Eur. Phys. J. D **20**, 199–204 (2002)
DOI: 10.1140/epjd/e2002-00132-1

THE EUROPEAN PHYSICAL JOURNAL D

Radiative lifetime and oscillator strength determination in Mg-like potassium (K VIII)

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Received 23 January 2002 / Received in final form 23 April 2002
Published online 19 July 2002 –

Abstract. Theoretical transition probabilities have been obtained for 54 $n = 3$ transitions depopulating the $3s3p\ ^1\mathrm{P^o}$, $3p^2\ ^3\mathrm{P}$, $^1\mathrm{D}$, $^1\mathrm{S}$, $3s3d\ ^1\mathrm{D}$, $^3\mathrm{D}$ and $3p3d\ ^3\mathrm{P^o}$, $^3\mathrm{D^o}$, $^3\mathrm{F^o}$, $^1\mathrm{F^o}$, $^1\mathrm{D^o}$, $^1\mathrm{P^o}$ levels, including 14 transitions not yet observed. Some of these predictions have been compared with experimental lifetimes obtained by beam-foil spectroscopy for four $n = 3$ levels of K^{7+}. An excellent agreement is observed between theory and experiment for all the levels.

PACS. 34.50.Fa Electronic excitation and ionization of atoms (including beam-foil excitation and ionization) – 32.30.Jc Visible and ultraviolet spectra

1 Introduction

Transition probabilities for potassium in various ionisation stages are needed in different fields of science such as astrophysics, fusion research, laser-produced plasmas or soft X-ray lasers. In the present paper, we focus on the calculation and measurement of radiative lifetimes for most $n = 3$ levels of Mg-like potassium, (K VIII). For this ion, unexpectedly, no experimental data are available so far in the literature although, in the past, numerous papers have been dedicated to the study of different isoelectronic ions along the magnesium sequence.

On the theoretical side, the situation regarding the K VIII spectrum is more favourable. Results for $n = 3$ transitions have been obtained using the Relativistic Hartree-Plus-Exchange (HXR) method [1], the Multiconfiguration Relativistic Random-Phase Approximation (MCRRPA) [2,3] and the Single-Manifold Dirac-Fock (SMDF), the Multiconfiguration Dirac-Fock (MCDF) and the Multiconfiguration Dirac-Fock with core-polarization corrections (MCDF+CP) techniques [4]. Theoretical investigations along the magnesium sequence have also been performed [5–9]. All these results however need to be checked by experiment. Extensive experimental oscillator strengths are indeed available for the $3s^2\ ^1\mathrm{S}_0$–$3s3p\ ^1\mathrm{P}^\mathrm{o}_1$ transition in Mg I–Ar VII and Ca IX ions (see *e.g.* [10]), in Mg I [11], Al II [12,13], Si III [14,15], and P IV [16]. The $3s^2\ ^1\mathrm{S}_0$–$3s3p\ ^3\mathrm{P}^\mathrm{o}_1$ intercombination transition has been investigated both for low ionisation degrees (see *e.g.* Mg I [17–19]; Al II [20,21]; Si III [18,22] and also for highly charged ions such as Fe XV, Ni XVII, Cu XVIII, Zn XIX [23,24] and Br XXIV [25]). No experimental transition rate data, however, are available for the intermediate ionisation stages.

The purpose of the present work is to provide radiative transition probabilities and lifetimes in K VIII. Theoretical results have been obtained with the Relativistic Hartree-Fock (HFR) and Multiconfiguration Dirac-Fock (MCDF) methods including both intravalence and core-valence correlation in an extensive way. To assess the theoretical models, a comparison of these calculations with lifetime measurements deduced from beam-foil decay curve analysis is also discussed.

2 HFR calculations

We first applied, in the present work, the HFR method [26] modified with the inclusion of core-polarization (CP) effects by means of a core-polarization potential and a correction to the dipole operator [27]. The estimate of these contributions requires the knowledge of the dipole polarisability of the ionic core, α_d, and of the cut-off radius, r_c. As the K VIII ion has a Ne-like ionic core of the type $1s^2 2s^2 2p^6$ and two valence electrons surrounding the core, we used, for α_d, the value of the static dipole polarisability computed in [28] for K X, *i.e.* $\alpha_\mathrm{d} = 0.03a_0^3$. The cut-off radius was chosen equal to $0.35a_0$ which corresponds to the HFR average value $\langle r \rangle$ of the outermost core orbital ($2p^6$). For more details about the method, see *e.g.* [29–32]. Intravalence correlation was considered by retaining explicitly in the calculations the following 32 even-parity and 32 odd-parity configurations, respectively: $3s^2 + 3p^2 + 3d^2 + 4s^2 + 4p^2 + 4d^2 + 3sns$ ($n = 4$–8) + $3snd$ ($n = 3$–8) + $3pnp$ ($n = 4$–8) + $3dns$ ($n = 4$–8) + $3dnd$ ($n = 4$–8)

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Table 1. Adopted values for the radial parameters of even-parity configurations in K VIII.

