Transition properties of a potassium atom

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We report here oscillator strengths, transition rates, branching ratios, and lifetimes due to the allowed transitions in the potassium (K) atom. We evaluate electric dipole ($E1$) amplitudes using an all-order relativistic many-body perturbation method. The obtained results are compared with previously available experimental and theoretical studies. Using the $E1$ matrix elements mentioned above and estimated from the lifetimes of the $4p\ ^2P_{1/2,3/2}$ states, we determine precise values of static and dynamic polarizabilities for the first five low-lying states in the considered atom. The static polarizabilities of the ground and $4p\ ^2P_{1/2,3/2}$ states in the present work are more precise than the available measurements in these states. Only the present work employs relativistic theory to evaluate the polarizabilities in the $3d\ ^2D_{3/2,5/2}$ states for which no experimental results are known with which to compare. We also reexamine "magic wavelengths" for the $4p\ ^2P_{1/2} \rightarrow 4s\ ^2S_{1/2}$ and $4p\ ^2P_{3/2} \rightarrow 4s\ ^2S_{1/2}$ transitions due to the linearly polarized light, which are useful to perform the state-insensitive trapping of K atoms.

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I. INTRODUCTION

The potassium (K) atom is one of the suitable alkali-metal atoms whose two stable isotopes are fermions and one of them is a boson that makes it a special system for cold-atom studies [1,2]. Studies of its transition properties are very useful in manipulating the trapping and cooling of this atom [3–5]. Specifically, to find out its "magic wavelengths" at which the differential Stark shifts of a transition become zero [6], accurate knowledge of the transition properties are necessary [7,8]. Sophisticated experiments are generally performed to measure these magic wavelengths [9,10], however, they can also be determined precisely by evaluating differential polarizabilities using accurate relativistic many-body methods [7,8]. In fact, the K atom is a one-valence electron system, whose properties can be evaluated precisely, which can ultimately act as benchmark tests for the experimental results. Also, a suitable trapping technique of alkali-metal atoms is very much useful in various fields like in the atomic clock, quantum computing, quantum information, and so on experiments. In an optical lattice atomic clock experiment, the atoms are trapped by a periodic potential formed by the applied laser beam [11,12] for which the trapped atoms interact with the oscillating electric field of the trapping beam that causes the shift in the energy levels inside the atoms. But to achieve the maximum stability of an atomic clock, it is very crucial to tune the laser beam at a particular wavelength such that there will be no effects to the internal clock transition frequency [6,10,12]. These effects can be estimated by estimating the dynamic polarizabilities of the atomic states [6–8,10,12].

Accurate values of the transition properties in K are also useful in astrophysical studies [13–15]. K is produced in massive stars after oxygen burning and its isotopes abundances are analyzed in 58 metal-poor stars. In these analyses, the theoretical estimate of ratios of abundances of [K/Fe] with [Fe/H] during the chemical evolution of a galaxy are compared with the observations [16]. There are also various astrophysical objects such as L dwarfs, T dwarfs and irradiated giant planets whose spectra are dominated by absorption lines of many alkali-metal atoms [17–20]. Many telescopes operating at various wavelengths from the ultraviolet (UV) to infrared (IR) range are used to study various spectral properties of astronomical objects, but these IR telescopes require information about the detailed spectroscopic data of atomic systems such as oscillator strengths, transition probabilities, and so on. [21–23]. Also, the identification of new IR lines will be useful in understanding equilibrium temperature, gravity, and abundance for many ultra-cool dwarf stars as well as extra solar giant planets in our galaxy [24]. Therefore it is always very useful to have enough atomic information on new IR atomic lines based on high-precision relativistic calculations, so that they can be used in the analysis of spectral measurements generally carried out by sophisticated IR telescopes.

In this paper, we evaluate electric dipole ($E1$) matrix elements and determine the oscillator strengths, transition probabilities, branching ratios, lifetimes, and polarizabilities of many states of a K atom. Furthermore, we determine the magic wavelengths due to the linearly polarized light for the $4p\ ^2P_{1/2} \rightarrow 4s\ ^2S_{1/2}$ and $4p\ ^2P_{3/2} \rightarrow 4s\ ^2S_{1/2}$ transitions and compare them with the available results.

The rest of the paper is organized as follows. In Secs. II and III, we give the theories of the transition probability due to the allowed transition and linear Stark shift and describe briefly the method of calculation, respectively. In the next section, we present the results and discuss them. Unless stated otherwise, we use atomic units (a.u.) for all physical properties throughout the paper.

II. THEORY AND METHOD OF CALCULATIONS

A. Allowed radiative properties

The transition probability (in s^{-1}) due to the $E1$ matrix element from an atomic state $|\Psi_k\rangle$ to a state $|\Psi_i\rangle$ is given by

$$A_{ki} = \frac{2.0261 \times 10^{-6}}{\lambda_{ki}^3 g_k} S_{ki}, \quad (1)$$

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TABLE I. Results of attachment energies (EAs) in cm^{-1} of different states K using DHF, CCSD, and CCSD(T) methods. The results are compared with the experimental values given in the NIST data table [31] and the difference between the NIST data and results obtained from the CCSD(T) method are quoted as Δ in percent (%).

State	DHF	CCSD	CCSD(T)	NIST [31]	Δ
$4s\ ^2S_{1/2}$	−32370.47	−35016.98	−35016.59	−35009	0.02
$4p\ ^2P_{1/2}$	−21006.47	−22010.66	−22013.81	−22025	0.05
$4p\ ^2P_{3/2}$	−20959.41	−21950.59	−21953.72	−21967	0.06
$5s\ ^2S_{1/2}$	−13407.12	−13982.93	−13982.35	−13983	0.004
$3d\ ^2D_{5/2}$	−12747.04	−13418.72	−13417.33	−13475	0.44
$3d\ ^2D_{3/2}$	−12744.31	−13417.27	−13415.78	−13473	0.41
$5p\ ^2P_{1/2}$	−10012.08	−10303.07	−10304.42	−10308	0.03
$5p\ ^2P_{3/2}$	−9995.88	−10283.56	−10284.89	−10290	0.05
$4d\ ^2D_{5/2}$	−7206.85	−7572.74	−7571.24	−7613	0.53
$4d\ ^2D_{3/2}$	−7205.25	−7571.88	−7570.84	−7612	0.53
$6s\ ^2S_{1/2}$	−7338.12	−7558.71	−7558.34	−7559	0.01
$4f\ ^2F_{5/2}$	−6859.21	−6881.92	−6881.95	−6882	0.00
$4f\ ^2F_{7/2}$	−6859.21	−6881.92	−6881.94	−6882	0.00
$6p\ ^2P_{1/2}$	−5881.48	−6008.02	−6008.75	−6011	0.04
$6p\ ^2P_{3/2}$	−5874.06	−5999.25	−5999.98	−6002	0.03
$5d\ ^2D_{5/2}$	−4596.71	−4800.51	−4799.29	−4825	0.51
$5d\ ^2D_{3/2}$	−4595.80	−4800.46	−4799.23	−4824	0.51
$7s\ ^2S_{1/2}$	−4627.27	−4735.10	−4734.85	−4736	0.02
$5f\ ^2F_{7/2}$	−4390.01	−4403.00	−4403.01	−4403	0.00
$5f\ ^2F_{5/2}$	−4390.01	−4403.00	−4403.01	−4403	0.00
$5g\ ^2G_{7/2}$	−4389.50	−4390.90	−4390.91	−4392	0.02
$5g\ ^2G_{9/2}$	−4389.50	−4390.90	−4390.90	−4392	0.02
$7p\ ^2P_{1/2}$	−3871.88	−3938.52	−3938.99	−3940	0.02
$7p\ ^2P_{3/2}$	−3867.88	−3933.84	−3934.31	−3935	0.02
$6d\ ^2D_{5/2}$	−3177.17	−3298.89	−3298.31	−3314	0.47
$6d\ ^2D_{3/2}$	−3176.62	−3298.69	−3297.97	−3314	0.48
$8s\ ^2S_{1/2}$	−3182.99	−3244.03	−3243.85	−3245	0.03

where $S_{ki} = |\langle\Psi_k||D||\Psi_i\rangle|^2$ is the line strength, λ_{ki} is the wavelength (in cm^{-1}), and $g_k = 2J_k + 1$ is the degeneracy factor for angular momentum J_k of the state $|\Psi_k\rangle$.

The relative intensities of radiative transitions are generally estimated by their oscillator strengths, which for an allowed transition is given by

$$f_{ki} = 1.4992 \times 10^{-24} A_{ki} \frac{g_k}{g_i} \lambda_{ki}^2, \tag{2}$$

which again for the emission and absorption lines are related as

$$g_i f_{ik} = -g_k f_{ki}. \tag{3}$$

The lifetime of the $|\Psi_k\rangle$ state due to the allowed transitions (transition probabilities via other multipoles are neglected for the considered states in the present atom) is estimated by

$$\tau_k = \frac{1}{\sum_i A_{ki}}. \tag{4}$$

The branching ratio of a transition probability from the state $|\Psi_k\rangle$ to a lower state $|\Psi_i\rangle$ is given by

$$\Gamma_{ki} = \frac{A_{ki}}{\sum_l A_{kl}} = \tau_k A_{ki}, \tag{5}$$

where the sum over l represents all possible allowed transitions from $|\Psi_k\rangle$.

