronic \( \text{Ba}^+ \) \cite{15}, since the \( 5d \) state is directly involved in this experiment.

In outline, our approach uses a relativistic all-order method to calculate electric-dipole matrix elements for Cs \( 6p - nd \) transitions for \( n = 5, 6, 7 \). These are used to evaluate \( 5d \) radiative lifetimes and \( 6p \) polarizabilities (for the latter, we also include contributions from all other relevant states). Our calculations of the \( 6p \) scalar polarizabilities, which are in good agreement with experiment, show that they are dominated by contributions from \( 5d - 6p \) transitions. These are the only electric-dipole transitions contributing to the \( 5d \) state lifetimes (as we mention below, the \( 5d - 6s \) electric quadrupole transition rates are negligibly small). Thus, it is possible to check consistency between polarizability and lifetime measurements by deriving \( 5d - 6p \) matrix elements from \( 5d \) lifetime measurements and substituting these values into the \( 6p \) polarizability calculations. For either of the two experimental lifetimes, \cite{10,11} this procedure yields a result that disagrees with directly measured polarizabilities \cite{12,13,14} by several standard deviations.

The particular all-order method used here is the linearized coupled-cluster method which sums infinite sets of many-body perturbation theory terms. We refer the reader to Refs. \cite{16,17,18} for a detailed description of the approach. The wave function of the valence electron \( v \) is represented as an expansion

\[
|\Psi_v\rangle = \left[ 1 + \sum_{m} \rho_{m} \alpha_{m}^{a}\alpha_{a}^{+} + \frac{1}{2} \sum_{mnab} \rho_{mnab} \alpha_{m}^{a}\alpha_{b}^{+}\alpha_{a}\alpha_{b} \right. \\
+ \sum_{m \neq v} \rho_{mv} \alpha_{m}^{a}\alpha_{v}^{+} + \sum_{mna} \rho_{mna} \alpha_{m}^{a}\alpha_{n}^{+}\alpha_{a}\alpha_{v} \\
+ \frac{1}{6} \sum_{mnrvab} \rho_{mnrvab} \alpha_{m}^{a}\alpha_{n}^{+}\alpha_{r}^{+}\alpha_{v}\alpha_{a}\alpha_{b} \right] |\Phi_v\rangle, \quad (1)
\]

where \( |\Phi_v\rangle \) is the lowest-order atomic state function, which is taken to be the \textit{frozen-core} Dirac-Hartree-Fock (DHF) wave function of a state \( v \). This lowest-order atomic wave

Inconsistencies between lifetime and polarizability measurements in Cs

M. S. Safronov\textsuperscript{1} and Charles W. Clark

Electron and Optical Physics Division, National Institute of Standards and Technology, Technology Administration, U.S. Department of Commerce, Gaithersburg, Maryland 20899-8410

(Dated: February 15, 2022)

Electric-dipole matrix elements for \( 6p - nd, n = 5, 6, 7 \) transitions in cesium are calculated using a relativistic all-order method. The resulting matrix elements are used to evaluate \( 5d \) lifetimes and \( 6p \) polarizabilities. The data are compared with experimental lifetime and polarizability measurements made by different groups. Dominance of the \( 6p \) scalar polarizabilities by \( 5d - 6p \) dipole matrix elements facilitates an exacting consistency check of \( 5d \) lifetime and \( 6p \) polarizability data. Values of \( 5d - 6p \) matrix elements obtained from experimental \( 5d \) lifetime data are found to be inconsistent with those inferred from \( 6p \) polarizabilities derived from experimental Stark shift data. Our \textit{ab initio} calculated \( 6p \) polarizabilities agree well with experimental determinations.