Config.	Parameter	Adopted value (cm^{-1})	Ratio[c]
$3s^2$	E_{av}	11788	
$3p^2$	E_{av}	319653	
	$F^2(3p,3p)$	83981	0.928
	α	−13	
	ζ_{3p}	2335	1.091
$3s4s$	E_{av}	638550	
	$G^0(3s,4s)$	7826	0.911
$3s5s$	E_{av}	885325	
	$G^0(3s,5s)$	2594	0.900[a]
$3s6s$	E_{av}	1008743	
	$G^0(3s,6s)$	1227	0.900[a]
$3s3d$	E_{av}	375153	
	ζ_{3d}	84	0.672
	$G^2(3s,3d)$	68217	0.812
$3s4d$	E_{av}	774123	
	ζ_{4d}	38	0.717
	$G^2(3s,4d)$	9798	1.067
$3s5d$	E_{av}	948836	
	ζ_{5d}	27	1.000[b]
	$G^2(3s,5d)$	3065	0.900[a]
$3s6d$	E_{av}	1043652	
	ζ_{6d}	15	1.000[b]
	$G^2(3s,6d)$	1558	0.900[a]
$3s7d$	E_{av}	1099358	
	ζ_{7d}	10	1.000[b]
	$G^2(3s,7d)$	917	0.900[a]
$3p4p$	E_{av}	856624	
	ζ_{3p}	2738	1.198
	ζ_{4p}	458	0.609
	$F^2(3p,4p)$	29810	0.876
	$G^0(3p,4p)$	8654	0.900[a]
	$G^2(3p,4p)$	10254	0.900[a]

[a] Parameter fixed to 90% of its *ab initio* value. [b] Parameter fixed to its *ab initio* value. [c] Ratio = fitted/*ab initio*.

Table 2. Adopted values for the radial parameters of odd-parity configurations in K VIII.

Config.	Parameter	Adopted value (cm^{-1})	Ratio[c]
$3s3p$	E_{av}	150856	
	ζ_{3p}	2336	1.091
	$G^1(3s,3p)$	111793	0.929
$3s4p$	E_{av}	697587	
	ζ_{4p}	755	1.000[b]
	$G^1(3s,4p)$	10124	0.900[a]
$3s5p$	E_{av}	914063	
	ζ_{5p}	357	1.000[b]
	$G^1(3s,5p)$	3582	0.900[a]
$3s6p$	E_{av}	1023626	
	ζ_{6p}	197	1.000[b]
	$G^1(3s,6p)$	1742	0.900[a]
$3s7p$	E_{av}	1098072	
	ζ_{7p}	120	1.000[b]
	$G^1(3s,7p)$	993	0.900[a]
$3s4f$	E_{av}	803294	
	ζ_{4f}	10	1.000[b]
	$G^3(3s,4f)$	16927	0.805
$3s5f$	E_{av}	964426	
	ζ_{5f}	5	1.000[b]
	$G^3(3s,5f)$	7271	0.734
$3s6f$	E_{av}	1051900	
	ζ_{6f}	3	1.000[b]
	$G^3(3s,6f)$	4809	0.900[a]
$3s7f$	E_{av}	1104529	
	ζ_{7f}	2	1.000[b]
	$G^3(3s,7f)$	2890	0.900[a]
$3p4s$	E_{av}	800241	
	ζ_{3p}	2454	1.081
	$G^1(3p,4s)$	10450	0.900[a]
$3p3d$	E_{av}	528354	
	ζ_{3p}	1956	0.912
	ζ_{3d}	322	2.555
	$F^2(3p,3d)$	38699	0.438
	$G^1(3p,3d)$	71985	0.679
	$G^3(3p,3d)$	2082	0.309

[a] Parameter fixed to 90% of its *ab initio* value. [b] Parameter fixed to its *ab initio* value. [c] Ratio = fitted/*ab initio*.

and $3snp$ (n = 3–8) + $3snf$ (n = 4–8) + $3pns$ (n = 4–8) + $3pnd$ (n = 3–8) + $3dnp$ (n = 4–8) + $3dnf$ (n = 4–8).