B. Linear Stark shift

In the application of an external electric field described by a plane electromagnetic wave of angular frequency ω, the energy level of a state $|\Psi_k\rangle$ of an atom shifted by

$$\Delta E_k(\omega) = -\tfrac{1}{2}\alpha_k(\omega)\mathcal{E}^2, \tag{6}$$

where α_k is the known polarizability of the $|\Psi_k\rangle$ state and $\mathcal{E}$ is the strength of the applied electric field. In a more general form α_k in M_{J_k} quantum-number-independent parameters is expressed as

$$\alpha_k(\omega) = \alpha_v^0(\omega) + \frac{3M_{J_k}^2 - J_k(J_k+1)}{J_k(2J_k-1)}\alpha_k^2(\omega), \tag{7}$$

where the parameters $\alpha_k^0(\omega)$ and $\alpha_k^2(\omega)$ are called as the scalar and tensor polarizabilities, respectively. They are given in terms of the reduced matrix elements of dipole operator D as

$$\alpha_k^0(\omega) = \frac{1}{3(2J_k+1)} \sum_l |\langle J_k\|D\|J_l\rangle|^2 \times \left[\frac{1}{E_l - E_k + \omega} + \frac{1}{E_l - E_k - \omega}\right] \tag{8}$$

TABLE II. Calculated $E1$ matrix elements and their line strengths in a.u. for all the allowed transitions among the states up to $8s\ ^2S_{1/2}$ states.

Transition $k \rightarrow i$		DHF	CCSD(T)	S_{ki}
$4p\ ^2P_{1/2}$	$\rightarrow 4s\ ^2S_{1/2}$	4.554	4.131(20)	17.065(160)
$4p\ ^2P_{3/2}$	$\rightarrow 4s\ ^2S_{1/2}$	6.439	5.841(20)	34.117(234)
$5s\ ^2S_{1/2}$	$\rightarrow 4p\ ^2P_{3/2}$	5.658	5.524(20)	30.515(221)
	$\rightarrow 4p\ ^2P_{1/2}$	3.974	3.876(10)	15.023(77)
$3d\ ^2D_{5/2}$	$\rightarrow 4p\ ^2P_{3/2}$	11.564	10.749(50)	115.54(107)
$3d\ ^2D_{3/2}$	$\rightarrow 4p\ ^2P_{3/2}$	3.855	3.583(20)	12.838(143)
	$\rightarrow 4p\ ^2P_{1/2}$	8.596	7.988(40)	63.808(639)
$5p\ ^2P_{1/2}$	$\rightarrow 3d\ ^2D_{3/2}$	8.198	7.278(130)	52.97(189)
	$\rightarrow 5s\ ^2S_{3/2}$	9.935	9.489(10)	90.041(190)
	$\rightarrow 4s\ ^2S_{5/2}$	0.312	0.282(6)	0.079(0.003)
$5p\ ^2P_{3/2}$	$\rightarrow 3d\ ^2D_{5/2}$	10.955	9.729(150)	94.65(292)
	$\rightarrow 3d\ ^2D_{3/2}$	3.655	3.242(50)	10.511(324)
	$\rightarrow 5s\ ^2S_{1/2}$	14.031	13.399(20)	179.533(536)
	$\rightarrow 4s\ ^2S_{1/2}$	0.456	0.416(6)	0.173(5)
$4d\ ^2D_{5/2}$	$\rightarrow 5p\ ^2P_{3/2}$	23.116	22.842(300)	521.8(137)
	$\rightarrow 4p\ ^2P_{3/2}$	1.003	0.260(5)	0.067(3)
$4d\ ^2D_{3/2}$	$\rightarrow 5p\ ^2P_{3/2}$	7.704	7.613(100)	57.96(152)
	$\rightarrow 5p\ ^2P_{1/2}$	17.173	16.969(240)	287.95(814)
	$\rightarrow 4p\ ^2P_{3/2}$	0.336	0.088(5)	0.008(1)
	$\rightarrow 4p\ ^2P_{1/2}$	0.769	0.220(5)	0.048(2)
$6s\ ^2S_{1/2}$	$\rightarrow 5p\ ^2P_{3/2}$	12.656	12.470(20)	155.50(50)
	$\rightarrow 5p\ ^2P_{1/2}$	8.898	8.760(10)	76.738(175)
	$\rightarrow 4p\ ^2P_{3/2}$	1.309	1.287(10)	1.656(26)
	$\rightarrow 4p\ ^2P_{1/2}$	0.925	0.909(10)	0.826(18)
$4f\ ^2F_{5/2}$	$\rightarrow 4d\ ^2D_{3/2}$	25.230	25.37(146)	643.8(741)
	$\rightarrow 4d\ ^2D_{5/2}$	6.743	6.78(38)	46.0(52)
	$\rightarrow 3d\ ^2D_{3/2}$	14.112	12.41(11)	154.1(27)
	$\rightarrow 3d\ ^2D_{5/2}$	3.769	3.318(30)	11.01(20)
$4f\ ^2F_{7/2}$	$\rightarrow 4d\ ^2D_{5/2}$	30.158	30.34(170)	923(103)
	$\rightarrow 3d\ ^2D_{5/2}$	16.857	14.84(12)	220.3(36)
$6p\ ^2P_{1/2}$	$\rightarrow 6s\ ^2S_{1/2}$	17.195	16.613(20)	275.99(66)
	$\rightarrow 4d\ ^2D_{3/2}$	16.833	14.76(37)	217.9(109)
	$\rightarrow 3d\ ^2D_{3/2}$	1.025	1.037(10)	1.075(21)
	$\rightarrow 5s\ ^2S_{1/2}$	0.873	0.906(10)	0.820(18)
	$\rightarrow 4s\ ^2S_{1/2}$	0.104	0.087(5)	0.008(1)
$6p\ ^2P_{3/2}$	$\rightarrow 6s\ ^2S_{1/2}$	24.273	23.444(20)	549.621(938)
	$\rightarrow 4d\ ^2D_{3/2}$	7.502	6.57(16)	43.20(210)
	$\rightarrow 4d\ ^2D_{5/2}$	22.487	19.734(470)	389.4(185)
	$\rightarrow 3d\ ^2D_{3/2}$	0.462	0.467(3)	0.218(3)
	$\rightarrow 3d\ ^2D_{5/2}$	1.387	1.389(10)	1.954(28)
	$\rightarrow 5s\ ^2S_{1/2}$	1.263	1.312(6)	1.721(15)
	$\rightarrow 4s\ ^2S_{1/2}$	0.155	0.132(6)	0.017(2)
$5d\ ^2D_{5/2}$	$\rightarrow 6p\ ^2P_{3/2}$	38.150	38.72(74)	1499(57)
	$\rightarrow 4f\ ^2F_{7/2}$	5.803	8.42(10)	70.90(17)
	$\rightarrow 4f\ ^2F_{5/2}$	1.297	1.883(20)	3.546(75)
	$\rightarrow 5p\ ^2P_{3/2}$	2.690	1.461(5)	2.134(15)
	$\rightarrow 4p\ ^2P_{3/2}$	0.122	0.374(5)	0.141(4)
$5d\ ^2D_{3/2}$	$\rightarrow 6p\ ^2P_{3/2}$	12.712	12.90(26)	166.5(67)
	$\rightarrow 6p\ ^2P_{1/2}$	28.333	28.76(57)	827.3(328)
	$\rightarrow 4f\ ^2F_{5/2}$	4.844	7.034(90)	49.48(127)
	$\rightarrow 5p\ ^2P_{3/2}$	0.899	0.490(5)	0.240(5)
	$\rightarrow 5p\ ^2P_{1/2}$	2.042	1.138(10)	1.295(23)
	$\rightarrow 4p\ ^2P_{3/2}$	0.042	0.124(5)	0.015(1)
	$\rightarrow 4p\ ^2P_{1/2}$	0.105	0.264(5)	0.071(3)
$7s\ ^2S_{1/2}$	$\rightarrow 6p\ ^2P_{3/2}$	22.032	21.828(20)	476.46(87)
	$\rightarrow 6p\ ^2P_{1/2}$	15.496	15.342(10)	235.38(31)
	$\rightarrow 5p\ ^2P_{3/2}$	2.624	2.563(10)	6.569(51)
	$\rightarrow 5p\ ^2P_{1/2}$	1.857	1.814(10)	3.291(37)
	$\rightarrow 4p\ ^2P_{3/2}$	0.686	0.677(6)	0.458(8)
	$\rightarrow 4p\ ^2P_{1/2}$	0.485	0.479(5)	0.229(5)
$5f\ ^2F_{7/2}$	$\rightarrow 5d\ ^2D_{5/2}$	56.649	56.34(331)	3174(373)
	$\rightarrow 4d\ ^2D_{5/2}$	20.464	15.84(20)	250.84(63)
	$\rightarrow 3d\ ^2D_{5/2}$	6.131	5.913(40)	34.963(473)
$5f\ ^2F_{5/2}$	$\rightarrow 5d\ ^2D_{3/2}$	47.394	47.12(289)	2220(272)
	$\rightarrow 5d\ ^2D_{5/2}$	12.667	12.60(74)	158.7(186)
	$\rightarrow 4d\ ^2D_{3/2}$	17.142	13.24(17)	175.2(45)
	$\rightarrow 4d\ ^2D_{5/2}$	4.576	3.541(40)	12.54(28)
	$\rightarrow 3d\ ^2D_{3/2}$	5.123	4.949(30)	24.49(30)
	$\rightarrow 3d\ ^2D_{5/2}$	1.371	1.322(10)	1.748(26)
$5g\ ^2G_{7/2}$	$\rightarrow 5f\ ^2F_{5/2}$	41.688	41.79(418)	1746(349)
	$\rightarrow 5f\ ^2F_{7/2}$	8.019	8.04(80)	64.7(128)
	$\rightarrow 4f\ ^2F_{7/2}$	6.313	6.261(10)	39.20(12)
	$\rightarrow 4f\ ^2F_{5/2}$	32.803	32.53(16)	1058.4(104)
$5g\ ^2G_{9/2}$	$\rightarrow 5f\ ^2F_{7/2}$	47.441	47.58(480)	2264(457)
	$\rightarrow 4f\ ^2F_{7/2}$	37.348	37.040(20)	1372(15)
$7p\ ^2P_{1/2}$	$\rightarrow 7s\ ^2S_{1/2}$	26.351	25.595(20)	655.1(10)
	$\rightarrow 5d\ ^2D_{3/2}$	27.927	24.46(68)	598(33)
	$\rightarrow 6s\ ^2S_{1/2}$	1.658	1.735(10)	3.010(34)
	$\rightarrow 4d\ ^2D_{3/2}$	2.313	2.424(30)	5.876(145)
	$\rightarrow 3d\ ^2D_{3/2}$	0.484	0.500(6)	0.250(6)
	$\rightarrow 5s\ ^2S_{1/2}$	0.320	0.341(5)	0.460(3)
	$\rightarrow 4s\ ^2S_{1/2}$	0.053	0.041(5)	0.0020(4)
$7p\ ^2P_{3/2}$	$\rightarrow 7s\ ^2S_{1/2}$	37.187	36.107(20)	1303.7(14)
	$\rightarrow 5d\ ^2D_{3/2}$	12.445	10.89(36)	118.50(784)
	$\rightarrow 5d\ ^2D_{5/2}$	37.305	32.69(90)	1068.5(588)
	$\rightarrow 6s\ ^2S_{1/2}$	2.389	2.501(10)	6.255(50)
	$\rightarrow 4d\ ^2D_{3/2}$	1.041	1.089(10)	1.186(22)
	$\rightarrow 4d\ ^2D_{5/2}$	3.126	3.259(40)	10.62(26)
	$\rightarrow 3d\ ^2D_{3/2}$	0.218	0.225(5)	0.051(2)
	$\rightarrow 3d\ ^2D_{5/2}$	0.656	0.676(10)	0.587(13)
	$\rightarrow 5s\ ^2S_{1/2}$	0.469	0.499(5)	0.249(5)
	$\rightarrow 4s\ ^2S_{1/2}$	0.081	0.064(5)	0.004(1)
$6d\ ^2D_{5/2}$	$\rightarrow 7p\ ^2P_{3/2}$	56.587	58.30(141)	3399(164)
	$\rightarrow 5f\ ^2F_{5/2}$	2.843	4.070(60)	16.57(49)
	$\rightarrow 5f\ ^2F_{7/2}$	12.713	18.20(26)	331.39(946)
	$\rightarrow 6p\ ^2P_{3/2}$	4.838	2.993(20)	8.958(120)
	$\rightarrow 4f\ ^2F_{5/2}$	0.416	0.541(5)	0.293(5)
	$\rightarrow 4f\ ^2F_{7/2}$	1.862	2.421(10)	5.861(48)
	$\rightarrow 5p\ ^2P_{3/2}$	0.818	0.045(5)	0.0020(4)
	$\rightarrow 4p\ ^2P_{3/2}$	0.053	0.404(5)	0.163(4)
$6d\ ^2D_{3/2}$	$\rightarrow 7p\ ^2P_{3/2}$	18.854	19.43(48)	377.6(186)
	$\rightarrow 7p\ ^2P_{1/2}$	42.018	43.31(104)	1876(90)
	$\rightarrow 5f\ ^2F_{5/2}$	10.614	15.22(23)	232(7)
	$\rightarrow 6p\ ^2P_{3/2}$	1.617	1.002(5)	1.004(10)
	$\rightarrow 6p\ ^2P_{1/2}$	3.661	2.304(20)	5.308(92)
	$\rightarrow 4f\ ^2F_{5/2}$	1.555	2.029(20)	4.117(81)
	$\rightarrow 5p\ ^2P_{3/2}$	0.275	0.015(5)	0.0002(1)
	$\rightarrow 5p\ ^2P_{1/2}$	0.6346	0.059(5)	0.003(1)
	$\rightarrow 4p\ ^2D_{3/2}$	0.017	0.135(5)	0.018(1)
	$\rightarrow 4p\ ^2P_{1/2}$	0.031	0.293(5)	0.086(3)
$8s\ ^2S_{1/2}$	$\rightarrow 7p\ ^2P_{3/2}$	33.839	33.63(30)	1130.6(202)
	$\rightarrow 7p\ ^2P_{1/2}$	23.808	23.641(20)	558.90(95)
	$\rightarrow 6p\ ^2P_{3/2}$	4.308	4.207(6)	17.699(50)
	$\rightarrow 6p\ ^2P_{1/2}$	3.051	2.982(6)	8.892(36)