PACS numbers: 31.15.Ar, 32.70.Cs, 32.10.Dk, 31.15.Dv
state function can be written as $|\Phi_e\rangle = a_e^\dagger |0_C\rangle$, where $|0_C\rangle$ represent DHF wave function of a closed core. In equation (1), $a_e^\dagger$ and $a_e$ are creation and annihilation operators, respectively. The indices $m$, $n$, and $r$ designate excited states and indices $a$ and $b$ designate core states. The excitation coefficients $\rho_{mn}$, $\rho_{nv}$, $\rho_{anab}$, and $\rho_{mnra}$ are used to calculate matrix elements, which can be expressed in the framework of the all-order method as linear or quadratic functions of the excitation coefficients. We restrict the expansion given by Eq. (1) to single and double (SD) excitations, with partial inclusion of triple excitations. The results obtained using the SD expansion are referred to as SD data throughout the paper, following Ref. [19], to better understand the size of higher-order correlation corrections. Unless stated otherwise, all results in this paper are expressed in the framework of atomic units, a.u., in which unit values are assigned to the elementary charge, $e$, the mass of the electron, $m$, and the reduced Planck constant $\hbar$.

Table I lists the $5d - 6p$ reduced electric-dipole matrix elements in Cs as calculated using the Dirac-Hartree-Fock approximation (DHF), third-order many-body perturbation theory (III), single-double all-order method (SD), single-double all-order method including partial triple contributions (SDpT), and the corresponding scaled values. $R$ is the ratio of the $5d_{3/2} - 6p_{3/2}$ to $5d_{3/2} - 6p_{1/2}$ transition matrix elements. All values are given in atomic units ($e\alpha_0$, where $\alpha_0$ is the Bohr radius).

| Transition | DHF | III | SD | SDsc | SDpT | SDpTsc |
|------------|-----|-----|----|------|------|--------|
| $5d_{3/2} - 6p_{1/2}$ | 8.9784 | 6.9231 | 6.5809 | 7.0634 | 6.9103 | 7.0127 |
| $5d_{3/2} - 6p_{3/2}$ | 4.0625 | 3.1191 | 2.9575 | 3.1871 | 3.1112 | 3.1614 |
| $R$ | 0.4525 | 0.4505 | 0.4494 | 0.4512 | 0.4502 | 0.4508 |
| $5d_{3/2} - 6p_{3/2}$ | 12.1865 | 9.4545 | 9.0238 | 9.6588 | 9.4541 | 9.5906 |

The results are listed in Table I. The experimental energies from [22] are used. The scaled SD values are taken as final values based on the comparison of a number of Rb, Cs, and Fr results [22, 23, 24] with experiment. The theoretical values differ substantially, by over 5%, from the experimental results (we note that that the experimental values from Refs. [10, 11] differ by 4%, which exceeds their stated uncertainties of 0.7% and 1%, respectively). One possible source of such a discrepancy is the contribution of the $5d - 6s$ electric-quadrupole transition to the $5d$ lifetime. Our calculation of this rate, using the all-order method, yields a corresponding Einstein A-coefficient for the $5d_{3/2} - 6s$ transition of 19 Hz, which is only 0.02% of the corresponding electric-dipole A-coefficient of 74 kHz (see Table I). Thus, the contribution of the electric-quadrupole transition to $5d$ lifetime is entirely negligible within the present experimental and theoretical uncertainties.

To clarify such a large disagreement we check the consistency of the experimental $5d$ lifetime measurements with $6p$ polarizability measurements, which involves contributions from the same transitions. First, we use experimental $5d$ lifetimes from [10] to determine the $5d - 6p$ reduced matrix elements. Inverting Eq. (3), we find for the $5d_{5/2} - 6p_{3/2}$ matrix element:

$$\langle 5d_{5/2} | D | 6p_{3/2} \rangle = 9.916(35).$$

To derive the $5d_{3/2} - 6p_{1/2}$ and $5d_{3/2} - 6p_{3/2}$ matrix element, the lifetime of the $5d_{3/2}$ level alone is not sufficient and some assumption about the ratio $R$ of these matrix elements must be made. We use the theoretical SDsc value 0.4512(18) from Table I for the ratio and assume the deviation of other high-precision theoretical results in Table I from this value to be its uncertainty. The variation of the ratio from one approximation to another is far smaller than the variation in the individual matrix elements, thus the uncertainty is rather low (0.4%). The resulting values of the $5d_{3/2} - 6p$ matrix elements are:

$$\langle 5d_{3/2} | D | 6p_{1/2} \rangle = 7.283(60),$$
$$\langle 5d_{3/2} | D | 6p_{3/2} \rangle = 3.286(27)(13).$$