The relativistic Hartree-Fock method, including core-polarization effects (HF + CP), was used in combination with a well known semi-empirical fitting procedure of the calculated eigenvalues to all the experimental levels compiled in [33] and taken from previous analyses [34–36]. Thus 36 even levels belonging to the $3s^2$, $3p^2$, $3sns$ (n = 4–6), $3snd$ (n = 3–7) and $3p4p$ configurations were fitted with 22 variable parameters. 33 odd levels belonging to the $3snp$ (n = 3–7), $3snf$ (n = 4–7), $3p4s$ and $3p3d$ configurations were fitted with 25 adjustable parameters, *i.e.* average energies (E_{av}), Slater integrals ($F^k(nl,n'l')$ or $G^k(nl,n'l')$) and spin-orbit integrals (ζ_{nl}). The mean deviations in the fitting procedure were 234 cm^{-1} for the even parity (32 parameters) and 25 cm^{-1} for the odd parity (36 parameters), respectively. The rather large deviation observed for the even levels comes essentially from the n = 5 levels for which the fit was not entirely satisfactory (due probably to the fact that some levels are badly determined). The deviation however is very small (only 1 cm^{-1}) for the n = 3 levels of the even parity concerned by the present work. The Slater integrals, not optimized in the semi-empirical approach, were scaled down by 0.90. The optimized parameters are given in Tables 1 and 2.

3 MCDF calculations

In order to assess the reliability of the HFR+CP results, we compared them with lifetimes calculated with another independent method, *i.e.*, the fully relativistic MCDF approach. The code used, GRASP92, is a version of the general relativistic atomic structure package (GRASP) initially developed by Grant and coworkers [37,38]. GRASP92 uses sparse-matrix representation and dynamic memory allocation techniques [39]. It has been used with success for computing transition probabilities in heavy ions like Tl II and Tl III [40], Hg II [41] and more recently Cd-like ions [31] and Bi II [42].

We have considered the active space (AS) method for building the MCDF expansion. The latter is produced by exciting the electrons from the reference configurations to a given set of orbitals. The rules adopted for generating the configuration space differ according to the correlation model being used. Within a given correlation model, the active set of orbitals spanning the configuration space is increased to monitor the convergence of the total energies and the oscillator strengths.

The present MCDF calculations were focused on the radiative lifetimes of the $3s3p\ ^1\mathrm{P}^\mathrm{o}_1$ and $3p^2\ ^3\mathrm{P}_2$ levels. We have followed two different approaches, one for each level. In these two calculations, a Fermi nucleus [39] has been adopted by considering the most abundant isotope, *i.e.* ^{39}K (93%).

The $3s3p\ ^1\mathrm{P}^\mathrm{o}_1$ energy level decays only to the ground state $3s^2\ ^1\mathrm{S}_0$. In that way, in the framework of the Extended Optimal Level (EOL) scheme [39], we have minimized an energy functional built on these two levels assigning the same weight to each of them. We have proceeded in three steps (*nl* stands for *nl* and *nl*-). In the first step, the orbitals of the core, *i.e.* $1s$ to $2p$, together with the $3s$ and $3p$ orbitals were optimized in an AS containing only 3 configuration state functions (CSF). These CSF's were built from $3s^2$ ($J = 0$) and $3s3p$ ($J = 1$) configurations and no correlation was introduced. The second step consisted in an AS of 82 CSF's generated by single excitations from the above mentioned configurations to the {$1s$, $2s$, $2p$, $3s$, $3p$, $3d$} set of orbitals in order to model the core-valence correlation and, by single and double excitations from the same configurations to the {$3s$, $3p$, $3d$} set, to include intravalence correlations. We have optimized $3d$ while keeping the other orbitals fixed to their values as obtained in the first step. Finally, we have extended the AS to 312 CSF's adding, in the last step, all the valence subshells with $n = 4$. Core-valence and intravalence correlations have been introduced in the same way as in the previous step. All the $n = 4$ orbitals were optimized, the $n < 4$ orbitals being fixed at the values obtained in the previous step. In the second step, we have tested different additional effects like the transverse photon interaction, the lowest-order nuclear motional corrections (the normal mass shift and the specific mass shift) and the dominant quantum-electrodynamical corrections (the self energy and the vacuum polarization contributions). All these effects have resulted in a wavenumber change of 11 cm^{-1} and have affected the calculated lifetimes by less than 0.1%. So, we have decided to neglect all these corrections in the final calculations.

In the case of the $3p^2\ ^3\mathrm{P}_2$ level, there are three decay channels, *i.e.* $3p^2\ ^3\mathrm{P}_2 \rightarrow 3s3p\ ^3\mathrm{P}^\mathrm{o}_{1,2}, ^1\mathrm{P}^\mathrm{o}_1$. Calculations were performed following the same procedure as for the $3s3p\ ^1\mathrm{P}^\mathrm{o}_1$ lifetime except that a different energy functional was used in the variational procedure. The latter was in fact defined as the $(2J + 1)$ weighted linear combination of the four levels involved in the decay scheme. In the first step, the AS contained the 5 CSF's built from the $3s3p$ ($J = 1, 2$) and $3p^2$ ($J = 2$) configurations. The AS was extended to 151 CSF's in the second step and to 512 CSF's in the last step.