TABLE II. (*Continued.*)

Transition $k \rightarrow i$		DHF	CCSD(T)	S_{ki}
	$\rightarrow 5p\ ^2P_{3/2}$	1.331	1.310(6)	1.716(16)
	$\rightarrow 5p\ ^2P_{1/2}$	0.943	0.918(6)	0.843(11)
	$\rightarrow 4p\ ^2P_{3/2}$	0.452	0.447(5)	0.211(4)
	$\rightarrow 4p\ ^2P_{1/2}$	0.321	0.316(5)	0.111(3)
$6f\ ^2F_{7/2}$	$\rightarrow 3d\ ^2D_{5/2}$	3.479	3.455(30)	11.94(21)
$6f\ ^2F_{5/2}$	$\rightarrow 3d\ ^2D_{5/2}$	0.778	0.777(10)	0.006(16)
	$\rightarrow 3d\ ^2D_{3/2}$	2.910	2.908(30)	8.456(174)
$8p\ ^2P_{1/2}$	$\rightarrow 3d\ ^2D_{3/2}$	0.307	0.321(5)	0.103(3)
	$\rightarrow 4s\ ^2S_{1/2}$	0.033	0.023(3)	0.0010(1)
$8p\ ^2P_{3/2}$	$\rightarrow 3d\ ^2D_{5/2}$	0.415	0.432(5)	0.187(4)
	$\rightarrow 3d\ ^2D_{3/2}$	0.138	0.144(4)	0.021(1)
	$\rightarrow 4s\ ^2S_{1/2}$	0.051	0.038(3)	0.0014(2)
$7d\ ^2D_{5/2}$	$\rightarrow 4p\ ^2P_{3/2}$	0.093	0.356(5)	0.127(4)
$7d\ ^2D_{3/2}$	$\rightarrow 4p\ ^2P_{3/2}$	0.031	0.119(3)	0.014(1)
	$\rightarrow 4p\ ^2P_{1/2}$	0.062	0.261(4)	0.068(2)
$9s\ ^2S_{1/2}$	$\rightarrow 4p\ ^2P_{3/2}$	0.322	0.317(5)	0.100(3)
	$\rightarrow 4p\ ^2P_{1/2}$	0.228	0.225(3)	0.051(1)
$7f\ ^2F_{7/2}$	$\rightarrow 3d\ ^3D_{5/2}$	2.347	2.386(20)	5.693(95)
$7f\ ^2F_{5/2}$	$\rightarrow 3d\ ^3D_{5/2}$	0.526	0.535(10)	0.286(10)
	$\rightarrow 3d\ ^3D_{3/2}$	1.968	2.002(20)	4.008(80)
$9p\ ^2P_{1/2}$	$\rightarrow 3d\ ^2D_{3/2}$	0.246	0.250(4)	0.062(2)
	$\rightarrow 4s\ ^2S_{1/2}$	0.026	0.016(3)	0.0002(1)
$9p\ ^2P_{3/2}$	$\rightarrow 3d\ ^2D_{5/2}$	0.334	0.339(5)	0.115(3)
	$\rightarrow 3d\ ^2D_{3/2}$	0.111	0.113(3)	0.013(1)
	$\rightarrow 4s\ ^2S_{1/2}$	0.041	0.027(3)	0.0010(2)
$8d\ ^2D_{5/2}$	$\rightarrow 4p\ ^2P_{3/2}$	0.096	0.286(5)	0.082(3)
$8d\ ^2D_{3/2}$	$\rightarrow 4p\ ^2P_{3/2}$	0.033	0.101(3)	0.010(1)
	$\rightarrow 4p\ ^2P_{1/2}$	0.071	0.221(4)	0.049(2)
$10s\ ^2S_{1/2}$	$\rightarrow 4p\ ^2P_{3/2}$	0.258	0.242(5)	0.058(2)
	$\rightarrow 4p\ ^2P_{1/2}$	0.182	0.171(3)	0.029(1)

and

$$\alpha_k^2(\omega) = -2\sqrt{\frac{5J_k(2J_k-1)}{6(J_k+1)(2J_k+1)(2J_k+3)}} \times \sum_l \begin{Bmatrix} J_k & 2 & J_k \\ 1 & J_l & 1 \end{Bmatrix} (-1)^{J_k+J_l+1} |\langle J_k \| D \| J_l \rangle|^2 \times \left[\frac{1}{E_l - E_k + \omega} + \frac{1}{E_l - E_k - \omega}\right], \quad (9)$$

for all the allowed states $|\Psi_l\rangle$ from $|\Psi_k\rangle$.

Magic wavelengths of a transition can be determined by evaluating Stark shifts for both the associated states and finding out the ω values where the shifts are equal for these states. Owing to the fact that these effects are directly proportional to the differential polarizabilities of the associated states, magic wavelengths finally correspond to the finding values of ω that produce null differential dynamic polarizabilities of the transition.