We separated the uncertainties in the $5d_{3/2} - 6p_{3/2}$ matrix elements into contributions from the $5d_{3/2}$ lifetime measurement (0.027) and from the estimation of $R$ (0.013).
TABLE II: The values of Einstein A-coefficients $A_{\omega \nu}$ (in MHz) and final lifetimes (in ns) for 5d$_{5/2}$ and 5d$_{3/2}$ states in Cs. The theoretical values are compared with experimental results from [10] and [11].

| Level     | Transition | $A_{\omega \nu}$ | SD | $A_{\omega \nu}$ | SDpT | SDpT$_{av}$ | Expt. [10] | Expt. [11] |
|-----------|------------|------------------|----|-----------------|------|------------|------------|------------|
| 5d$_{5/2}$ | 5d$_{5/2}$ - 6p$_{3/2}$ | 0.646 | 0.711 | 0.710 | 0.730 | 1281(9)  | 1226(12) |
|           |            | $\tau$          | 1547 | 1350 | 1409 | 1369 |          |            |
| 5d$_{3/2}$ | 5d$_{3/2}$ - 6p$_{3/2}$ | 0.904 | 0.926 | 0.886 | 0.913 | 981   | 909(15) |
|           |            | $\tau$          | 1114 | 966  | 1010 |     |          |            |

The values of corresponding matrix elements $d$ (in a.u.), their sources and uncertainties $\delta d$ (in %) are also given. The $6p$ – $6d$ and $6p$ – $7d$ matrix elements are from the present SDpT all-order calculation.

Combining them, we obtain 3.286(30). The contribution of the uncertainty in $R$ to the uncertainty in the value of 5d$_{3/2}$ – 6p$_{1/2}$ matrix element is negligible.

The scalar $\alpha_0$ and tensor $\alpha_2$ polarizabilities of of an atomic state $v$ are calculated using formulas

$$\alpha_0 = \frac{2}{3(2j_v + 1)} \sum_n \langle n|D||v\rangle^2 \frac{E_n}{E_v},$$

$$\alpha_2 = 4 \left( \frac{5j_v(2j_v - 1)}{6(j_v + 1)(2j_v + 1)(2j_v + 3)} \right)^{1/2} \sum_n (-1)^{j_v + j_n + 1} \left\{ j_v \begin{array}{c} 1 \\ 1 \\ 2 \end{array} j_n \begin{array}{c} 1 \\ 1 \\ 2 \end{array} \right\} \langle n|D||v\rangle^2 \frac{E_n}{E_v},$$

where $D$ is the dipole operator and formula for $\alpha_0$ includes only valence part of the polarizability. The main contributions to the polarizability, $\alpha_{\text{main}}$, come from transitions between $6s$, $7s$, $8s$, $9s$, $6p$, $7p$, $8p$, $9p$, $5d$, $6d$, and $7d$ levels; the remainder, $\alpha_{\text{tail}}$, is calculated from summing over all other valence-excited states of the system (which is confined in a sphere of radius 75 $a_0$). The core contribution to the scalar polarizability $\alpha_{\text{core}} = 15.8 a_0^3$, is taken from [21], where it was calculated in random-phase-approximation (RPA). We note that this value includes the contribution from the valence shell and, therefore, must be compensated by the additional term, $\alpha_{\text{cv}}$, which is equal to the contribution from the valence shell divided by $\langle 2j_v + 1 \rangle$ with an opposite sign. We find that the $\alpha_{\text{cv}}$ term is negligible for $np$ states and very small (below 0.2%) for the $6s$ state. We list the contributions to Cs 6p polarizabilities in Tables III and IV. The corresponding electric-dipole matrix elements $d$, their sources, and uncertainties $\delta d$ are also given. The values for $6s$ – $np$ and $7s$ – $np$ transitions are taken from Ref. [3], where the “best value” set of these matrix elements was compiled for the calculation of the tensor transition polarizability $\beta$. The 6p – 6d and 6p – 7d matrix elements are from the present ab initio SDpT calculation. The values of the 5d – 6p matrix elements are derived from the 5d lifetime experiment [10]. The same data set