C. Method of calculations

In the coupled-cluster ansatz, we express the atomic states with a closed core and one valence orbital as

$$|\Psi_k\rangle = e^T\{1 + S_k\}|\Phi_k\rangle, \quad (10)$$

where the initial state is constructed as $|\Phi_k\rangle = a_k^\dagger|\Phi_0\rangle$ where $|\Phi_0\rangle$ is the mean-field wave function for the closed core obtained by the Dirac-Hartree-Fock (DHF) method and $a_k^\dagger$ represents appending the valence orbital denoted by k. Here T and S_k are the excitation operators that account for the correlation effects to all orders by exciting electrons from the core orbitals and valence along with core orbitals from the corresponding DHF states, respectively. In the present calculations, only singly and doubly excited configurations are generated using both the T and S_k operators which is known as coupled-cluster singles and doubles (CCSD method) approximation; also, important correlation effects involving the valence electron are accounted for through the S_k operator perturbatively in the CCSD(T) method approximation. Discussions on these approaches can be found more elaborately in Ref. [25]. The details of the single-particle construction and size of the active space for the calculation of atomic wave functions for the considered atom are described in our previous work [26].

Following the approach given in Ref. [27], we evaluate the polarizabilities of the considered states in the K atom by expressing different contributions as

$$\alpha_k^\lambda = \alpha_k^\lambda(c) + \alpha_k^\lambda(vc) + \alpha_k^\lambda(v), \quad (11)$$

where superscript λ with values 0 and 1 corresponds to the scalar and tensor polarizabilities, respectively, and notations c, vc, and v in the parentheses represent the correlation contributions from the core, core-valence, and valence orbitals, respectively. It has to be noted that the core contribution to the tensor polarizability is zero.

III. RESULTS AND DISCUSSION

We present below first the electron attachment energies (EAs) of valence electrons from the states having different valence orbitals with the closed core $[3p^6]$. Then we present $E1$ matrix elements and use them with the experimental energies and we determine transition probabilities and other related transition properties. Also, we evaluate $\alpha_k^\lambda(v)$ for various states from these $E1$ matrix elements and experimental energies. Other $\alpha_k^\lambda(c)$ and $\alpha_k^\lambda(vc)$ contributions to α_k, which are found to be smaller in magnitude compared to $\alpha_k^\lambda(v)$, are evaluated using a third-order many-body perturbation theory [MBPT(3) method] following similar approaches as employed in Refs. [28–30]. Using the dynamic polarizabilities, we verify the "magic wavelengths" in the $4p\ ^2P_{1/2} \rightarrow 4s\ ^2S_{1/2}$ and $4p\ ^2P_{3/2} \rightarrow 4s\ ^S_{1/2}$ transitions and compare them with previously reported values.

A. Electron attachment energies

In Table I, we present EAs corresponding to many states using our DHF, CCSD, and CCSD(T) methods and they are compared with the corresponding values given by the National Institute of Science and Technology (NIST) [31]. We consider the results obtained from the CCSD(T) method as the final calculated results. In the table, we also present the differences between the results from the CCSD(T) method and quoted by NIST in percent as Δ. As seen in the table, all the calculated results are sub-one-percent accurate. Among all

TABLE III. Wavelengths (λ in Å), transition rates (A in s^{-1}), oscillator strengths (f), and branching ratios (Γ) from different works. The values given in square brackets represent the power of 10.

Upper state (f)	Lower state (i)	λ_{ki}	A_{ki}		f_{ki}		Γ_{ki}
			Others	Present	Others	Present	Present
$4p\ ^2P_{1/2}$	$\rightarrow 4s\ ^2S_{1/2}$	7701.08		3.785[7]	2.93[−1][a]	3.34[−1]	1.0
$4p\ ^2P_{3/2}$	$\rightarrow 4s\ ^2S_{1/2}$	7666.99		3.834[7]	5.88[−1][a]	6.72[−1]	∼1.0
$5s\ ^2S_{1/2}$	$\rightarrow 4p\ ^2P_{3/2}$	12525.58	1.58[7][b]	1.573[7]	1.72[−1][a], 1.86[−1][b]	1.84[−1]	0.665
	$\rightarrow 4p\ ^2P_{1/2}$	12435.70	7.95[6][b]	7.914[6]	1.71[−1][a], 1.84[−1][b]	1.82[−1]	0.335
$3d\ ^2D_{5/2}$	$\rightarrow 4p\ ^2P_{3/2}$	11776.10	2.38[7][b]	2.390[7]	7.69[−1][a], 7.42[−1][b]	7.40[−1]	∼ 1.0
$3d\ ^2D_{3/2}$	$\rightarrow 4p\ ^2P_{3/2}$	11772.89	3.97[6][b]	3.985[6]	8.54[−1][a], 8.24[−1][b]	8.20[−1]	0.165
	$\rightarrow 4p\ ^2P_{1/2}$	11693.44	2.01[7][b]	2.021[7]	8.55[−1][a], 8.25[−1][b]	8.24[−1]	0.835
$5p\ ^2P_{1/2}$	$\rightarrow 3d\ ^2D_{3/2}$	31601.63	1.65[6][b]	1.700[6]	1.31[−1][a], 1.23[−1][b]	1.26[−1]	0.228
	$\rightarrow 5s\ ^2S_{1/2}$	27212.13		4.535[6]	4.87[−1][a]	4.99[−1]	0.608
	$\rightarrow 4s\ ^2S_{1/2}$	4048.36		1.214[6]	2.48[−3][a]	2.96[−3]	0.163
$5p\ ^2P_{3/2}$	$\rightarrow 3d\ ^2D_{3/2}$	31392.64	1.66[5][b]	1.717[5]	2.46[−2][b]	2.52[−2]	0.022
	$\rightarrow 3d\ ^2D_{5/2}$	31415.32	1.50[6][b]	1.550[6]	1.48[−1][b]	1.52[−1]	0.203
	$\rightarrow 5s\ ^2S_{1/2}$	27073.93		4.582[6]	9.76[−1][a]	1.001	0.601
	$\rightarrow 4s\ ^2S_{1/2}$	4045.28		1.324[6]	5.40[−3][a]	6.48[−3]	0.174
$4d\ ^2D_{5/2}$	$\rightarrow 5p\ ^2P_{3/2}$	37356.22		3.380[6]	1.09[a]	1.054	0.981
	$\rightarrow 4p\ ^2P_{3/2}$	6966.61	1.37[4][b]	6.751[4]	2.56[−4][a], 1.49[−4][b]	7.324[−4]	0.019
$4d\ ^2D_{3/2}$	$\rightarrow 5p\ ^2P_{3/2}$	37341.30		5.638[5]	1.22[−1][a]	1.17[−1]	0.161
	$\rightarrow 5p\ ^2P_{1/2}$	37081.53		2.860[6]	1.22[−1][a]	1.17[−1]	0.815
	$\rightarrow 4p\ ^2P_{3/2}$	6966.09	2.40[3][b]	1.160[4]	2.96[−5][a], 1.75[−5][b]	8.39[−5]	0.003
	$\rightarrow 4p\ ^2P_{1/2}$	6938.20	1.90[4][b]	7.340[4]	4.19[−4][a], 2.75[−4][b]	1.05[−3]	0.021
$6s\ ^2S_{1/2}$	$\rightarrow 5p\ ^2P_{3/2}$	36622.39		3.207[6]	3.17[−1][a]	3.20[−1]	0.259
	$\rightarrow 5p\ ^2P_{1/2}$	36372.50		1.615[6]	3.15[−1][a]	3.18[−1]	0.131
	$\rightarrow 4p\ ^2P_{3/2}$	6940.68	4.95[6][b]	5.019[6]	1.79[−2][b]	1.80[−2]	0.406
	$\rightarrow 4p\ ^2P_{1/2}$	6912.99	2.50[6][b]	2.534[6]	1.71[−2][a], 1.79[−2][b]	1.80[−2]	0.205
$4f\ ^2F_{5/2}$	$\rightarrow 4d\ ^2D_{3/2}$	137040.74		8.457[4]	3.70[−1][a]	3.54[−1]	0.005
	$\rightarrow 4d\ ^2D_{5/2}$	136841.40		6.063[3]	1.76[−2][a]	1.69[−2]	0.0004
	$\rightarrow 3d\ ^2D_{3/2}$	15172.52	1.45[7][b]	1.490[7]	8.24[−1][a], 7.51[−1][b]	7.66[−1]	0.928
	$\rightarrow 3d\ ^2D_{5/2}$	15167.21	1.04[6][b]	1.065[6]	3.92[−2][a], 3.57[−2][b]	3.65[−2]	0.066
$4f\ ^2F_{7/2}$	$\rightarrow 4d\ ^2D_{5/2}$	136840.10		9.097[4]	3.53[−1][a]	3.38[−1]	0.006
	$\rightarrow 3d\ ^2D_{5/2}$	15167.21	1.55[7][b]	1.599[7]	7.85[−1][a], 7.15[−1][b]	7.31[−1]	0.994
$6p\ ^2P_{1/2}$	$\rightarrow 6s\ ^2S_{1/2}$	64576.12		1.038[6]	6.41[−1][a]	6.45[−1]	0.345
	$\rightarrow 4d\ ^2D_{3/2}$	62456.16		9.061[5]	2.61[−1][a]	2.63[−1]	0.301
	$\rightarrow 3d\ ^2D_{3/2}$	13400.73	4.47[5][b]	4.527[5]	6.48[−3][a], 6.02[−3][b]	6.06[−3]	0.151
	$\rightarrow 5s\ ^2S_{1/2}$	12542.77		4.214[5]	9.42[−3][a]	9.88[−3]	0.140
	$\rightarrow 4s\ ^2S_{1/2}$	3448.36		1.871[5]	2.51[−4][a]	3.31[−4]	0.062
$6p\ ^2P_{3/2}$	$\rightarrow 6s\ ^2S_{1/2}$	64226.09		1.051[6]	1.28[a]	1.292	0.341
	$\rightarrow 4d\ ^2D_{3/2}$	62128.66		9.125[4]	5.21[−2][a]	5.25[−2]	0.030
	$\rightarrow 4d\ ^2D_{5/2}$	62087.39		8.242[5]	3.12[−1][a]	3.16[−1]	0.267
	$\rightarrow 3d\ ^2D_{3/2}$	13385.59	4.54[4][b]	4.606[4]	1.31[−3][a], 1.22[−3][b]	1.23[−3]	0.149
	$\rightarrow 3d\ ^2D_{5/2}$	13381.45	4.54[4][b]	4.131[5]	7.88[−3][a], 7.36[−3][b]	7.35[−3]	0.134
	$\rightarrow 5s\ ^2S_{1/2}$	12529.51		4.433[5]	1.98[−2][a]	2.07[−2]	0.144
	$\rightarrow 4s\ ^2S_{1/2}$	3447.36		2.154[5]	5.91[−4][a]	7.63[−4]	0.070
$5d\ ^2D_{5/2}$	$\rightarrow 6p\ ^2P_{3/2}$	84923.52		8.267[5]	1.380[a]	1.332	0.590
	$\rightarrow 4f\ ^2F_{7/2}$	48605.27		2.085[5]	6.10[−2][a]	5.50[−2]	0.150
	$\rightarrow 4f\ ^2F_{5/2}$	48605.27		1.043[4]	4.07[−3][a]	3.67[−3]	0.007
	$\rightarrow 5p\ ^2P_{3/2}$	18297.93		1.176[5]	6.10[−3][a]	8.80[−3]	0.084
	$\rightarrow 4p\ ^2P_{3/2}$	5833.51	3.71[5][b]	2.379[5]	2.47[−3][a], 2.84[−3][b]	1.81[−3]	0.170
$5d\ ^2D_{3/2}$	$\rightarrow 6p\ ^2P_{3/2}$	84886.93		1.379[5]	1.53[−1][a]	1.48[−1]	0.098
	$\rightarrow 6p\ ^2P_{1/2}$	84283.10		6.999[5]	1.530[a]	1.482	0.510
	$\rightarrow 4f\ ^2F_{5/2}$	48593.28		2.184[5]	5.69[−2][a]	5.12[−2]	0.156
	$\rightarrow 5p\ ^2P_{3/2}$	18296.22		1.986[4]	6.83[−4][a]	9.90[−4]	0.014
	$\rightarrow 5p\ ^2P_{1/2}$	18233.65		1.082[5]	7.49[−3][a]	1.07[−2]	0.077
	$\rightarrow 4p\ ^2P_{3/2}$	5833.33	6.13[4][b]	3.924[4]	2.72[−4][a], 3.13[−4][b]	1.99[−4]	0.028
	$\rightarrow 4p\ ^2P_{1/2}$	5813.76	2.86[5][b]	1.796[5]	2.52[−3][a], 2.90[−3][b]	1.81[−3]	0.128
$7s\ ^2S_{1/2}$	$\rightarrow 6p\ ^2P_{3/2}$	78955.34		9.807[5]	4.56[−1][a]	4.55[−1]	0.145
	$\rightarrow 6p\ ^2P_{1/2}$	78432.68		4.942[5]	4.54[−1][a]	4.53[−1]	0.073

TABLE III. (*Continued*.)

Upper state (f)	Lower state (i)	λ_{ki}	A_{ki}		f_{ki}		Γ_{ki}
			Others	Present	Others	Present	Present
	$\rightarrow 5p\ ^2P_{3/2}$	18004.69		1.140[6]	2.70[−2][a]	2.75[−2]	0.168
	$\rightarrow 5p\ ^2P_{1/2}$	17944.11		5.770[5]	2.71[−2][a]	2.77[−2]	0.085
	$\rightarrow 4p\ ^2P_{3/2}$	5803.37	2.35[6][b]	2.375[6]	5.68[−3][a], 5.93[−3][b]	5.96[−3]	0.351
	$\rightarrow 4p\ ^2P_{1/2}$	5784.00	1.19[6][b]	1.201[6]	5.71[−3][a], 5.95[−3][b]	5.99[−3]	0.177
$5f\ ^2F_{7/2}$	$\rightarrow 5d\ ^2D_{5/2}$	237255.75		6.019[4]	6.87[−1][a]	6.73[−1]	0.007
	$\rightarrow 4d\ ^2D_{5/2}$	31156.02		2.101[6]	3.93[−1][a]	4.05[−1]	0.239
	$\rightarrow 3d\ ^2D_{5/2}$	11022.87	6.54[6][b]	6.612[6]	1.76[−1][a], 1.59[−1][b]	1.60[−1]	0.754
$5f\ ^2F_{5/2}$	$\rightarrow 5d\ ^2D_{3/2}$	237539.62		5.593[4]	7.20[−1][a]	7.05[−1]	0.006
	$\rightarrow 5d\ ^2D_{5/2}$	237255.75		4.012[3]	3.43[−2][a]	3.36[−2]	0.0004
	$\rightarrow 4d\ ^2D_{3/2}$	31166.41		1.954[6]	4.13[−1][a]	4.24[−1]	0.223
	$\rightarrow 4d\ ^2D_{5/2}$	31156.02		1.400[5]	1.97[−2][a]	2.02[−2]	0.016
	$\rightarrow 3d\ ^2D_{3/2}$	11025.67	6.10[6][b]	6.171[6]	1.84[−1][a], 1.67[−1][b]	1.68[−1]	0.734
	$\rightarrow 3d\ ^2D_{5/2}$	11022.87	4.36[5][b]	4.406[5]	8.78[−3][a], 7.94[−3][b]	7.98[−3]	0.050
$5g\ ^2G_{7/2}$	$\rightarrow 5f\ ^2F_{5/2}$	9451795.84		0.524		9.30[−3]	∼0
	$\rightarrow 5f\ ^2F_{7/2}$	9451795.84		0.020		2.58[−4]	∼0
	$\rightarrow 4f\ ^2F_{7/2}$	40169.35		1.532[5]	3.70[−2][a]	3.68[−2]	0.036
	$\rightarrow 4f\ ^2F_{5/2}$	40169.35		4.136[6]	1.340[a]	1.326	0.964
$5g\ ^2G_{9/2}$	$\rightarrow 5f\ ^2F_{7/2}$	9451795.84		0.543		9.04[−3]	∼0
	$\rightarrow 4f\ ^2F_{7/2}$	40169.35		4.289[6]	1.300[a]	1.289	1.000
$7p\ ^2P_{1/2}$	$\rightarrow 7s\ ^2S_{1/2}$	125683.20		3.343[5]	7.87[−1][a]	7.87[−1]	0.211
	$\rightarrow 5d\ ^2D_{3/2}$	113102.67		4.187[5]	3.88[−1][a]	3.99[−1]	0.265
	$\rightarrow 6s\ ^2S_{1/2}$	27630.49		1.446[5]	1.60[−2][a]	1.64[−2]	0.091
	$\rightarrow 4d\ ^2D_{3/2}$	27234.95		2.946[5]	1.70[−2][a]	1.63[−2]	0.186
	$\rightarrow 3d\ ^2D_{3/2}$	10489.97	2.17[5][b]	2.194[5]	1.93[−3][a], 1.79[−3][b]	1.80[−3]	0.139
	$\rightarrow 5s\ ^2S_{1/2}$	9956.84		1.193[5]	1.66[−3][a]	1.76[−3]	0.075
	$\rightarrow 4s\ ^2S_{1/2}$	3218.55		5.108[4]	5.37[−5][a]	7.88[−5]	0.003
$7p\ ^2P_{3/2}$	$\rightarrow 7s\ ^2S_{1/2}$	124976.36		3.383[5]	1.570[a]	1.575	0.201
	$\rightarrow 5d\ ^2D_{3/2}$	112529.94		4.212[4]	7.74[−2][a]	7.95[−2]	0.025
	$\rightarrow 5d\ ^2D_{5/2}$	112466.19		3.805[5]	4.64[−1][a]	4.78[−1]	0.227
	$\rightarrow 6s\ ^2S_{1/2}$	27596.18		1.508[5]	3.30[−2][a]	3.42[−2]	0.090
	$\rightarrow 4d\ ^2D_{3/2}$	27201.61		2.984[4]	3.44[−3][a]	3.29[−3]	0.018
	$\rightarrow 4d\ ^2D_{5/2}$	27193.69		2.675[5]	2.06[−2][a]	1.96[−2]	0.159
	$\rightarrow 3d\ ^2D_{3/2}$	10485.02	2.21[4][b]	2.225[4]	3.92[−4][a], 3.64[−4][b]	3.64[−4]	0.013
	$\rightarrow 3d\ ^2D_{5/2}$	10482.49	1.99[4][b]	2.580[5]	2.35[−3][a], 2.18[−3][b]	2.19[−3]	0.154
	$\rightarrow 5s\ ^2S_{1/2}$	9952.38		1.279[5]	3.57[−3][a]	3.78[−3]	0.076
	$\rightarrow 4s\ ^2S_{1/2}$	3218.08		6.187[4]	1.36[−4][a]	1.92[−4]	0.037
$6d\ ^2D_{5/2}$	$\rightarrow 7p\ ^2P_{3/2}$	160990.92		2.755[5]		1.594	0.293
	$\rightarrow 5f\ ^2F_{5/2}$	91812.99		7.227[3]		9.08[−3]	0.008
	$\rightarrow 5f\ ^2F_{7/2}$	91812.99		1.446[5]		1.36[−1]	0.154
	$\rightarrow 6p\ ^2P_{3/2}$	37199.74		5.876[4]		1.82[−2]	0.063
	$\rightarrow 4f\ ^2F_{5/2}$	28026.51		4.489[3]		5.25[−4]	0.005
	$\rightarrow 4f\ ^2F_{7/2}$	28026.51		8.991[4]		7.89[−3]	0.096
	$\rightarrow 5p\ ^2P_{3/2}$	14335.35		2.321[2]		1.07[−5]	0.0002
	$\rightarrow 4p\ ^2P_{3/2}$	5361.07	4.86[5][b]	3.577[5]	2.81[−3][a], 3.14[−3][b]	2.30[−3]	0.004
$6d\ ^2D_{3/2}$	$\rightarrow 7p\ ^2P_{3/2}$	160832.18		4.597[4]		1.77[−1]	0.049
	$\rightarrow 7p\ ^2P_{1/2}$	159676.53		2.333[5]		1.773	0.250
	$\rightarrow 5f\ ^2F_{5/2}$	91790.61		1.517[5]		1.27[−1]	0.162
	$\rightarrow 6p\ ^2P_{3/2}$	37196.07		9.882[3]		2.04[−3]	0.011
	$\rightarrow 6p\ ^2P_{1/2}$	37079.66		5.274[4]		2.16[−2]	0.056
	$\rightarrow 4f\ ^2F_{5/2}$	28024.42		9.475[4]		7.40[−3]	0.101
	$\rightarrow 5p\ ^2P_{3/2}$	14334.81		38.69		1.18[−6]	∼0
	$\rightarrow 5p\ ^2P_{1/2}$	14296.37		6.034[2]		3.67[−5]	0.0006
	$\rightarrow 4p\ ^2P_{3/2}$	5360.99	8.06[4][b]	5.991[4]	3.10[−4][a], 3.47[−4][b]	2.56[−4]	0.064
	$\rightarrow 4p\ ^2P_{1/2}$	5344.45	3.86[5][b]	2.849[5]	2.96[−3][a], 3.30[−3] [b]	2.42[−3]	0.305
$8s\ ^2S_{1/2}$	$\rightarrow 7p\ ^2P_{3/2}$	144722.68		3.779[5]	5.93[−1][a]	5.90[−1]	0.093
	$\rightarrow 7p\ ^2P_{1/2}$	143786.27		1.905[5]	5.91[−1][a]	5.87[−1]	0.047
	$\rightarrow 6p\ ^2P_{3/2}$	36262.54		3.760[5]	3.60[−2][a]	3.68[−2]	0.093