TABLE III: Contributions to the 6p$_{3/2}$ and 6p$_{1/2}$ scalar polarizabilities $\alpha_0$ in Cs and their uncertainties $\delta \alpha_0$, in units of $a_0^3$. The values of corresponding matrix elements $d$ (in a.u.), their sources and uncertainties $\delta d$ (in %) are also given.

| $\alpha_0(6p_{1/2})$ | $d$ | $\delta d$ | $\alpha_0$ | $\delta \alpha_0$ |
|----------------------|-----|-----------|-------------|-------------------|
| 6p$_{1/2}$ – 5d$_{5/2}$ | -7.283 | 0.8 | 1168.4 | 18.7 |
| 6p$_{1/2}$ – 6s | -4.489 | 0.3 | 131.9 | 0.3 |
| 6p$_{1/2}$ – 6d$_{5/2}$ | 4.145 | 4.8 | 110.2 | 10.6 |
| 6p$_{1/2}$ – 7s | -4.236 | 0.5 | 20.3 | 0.7 |
| 6p$_{1/2}$ – 8s | -1.026 | 0.6 | 5.9 | 0.1 |
| 6p$_{1/2}$ – 9s | 0.650 | 0.5 | 1.4 | 0.0 |
| $\alpha_{\text{core}}$ | | | 15.8 | 0.3 |
| Total | | | 1404 | 24 |

$\alpha_0(6p_{3/2})$ | $d$ | $\delta d$ | $\alpha_0$ | $\delta \alpha_0$ |
|----------------------|-----|-----------|-------------|-------------------|
| 6p$_{3/2}$ – 5d$_{5/2}$ | 3.286 | 0.9 | 142.7 | 2.6 |
| 6p$_{3/2}$ – 5d$_{3/2}$ | 9.916 | 0.3 | 1255.5 | 8.8 |
| 6p$_{3/2}$ – 6s | -6.324 | 0.1 | 124.7 | 0.2 |
| 6p$_{3/2}$ – 6d$_{5/2}$ | -2.053 | 0.4 | 14.2 | 1.3 |
| 6p$_{3/2}$ – 6d$_{3/2}$ | -6.010 | 4.3 | 121.2 | 10.4 |
| 6p$_{3/2}$ – 7s | -6.473 | 0.5 | 225.3 | 2.3 |
| 6p$_{3/2}$ – 7d$_{5/2}$ | 10.4 | 1.5 | 2.4 | 0.1 |
| 6p$_{3/2}$ – 7d$_{3/2}$ | -2.868 | 1.4 | 21.0 | 0.6 |
| 6p$_{3/2}$ – 8s | -1.462 | 0.6 | 6.2 | 0.1 |
| 6p$_{3/2}$ – 9s | 0.774 | 0.6 | 1.4 | 0.0 |
| $\alpha_{\text{core}}$ | | | 15.8 | 0.3 |
| Total | | | 1720 | 18 |

TABLE IV: Contributions to the 6p$_{3/2}$ tensor polarizability $\alpha_2$ in Cs and their uncertainties $\delta \alpha_2$, in units of $a_0^3$. The values of corresponding matrix elements $d$ (in a.u.), their sources and uncertainties $\delta d$ (in %) also given.

| $\alpha_2(6p_{3/2})$ | $d$ | $\delta d$ | $\alpha_2$ | $\delta \alpha_2$ |
|----------------------|-----|-----------|-------------|-------------------|
| 6p$_{3/2}$ – 5d$_{5/2}$ | 3.286 | 0.9 | 114.2 | 2.1 |
| 6p$_{3/2}$ – 5d$_{3/2}$ | 9.916 | 0.3 | -251.1 | -1.8 |
| 6p$_{3/2}$ – 6s | -6.324 | 0.1 | 124.7 | 0.2 |
| 6p$_{3/2}$ – 6d$_{5/2}$ | -2.053 | 4.6 | 11.4 | 1.0 |
| 6p$_{3/2}$ – 6d$_{3/2}$ | -6.010 | 4.3 | -24.2 | -2.1 |
| 6p$_{3/2}$ – 7s | -6.473 | 0.5 | -225.3 | -2.3 |
| 6p$_{3/2}$ – 7d$_{5/2}$ | -0.969 | 1.5 | 1.9 | 0.1 |
| 6p$_{3/2}$ – 7d$_{3/2}$ | -2.868 | 1.4 | -4.2 | -0.1 |
| 6p$_{3/2}$ – 8s | 1.462 | 0.6 | 6.2 | 0.1 |
| 6p$_{3/2}$ – 9s | 0.774 | 0.6 | 1.4 | 0.0 |
| $\alpha_{\text{core}}$ | | | 7.0 | 2.1 |
| Total | | | 2673 | 4.7 |