TABLE III. (*Continued*.)

Upper state (f)	Lower state (i)	λ_{ki}	A_{ki} Others	A_{ki} Present	f_{ki} Others	f_{ki} Present	Γ_{ki} Present
	$\rightarrow 6p\ ^2P_{1/2}$	36151.89		1.906[5]	3.60[−2][a]	3.71[−2]	0.047
	$\rightarrow 5p\ ^2P_{3/2}$	14193.98		6.079[5]	8.77[−3][a]	9.12[−3]	0.150
	$\rightarrow 5p\ ^2P_{1/2}$	14156.31		3.009[5]	8.84[−3][a]	8.98[−3]	0.074
	$\rightarrow 4p\ ^2P_{3/2}$	5341.17	1.31[6][b]	1.328[6]	2.70[−3][a], 2.81[−3][b]	2.82[−3]	0.328
	$\rightarrow 4p\ ^2P_{1/2}$	532.481	6.64[5][b]	6.700[5]	2.71[−3][a], 2.82[−3][b]	2.83[−3]	0.166

[a]Reference [32].
[b]Reference [33].

other states, the results of the D states have large differences with the NIST values. Also, there are large differences between the results obtained using the DHF and CCSD(T) methods which indicate the amount of correlation effects involved to determine them. The differences between the results obtained from the CCSD and CCSD(T) methods are small implying contributions from the triple excitations are not very significant in these calculations. We also estimate the contributions from the Breit interaction and find they are below 0.01 percent for these quantities in the considered states for which we

TABLE IV. Lifetimes (τ) of all the low-lying states up to $8s\ ^2S_{1/2}$ in the K atom (in ns).

State	This work	Others	Experiment
$5s\ ^2S_{1/2}$	42.31(1.1)	46.50[a], 42.5[b]	
$3d\ ^2D_{5/2}$	41.85(1.2)	45.85[a], 42.5[b]	
$3d\ ^2D_{3/2}$	41.32(1.0)	45.24[a], 41.9[b]	42(3)[g], 42(3)[d]
$5p\ ^2P_{1/2}$	134.40(3.0)	127.05[a], 137.1[b] 130[h]	137.6(1.3)[k]
$5p\ ^2P_{3/2}$	131.10(3.0)	124.02[a], 133.9[b]	133(3)[f], 134(2)[e]
$4d\ ^2D_{5/2}$	290.02(8.0)	291.18[a], 293.9[b]	
$4d\ ^2D_{3/2}$	284.10(7.3)	285.56[a], 289.4[b]	
$6s\ ^2S_{1/2}$	80.81(1.1)	87.12[a], 81.4[b]	88(2)[d], 68(9)[i]
$4f\ ^2F_{5/2}$	62.30(2.0)	70.65[a], 64.7[b]	
$4f\ ^2F_{7/2}$	62.20(2.0)	70.65[a], 63.9[b]	
$6p\ ^2P_{1/2}$	332.70(8.2)	321.67[a], 340.7[b]	344(3)[e]
$6p\ ^2P_{3/2}$	324.20(7.1)	312.77[a], 332.0[b]	333(3)[e], 310(15)[f]
$5d\ ^2D_{5/2}$	713.70(19.1)	769.63[a], 650.8[b]	
$5d\ ^2D_{3/2}$	712.70(21.1)	767.41[a], 653.1[b]	572(14)[d], 610(90)[j]
$7s\ ^2S_{1/2}$	147.71(1.2)	158.83[a], 148.8[b]	155(6)[d], 165(12)[j]
$5f\ ^2F_{7/2}$	114.11(3.2)	125.70[a], 117.9[b]	
$5f\ ^2F_{5/2}$	114.12(3.1)	125.70[a], 118.0[b]	117(3)[b]
$5g\ ^2G_{7/2}$	233.20(1.3)		
$5g\ ^2G_{9/2}$	233.20(1.3)		
$7p\ ^2P_{1/2}$	632.10(15.2)	619.47[a], 648.6[b]	623(6)[e]
$7p\ ^2P_{3/2}$	595.50(14.1)	601.80[a], 632.0[b]	592(6)[e]
$6d\ ^2D_{5/2}$	1066.10(24.1)	1168.54[b], 913.7[a]	
$6d\ ^2D_{3/2}$	1071.11(26.0)	1180.58[a], 925.7[b] 1050[h]	807(20)[d], 890(60)[j]
$8s\ ^2S_{1/2}$	247.40(2.0)	267.23[a], 250.7[b]	238(4)[d], 260(14)[j]

[a]Reference [34].
[b]Reference [33].
[c]Reference [35].
[d]Reference [36].
[e]Reference [37].
[f]Reference [38].
[g]Reference [39].
[h]Reference [40].
[i]Reference [41].
[j]Reference [42].
[k]Reference [43].

have neglected them. Although the calculated EAs seem to be promising for their sub-one-percent accuracies, but we consider the experimental energies wherever required to determine other physical properties to minimize uncertainties in the estimated results.

B. $E1$ matrix elements and oscillator strengths

We present $E1$ matrix elements from the DHF and CCSD(T) methods along with their line strengths from later in Table II. We estimate the uncertainties associated with the calculations using the CCSD(T) method as both DHF and CCSD methods are just part of this approach. We also find that the Breit interaction contributions to these quantities are below 0.01 percent as for the energies and neglect them. To estimate the net uncertainty of an $E1$ matrix element, we take into account the incompleteness of basis functions and the differences in the results obtained using the CCSD and CCSD(T) methods to estimate uncertainty due to the approximation in the level of excitations. We also find that the correlation contributions, estimated as the differences between the results obtained using the DHF and CCSD(T) methods, are significant in almost all the transitions.

It is not always possible to obtain precise values of either the $E1$ matrix elements or transition strengths from the measured lifetimes due to the association of many transition probabilities with these quantities. However, the $4p\ ^2P_{1/2,3/2}$ states are the first two excited states which decay to the ground state only via one allowed transition each. There are precise measurements of lifetimes of these states available in the K atom. The lifetime of the $4p\ ^2P_{1/2}$ state is reported to be 26.69(5) ns [44]. By combining this result with the experimental value of wavelength $\lambda = 7701.1$ Å [31] of the $4p\ ^2P_{1/2} \rightarrow 4s\ ^2S_{1/2}$ transition, we find the $E1$ matrix element of the $4p\ ^2P_{1/2} \rightarrow 4s\ ^2S_{1/2}$ transition to be 4.110(5) a.u. against our calculated result 4.131(20) a.u. Similarly, the lifetime of the $4p\ ^2P_{3/2}$ state is measured to be 26.34(5) ns [44]. This state has an allowed transition channel to the ground state and it can also decay to the first excited $4p\ ^2P_{1/2}$ state via both the electric quadrupole ($E2$) and magnetic dipole ($M1$) channels. It is found from our analysis that the transition probabilities of an electron due to the above forbidden channels from the $4p\ ^2P_{3/2}$ state are very small and can be neglected within our estimated uncertainties. Therefore combining the measured lifetime of the $4p\ ^2P_{3/2}$ state with the experimental value of the $4p\ ^2P_{3/2} \rightarrow 4s\ ^2S_{1/2}$ transition wavelength $\lambda = 7667.0$ Å, we obtain the $E1$ matrix element of the $4p\ ^2P_{3/2} \rightarrow 4s\ ^2S_{1/2}$ transition as 5.812(6) a.u. Although our calculated results from the CCSD(T) method are in agreement with the extracted values from the experimental lifetimes of the $4p\ ^2P_{1/2,3/2}$ states, however, we consider below the precise values obtained from the measurements to evaluate polarizabilities.

For the astrophysical interest, we also evaluate transition probabilities, oscillator strengths for emission lines, and branching ratios taking all possible allowed transitions among the considered states in the K atom using the above $E1$ matrix elements and the tabulated wavelengths in the NIST database [31]. These values are given in Table III. Four decades ago, Anderson and Ziltis carried out calculations of these quantities using a Coulomb approximation in the nonrelativistic method [45]. Safronova and Safronova have also reported a few of these quantities using a linearized approximation to the CCSD method (SD method) [33]. In a recent paper, Civiš *et al.* used a quantum defect theory to evaluate these quantities in many transitions, which are of particular astrophysical interest, and compared them with the estimated results from various measurements and observations [32] including those given in Ref. [45]. In the above table, we compare our results

TABLE V. Scalar polarizability of the ground state in a.u. in K along with individual contribution from various intermediate terms. Uncertainties are quoted in the parentheses.

Contribution		$\alpha_v^{(0)}$
α_v		
$4s\ ^2S_{1/2} \rightarrow$	$4p\ ^2P_{1/2}$	95.165(231)
	$4p\ ^2P_{3/2}$	189.471(391)
	$5p\ ^2P_{1/2}$	0.235(10)
	$5p\ ^2P_{3/2}$	0.514(10)
	$6p\ ^2P_{1/2}$	0.019(3)
	$6p\ ^2P_{3/2}$	0.044(3)
	$7p\ ^2P_{1/2}$	0.004(3)
	$7p\ ^2P_{3/2}$	0.010(3)
	$8p\ ^2P_{1/2}$	0.001(3)
	$8p\ ^2P_{3/2}$	0.003(2)
	$9p\ ^2P_{1/2}$	0.001(2)
	$9p\ ^2P_{3/2}$	0.002(2)
α_c		5.131(300)
α_{cn}		−0.127(20)
α_{tail}		0.062(10)
α_{total}		290.5(1.0)
Experiment		292.8(6.1) [46], 305.0(21.6) [47]
		290.58(1.42) [48]
Others		290.2(8) [49], 289.3 [33]

TABLE VI. Scalar polarizability of the $4p\ ^2P_{1/2}$ state of the K atom in a.u. Uncertainties are given in parentheses.

Contribution		$\alpha_v^{(0)}$
α_v		
$4p\ ^2P_{1/2} \rightarrow$	$4s\ ^2S_{1/2}$	−95.165(231)
	$5s\ ^2S_{1/2}$	136.679(705)
	$6s\ ^2S_{1/2}$	4.179(100)
	$7s\ ^2S_{1/2}$	0.971(20)
	$8s\ ^2S_{1/2}$	0.389(10)
	$9s\ ^2S_{1/2}$	0.188(10)
	$10s\ ^2S_{1/2}$	0.003(5)
	$3d\ ^2D_{3/2}$	545.86(683)
	$4d\ ^2D_{3/2}$	0.246(8)
	$5d\ ^2D_{3/2}$	0.296(10)
	$6d\ ^2D_{3/2}$	0.336(10)
	$7d\ ^2D_{3/2}$	0.017(5)
	$8d\ ^2D_{3/2}$	0.009(5)
α_c		5.131(300)
α_{cn}		−0.0002(1)
α_{tail}		6.4(20)
α_{total}		606(7)
Experiment		587(87) [50]
Others		604.1 [33], 602(11) [7], 697.4 [51]

TABLE VII. Contributions to both the scalar and tensor polarizabilities of the $4p\ ^2P_{3/2}$ state in the K atom in a.u. Uncertainties are mentioned in parentheses.

Contribution		$\alpha_v^{(0)}$	$\alpha_v^{(2)}$
α_v			
$4p\ ^2P_{3/2} \rightarrow$	$4s\ ^2S_{1/2}$	−95.56(21)	95.156(21)
	$5s\ ^2S_{1/2}$	138.81(101)	−138.81(101)
	$6s\ ^2S_{1/2}$	4.188(60)	−4.188(60)
	$7s\ ^2S_{1/2}$	0.971(20)	−0.971(20)
	$8s\ ^2S_{1/2}$	0.389(12)	−0.389(12)
	$9s\ ^2S_{1/2}$	0.187(11)	−0.187(11)
	$10s\ ^2S_{1/2}$	0.106(11)	−0.106(11)
	$3d\ ^2D_{3/2}$	54.91(101)	43.93(74)
	$4d\ ^2D_{3/2}$	0.021(3)	0.016(3)
	$5d\ ^2D_{3/2}$	0.033(4)	0.026(4)
	$6d\ ^2D_{3/2}$	0.036(4)	0.029(4)
	$7d\ ^2D_{3/2}$	0.026(4)	0.021(4)
	$8d\ ^2D_{3/2}$	0.018(3)	0.015(3)
	$3d\ ^2D_{5/2}$	494.34(552)	−98.87(110)
	$4d\ ^2D_{5/2}$	0.171(5)	−0.034(4)
	$5d\ ^2D_{5/2}$	0.297(6)	−0.059(4)
	$6d\ ^2D_{5/2}$	0.319(6)	−0.064(4)
	$7d\ ^2D_{5/2}$	0.236(6)	−0.047(4)
	$8d\ ^2D_{5/2}$	0.081(5)	−0.016(3)
α_c		5.131(300)	0.0
α_{cn}		−0.0002(1)	0.0002(1)
α_{tail}		9.13(30)	−1.4(2)
α_{total}		614(6)	−106(2)
Experiment		613(103) [50]	−107(2) [52]
		614(10) [52]	
Others		614.1 [33]	−107.9 [33]
		697.4 [51]	−96 [53]
		635 [53]	

along with the values reported in Refs. [32,33]. As seen in the table, all the results are in fair agreement among each other. Many of these results related to the $6d\ ^2D_{3/2,52}$ states were not known previously to compare with the present estimation. We also give the branching ratios explicitly of the individual allowed transition in the same table by considering into account all possible allowed transitions and neglecting transition probabilities due to the forbidden transitions.

C. Lifetimes of few excited states

As mentioned above, the lifetimes of the $4p\ ^2P_{1/2,3/2}$ states in the K atom were measured precisely by Wang *et al.* [44]. However, these quantities were not measured for some of the low-lying states. In fact, many measured values available for the states other than the $4p\ ^2P_{1/2,3/2}$ states are not very precise. Using our calculated transition probabilities given in Table III, we determine the lifetimes of all the considered states except for the $4P$ states. These results are given in Table IV and compared with other theoretical and experimental data in the same table. We have also estimated uncertainties to our estimated lifetime values from the reported error bars of the $E1$ matrix elements. Most of our results are within the error bars of the experimental values. It can be seen in the above table that the present values of lifetimes of many low-lying states match well with the other theoretical results given in Ref. [33] and differ from other calculated results reported in Ref. [34]; but our results for some of the higher states match better with the values given in Ref. [34] than the results given in Ref. [33]. The lifetimes of the $5g\ ^2G_{7/2,9/2}$ states were not found elsewhere to compare with our results.

TABLE VIII. Scalar and tensor polarizabilities of the $3d\ ^2D_{3/2}$ state along with the uncertainties in parentheses given in a.u.

Contribution		$\alpha_v^{(0)}$	$\alpha_v^{(2)}$
α_v			
$3d\ ^2D_{3/2} \rightarrow$	$4p\ ^2P_{1/2}$	−272.93(343)	272.93(343)
	$4p\ ^2P_{3/2}$	−55.29(103)	−44.23(75)
	$5p\ ^2P_{1/2}$	612.30(234)	−612.30(234)
	$5p\ ^2P_{3/2}$	120.8(121)	96.62(955)
	$6p\ ^2P_{1/2}$	5.271(204)	−5.271(204)
	$6p\ ^2P_{3/2}$	1.068(20)	0.854(10)
	$7p\ ^2P_{1/2}$	0.959(20)	−0.959(20)
	$7p\ ^2P_{3/2}$	0.194(5)	0.155(5)
	$8p\ ^2P_{1/2}$	0.352(20)	−0.352(20)
	$8p\ ^2P_{3/2}$	0.071(6)	0.057(5)
	$9p\ ^2P_{1/2}$	0.200(10)	−0.200(10)
	$9p\ ^2P_{3/2}$	0.041(5)	0.033(5)
	$4f\ ^2F_{5/2}$	855.2(166)	−171.03(332)
	$5f\ ^2F_{5/2}$	98.78(161)	−19.76(33)
	$6f\ ^2F_{5/2}$	29.697(620)	−5.94(13)
	$7f\ ^2F_{5/2}$	13.058(260)	−2.611(53)
α_c		5.131(300)	0.0
α_{cn}		−0.03(1)	0.02(1)
α_{tail}		50.6(100)	−10.6(30)
α_{total}		1465.5(21.5)	−502.6(12.5)
Others [55]		1613	−710

D. Static dipole polarizabilities ($\omega = 0$)

We evaluate the static dipole polarizabilities of the ground, $4p\ ^2P_{1/2,3/2}$, and $3d\ ^2D_{3/2,5/2}$ states in the K atom using the reported $E1$ matrix elements and experimental energies of the most important intermediate states. These results are reported in Tables V to IX along with individual contributions explicitly from various intermediate states and we compare them with other available experimental and calculations using both the nonrelativistic and relativistic methods. As has been stated earlier, the core and core-valence correlation contributions are estimated using the MBPT(3) method. Since these contributions are relatively smaller than the valence correlation contribution, the accuracies of the final results are uninfluenced by these results. In fact, we also give estimated uncertainties to these results by comparing the $E1$ matrix elements obtained using this method with the CCSD(T) method. It can be noticed from these result tables that only a few studies are carried out on the polarizabilities in K. Also, the experimental results from the direct measurements are not available precisely in any of the considered states. Recently, a result on the ground-state polarizability in K has been reported by combining the measured ground-state polarizability of the sodium (Na) atom with the ratio of these quantities between K and Na and reported as 290.58(1.42) a.u. [48]. Similarly, the differential polarizability of the $4p\ ^2P_{1/2} \rightarrow 4s\ ^2S_{1/2}$ transition has been measured to be

TABLE IX. Contributions to both the scalar and tensor polarizabilities of the $3d\ ^2D_{5/2}$ state in K (in a.u.) with their uncertainties in parentheses.