$^a$Derived from the experimental 5d$_{3/2}$ lifetime [10] using theoretical ratio of the 6p$_{3/2}$ – 5d$_{3/2}$ and 6p$_{1/2}$ – 5d$_{3/2}$ matrix elements.
TABLE V: Calculated and experimental values of Cs polarizabilities, in $\alpha_0^3$. Calculation (a) uses $5d - 6p$ matrix elements data derived from the 5d lifetime experiment $[^{10}]$ (results of Tables $^{[11]}$ and $^{[14]}$); calculation (b) uses $5d - 6p$ theoretical all-order values (SD scaled data). All other contributions in calculations (a) and (b) are the same.

|                  | Present | Expt. [12] | Expt. [13] | Expt. [14] |
|------------------|---------|------------|------------|------------|
|                  | $\alpha_0(6p_{3/2} - \alpha_0(6s)$ | 1324(18) | 1248 | 1264(13) | 1240.2(24) | 927.35(12) |
|                  | $\alpha_0(6p_{1/2} - \alpha_0(6s)$ | 1006(24) | 936 | 970(9) | 927.35(12) |
|                  | $\alpha_2(6p_{3/2})$ | -267(4.7) | -261.2 | -261(8) | -262.4(15) |

We also calculate the scalar polarizability of the 6s state using the same methods and data set as for the 6p polarizability. The resulting value $\alpha_0(6s) = 398.2(0.9) a_0^3$ and its uncertainty are dominated by contributions of the 6s – 6p matrix element taken from experiment of Ref. $^{[24]}$. We use this result when calculating differences of 6p and 6s polarizabilities. The recent measurement of the ground state polarizability in Cs yielded the value $\alpha_0(6s) = 401.0(0.6) a_0^3$ $^{[27]}$.

We compare the final results for the differences of the 6p and 6s scalar polarizabilities $\alpha_0$ and the tensor polarizability $\alpha_2$ with experiment in Table VI. The results of the above calculation (data from Table $^{[11]}$ $^{[14]}$), where we used 5d – 6p matrix elements derived from the 5d lifetime experiment are listed in column (a). We find that the difference of the 6p$_{3/2}$ and 6s scalar polarizabilities which uses numbers for 5d – 6p matrix elements derived from $^{[11]}$ 5d lifetime measurements $\alpha_0(6p_{3/2} - \alpha_0(6s) = 1322(18) a_0^3$ is inconsistent with both experimental values 1240.2(24) $a_0^3$ $^{[12]}$ and 1264(13) $a_0^3$ $^{[12]}$. The difference with first value, which has the smallest uncertainty is 4.5a and the difference with the second value is 2.6a. The difference of the 6p$_{1/2}$ and 6s scalar polarizabilities which uses numbers for 5d – 6p matrix elements derived from $^{[11]}$ 5d lifetime measurements $\alpha_0(6p_{1/2} - \alpha_0(6s) = 1006(24) a_0^3$ is also inconsistent with the most recent and most precise experimental value 927.35(12) $a_0^3$ $^{[14]}$ by 3.2a. The value for the 6p$_{3/2}$ tensor polarizability $-267.3(4.7) a_0^3$ has much larger uncertainty owing to strong cancellation of the contributions from different transitions, and the difference is 1%. We note that if we were to use another 5d$_{5/2}$ lifetime experiment $^{[11]}$, the discrepancies with polarizability measurements only increase. Thus, neither 5d$_{5/2}$ lifetime experiment $^{[10]}$ $^{[11]}$ is consistent with either $^{[12]}$, $^{[13]}$, or $^{[14]}$ Stark shift measurements within the quoted uncertainties.