Contribution		$\alpha_v^{(0)}$	$\alpha_v^{(2)}$
α_v			
$3d\ ^2D_{5/2} \rightarrow$	$4p\ ^2P_{3/2}$	−331.79(371)	331.79(371)
	$5p\ ^2P_{3/2}$	724.7(240)	−724.7(239)
	$6p\ ^2P_{3/2}$	6.378(182)	−6.378(182)
	$7p\ ^2P_{3/2}$	1.168(20)	−1.168(20)
	$8p\ ^2P_{3/2}$	0.425(15)	−0.425(15)
	$9p\ ^2P_{3/2}$	0.246(12)	−0.246(12)
	$4f\ ^2F_{5/2}$	40.7(101)	46.54(112)
	$4f\ ^2F_{7/2}$	814.7(144)	−290.96(512)
	$5f\ ^2F_{5/2}$	4.698(140)	5.369(160)
	$5f\ ^2F_{7/2}$	93.99(161)	−33.57(58)
	$6f\ ^2F_{5/2}$	1.413(20)	1.615(20)
	$6f\ ^2F_{7/2}$	27.94(485)	−9.98(173)
	$7f\ ^2F_{5/2}$	0.178(5)	0.203(5)
	$7f\ ^2F_{7/2}$	12.36(23)	−4.42(12)
α_c		5.131(300)	0.0
α_{cn}		−0.03(1)	0.03(1)
α_{tail}		50.6(100)	−15.4(40)
α_{total}		1452.8(32.5)	−701.7(25.6)
Others		1613 [55]	−710 [55]

317.11(4) a.u. [54]. By combining this result with the above ground-state value, we refer the experimental value of the $4p\ ^2P_{1/2}$ state polarizability as 607.69(2.97) a.u. which seems to be in excellent agreement with our calculated result. Other previous calculations reporting this value in Refs. [7,12,33,51] were based on methods using lower approximations than the present work. There are no experimental results in the $3d\ ^2D_{3/2,5/2}$ states available to compare the corresponding results with our calculations. However, a calculation in the nonrelativistic method using a pseudopotential is reported on both the scalar and tensor polarizabilities of the $3d\ ^2D_{3/2,5/2}$ states [55]. These values are also given in Tables VIII and IX, which also seem to be fairly in agreement with our calculations.

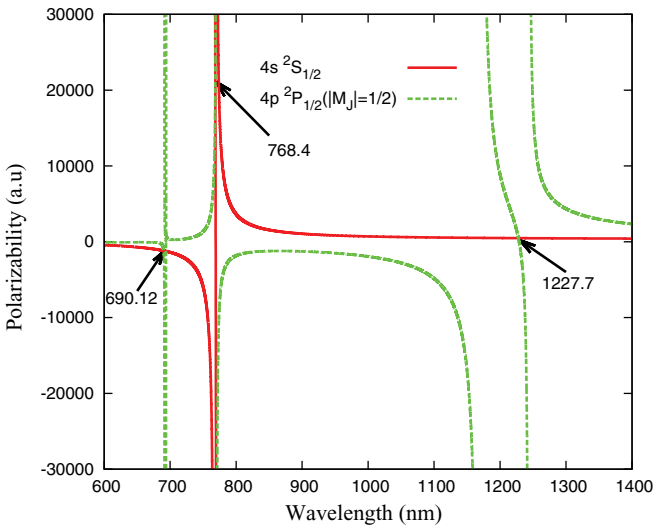

FIG. 1. (Color online) Dynamic polarizabilities (in a.u.) plots of the $4s\ ^2S_{1/2}$ (shown in red solid line) and $4p\ ^2P_{1/2}$ (shown in green dashed line) states against wavelengths (in nm). Intersection points are identified as magic wavelengths of the $4p\ ^2P_{1/2} - 4s\ ^2S_{1/2}$ transition. Resonance lines correspond at infinite values of polarizabilities.

TABLE X. Comparison of magic wavelengths and their corresponding polarizability values around different resonance lines for the $4p\ ^2P_{1/2} \rightarrow 4s\ ^2S_{1/2}$ transition with other works.

	λ_{magic}		$\alpha(\lambda_{\text{magic}})$	
λ_{res}	Present	Ref. [7]	Present	Ref. [7]
1243.57	1227.2(2)	1227.7(2)	474(2)	472(1)
1169.34				
770.11				
	768.412(3)	768.413(4)	21072(45)	20990(80)
693.30				
691.12				
	690.12(2)	690.15(1)	−1190(3)	−1186(2)

E. Reexamination of magic wavelengths

Since our reported static polarizabilities for the ground and $4p\ ^2P_{3/2,5/2}$ states seem to be more accurate than the results reported in Ref. [7], we intend here to further study the dynamic polarizabilities and estimate the magic wavelengths in the $4p\ ^2P_{1/2} \rightarrow 4s\ ^2S_{1/2}$ and $4p\ ^2P_{3/2} \rightarrow 4s\ ^2S_{1/2}$ transitions to compare them with the values given in Ref. [7]. In Fig. 1, we plot the dynamic polarizabilities of both the $4s\ ^2S_{1/2}$ and $4p\ ^2P_{1/2}$ states and look for the intersections outside the resonance lines. From this plot, we give the magic wavelengths corresponding to the intersection points of polarizabilities from both states. The polarizability values

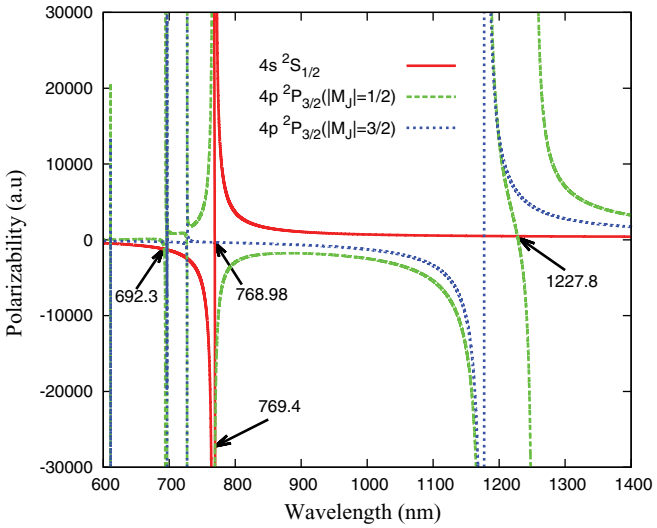

FIG. 2. (Color online) Dynamic polarizabilities (in a.u.) plots of the $4s\ ^2S_{1/2}$ and $4p\ ^2P_{3/2}$ states with different M_J values against wavelengths (in nm). Plots shown with (red) solid, (green) dashed, and (blue) dotted lines represent results of the $4s\ ^2S_{1/2}$ state, $4p\ ^2P_{3/2}$ state with $M_J = 1/2$, and $4p\ ^2P_{3/2}$ state with $M_J = 3/2$, respectively. Magic wavelengths are indicated by arrows.

TABLE XI. Magic wavelengths and their corresponding dynamic polarizabilities for the $4p\ ^2P_{3/2} \rightarrow 4s\ ^2S_{1/2}$ transition with $M_J = 1/2$ and $M_J = 3/2$ values from different works.

	λ_{magic}		$\alpha(\lambda_{\text{magic}})$	
λ_{res}	Present	Ref. [7]	Present	Ref. [7]
$\lvert M_{J_{3/2}}\rvert = 1/2$				
1252.56	1227.8(2)	1227.7(2)	474(2)	472(1)
1177.61				
1177.29				
	769.43(2)	769.432(2)	−27267(63)	−27190(60)
766.70				
696.66				
696.61				
694.07				
	692.26(3)	692.32(2)	−1230(3)	−1226(3)
$\lvert M_{J_{3/2}}\rvert = 3/2$				
1177.61				
1177.29				
	768.98(2)	768.980(3)	−336.52(6)	−356(8)

and magic wavelengths around different resonance lines for the $4p\ ^2P_{1/2} \rightarrow 4s\ ^2S_{1/2}$ transition are given in Table X. From the analysis of the above plot, we compare our results with the ones given in Ref. [7]. We also find the same number of magic wavelengths as in Ref. [7], but the corresponding values are obtained using more accurate values of the polarizabilities. Again, we find similar results for the $4p\ ^2P_{3/2} \rightarrow 4s\ ^2S_{1/2}$ transition which are shown in Fig. 2 and they are given in Table XI. As pointed out in Ref. [7] and also found in the present work, there is only one magic wavelength found for the $M_J = 3/2$ sublevel of the $4p\ ^2P_{3/2}$ state. It has to be noted that for the linearly polarized light, the Stark shift of an energy level is independent of the sign of the M_J value. However, this shift depends on the sign of the M_J value in the circularly polarized light due to the presence of the vector component of the polarizability. It was found in our another recent study on the rubidium (Rb) atom [8] that it is possible to obtain more numbers of magic wavelengths using the circularly polarized light than the linearly polarized light and we also anticipate similar results in the $4p\ ^2P_{3/2} \rightarrow 4s\ ^2S_{1/2}$ transition in K using circularly polarized light.

IV. CONCLUSION

We have studied electron attachment energies, electric dipole matrix elements, oscillator strengths, lifetimes, and dipole polarizabilities in the potassium atom. Some of the reported results are improved significantly than the previously known results. We affirm the reported magic wavelengths in the considered atom using our calculated dynamic polarizabilities. Our oscillator strength results will be useful in astrophysical studies and other improved results will also be helpful in guiding future experiments.

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