We calculate that the experimental value of $\alpha_0(6p_{1/2} - \alpha_0(6s) = 927.35(12) a_0^3$ $^{[14]}$ corresponds to the lifetime of the 5d$_{3/2}$ state $\tau_{5d_{3/2}} = 975(14)$ ns and the experimental value of $\alpha_0(6p_{1/2} - \alpha_0(6s) = 1240.2(24) a_0^3$ $^{[12]}$ corresponds to the lifetime of the 5d$_{5/2}$ state $\tau_{5d_{5/2}} = 1359(18)$ ns. The uncertainties in these lifetime values are dominated by the uncertainties in the values of 6p – 6d transitions and the uncertainty in the contribution $\alpha_{tail}$ as evident from Table $^{[11]}$.

Finally, we repeated the polarization calculation by replacing the 5d – 6p matrix elements derived from the lifetime experiment by our theoretical values (SD$_{ac}$) from Table $^{[11]}$. All other matrix elements and contributions are exactly the same as in the first calculation. The results are listed in column (b) of Table VI. As expected, they are quite different from the previous calculation (a) as our theoretical 5d – 6p matrix elements are substantially different from the values derived from 5d lifetimes. We find that our theoretical polarization data are in good agreement (0.4%-1%) with experimental results.

In conclusion, we find the experimental measurements of 5d lifetime and 6p scalar polarizabilities to be inconsistent within the uncertainties quoted by the experimental groups. Our theoretical calculations are consistent with polarization experiments but not with the lifetime measurements. Thus, further measurements of the properties of 5d and 6p states are of great interest for clarification of this issue and for providing benchmark values for 5d – 6p matrix elements.

[1] C. S. Wood et al., Science 275, 1759 (1997).
[2] S. C. Bennett and C. E. Wieman, Phys. Rev. Lett. 82, 2484 (1999).
[3] A. Derevianko, Phys. Rev. Lett. 85, 1618 (2000).
[4] V. A. Dzuba et al., Phys. Rev. A 63, 044103 (2001).
[5] W. R. Johnson et al., Phys. Rev. Lett. 87, 233001 (2001).
[6] A. A. Vasilyev et al., Phys. Rev. A 66, 020101 (2002).
[7] V. A. Dzuba et al., Phys. Rev. D 66, 076013 (2002).
[8] A. I. Milstein et al., Phys. Rev. Lett. 89, 283003 (2003).
[9] M. Y. Kuchiev and V. V. Flambaum, J. Phys. B 36, R191 (2003).
[10] D. DiBerardino et al., Phys. Rev. A 57, 4204 (1998).
[11] B. Hoeling et al., Opt. Lett. 21, 74 (1996).
[12] L. R. Hunter et al., Phys. Rev. A 37, 3283 (1988).
[13] C. E. Tanner and C. Wieman, Phys. Rev. A 38, 162 (1988).
[14] L. R. Hunter et al., Opt. Commun. 94, 210 (1992).
[15] T. W. Koerber et al., J. Phys. B 36, 637 (2003).
[16] S. A. Blundell et al., Phys. Rev. A 40, 2233 (1989).
[17] S. A. Blundell et al., Phys. Rev. A 43, 3407 (1991).
[18] M. S. Safronova et al., Phys. Rev. A 60, 4476 (1999).
[19] W. R. Johnson et al., At. Data and Nucl. Data Tables 64, 279 (1996).
[20] R. J. Rafac et al., Phys. Rev. A 60, 3648 (1999).
[21] W. R. Johnson et al., At. Data Nucl. Data Tables 28, 333 (1983).
[22] C. E. Moore, Atomic Energy Levels, vol. 35 of Natl. Bur. Stand. Ref. Data Ser. (U.S. GPO, Washington, D.C., 1971).
[23] M. S. Safronova, Ph.D. thesis, University of Notre Dame (2000).
[24] M. S. Safronova et al., arXiv:physics/0307057.
[25] J. M. Amini and H. Gould, Phys. Rev. Lett. 91, 153001 (2003).