4 Measurements

A comparison of the theoretical data with experiment was possible through measurements for 4 levels performed using beam-foil spectroscopy technique. Beams of K^+ ions have been produced by a 2 MV van de Graaff accelerator equipped with a radiofrequency ion source filled with neon as buffer gas. The potassium ions were sputtered from the source exit channel covered with a KCl mixture following a technique described previously [43]. The beam was analysed by a magnet and sent through a thin 20 μg/cm^2 carbon foil. The beam had a diameter of 6 mm and a current intensity of $\approx$0.15 μA.

Light emitted by the beam after the foil was observed at right angle with a 1m Seya-Namioka-type spectrometer equipped with a Pt coated 1 200 l/mm concave grating blazed for normal incidence at 80 nm. The light was measured by photon counting using three Mullard (Philips) channeltron detectors aligned along the curved exit slit of the spectrometer. The slit had a width of 110 μm giving a line width (FWHM) of $\approx$ 0.11 nm. The distance between the beam axis and the entrance slit, placed in the excitation chamber, was 15 mm, and the length of the ion beam viewed by the spectrometer reached about 0.3 mm. The ion beam current, penetrating into the electrically isolated excitation chamber that acted as a Faraday cup, was measured with an Ortec 439 current digitizer.

Potassium spectra were recorded in the wavelength region 35 to 95 nm at different ion beam energies in order to discriminate between ionisation stages by studying the variation of intensity as a function of the ion speed. The calibration of the spectra and the identification of the lines were based mainly on Kelly's tables [44] and the NIST web site [45].

The four lifetime measurements were made at a beam energy of 1.7 MeV which corresponds to an ion speed after the foil of 2.75 mm/ns. The recording of the line intensity as a function of the foil holder position along the beam axis was fully automatized [46] and the light intensity was normalized for each point to a constant beam charge. The displacement of the foil was measured with a resolution of 10 μm by a digital gauge (Mitutoyo 5 MQ65-5P). The lifetime values were obtained using different techniques for analysing the decay curves as explained hereafter.

4.1 3s3p ^{1}P^o

The lifetime of this level has been measured from the $3s^2\ ^1\mathrm{S}$–$3s3p\ ^1\mathrm{P}^\mathrm{o}$ resonance transition at 51.94 nm. This line is very strong in the 1.7 MeV spectra and is well isolated. The possible blend with a 52 nm K III line was ruled out as no other K III lines were observed in our spectra at that energy. Moreover, the line intensity decreases by a factor of 6 between 1.7 and 0.8 MeV confirming the identification with a high ionisation stage. Twelve curves have been recorded. The fitting of these curves revealed the necessity to include in the analysis a "growing in" component due to short lived levels cascading onto the observed level (see *e.g.* the discussion in [47] for that level in the other ions of the sequence). The influence of this short lifetime

Table 3. Experimental and calculated lifetimes for some $n = 3$ levels of K VIII.

Level	E (cm^{-1})	Experiment[a] (ns)	HFR+CP[b](ns)	MCDF[c] (ns)	Other calculations (ns)
$3s3p\ ^1\mathrm{P}^\mathrm{o}_1$	192537	0.11 ± 0.02	0.110	0.105/0.107	0.105[d], 0.103[e], 0.106[f] 0.083[g], 0.104[h], 0.108[i]
$3p^2\ ^3\mathrm{P}_2$	308826	0.14 ± 0.02	0.131	0.123/0.124	0.124[d]
$3s3d\ ^3\mathrm{D}_2$	368276	0.08 ± 0.02	0.087		0.086[d]
$3s3d\ ^1\mathrm{D}_2$	419100	0.05 ± 0.01	0.050		0.049[d]

[a] This work: Beam-foil technique. [b] This work: HFR calculations including core-polarization effects. [c] This work: MCDF calculations (Babushkin/Coulomb gauges). [d] HXR (Relativistic Hartree-Plus-Exchange method) [1]. [e] MCRRPA (Multiconfiguration relativistic random-phase approximation) [2]. [f] MCRRPA (Multiconfiguration relativistic random-phase approximation) [3]. [g] SMDF (Single-manifold Dirac-Fock) [4]. [h] MCDF (Multiconfiguration Dirac-Fock) [4]. [i] MCDF+CP (MCDF + core-polarization corrections) [4].

value on the results was very strong and it was impossible to confidently extract the lifetime of the main component without further assumptions. The cascade influence on a decay curve could be attenuated by the ANDC (arbitrary normalized decay curve) technique [48,49]. This elegant and, in principle, exact correction method implies that experimental decay curves could be recorded for all levels cascading onto the observed one under similar conditions. This was not possible in the present work due to experimental limitations. However, we did rely on a conceptually similar idea, which consists in checking the consistency of our observations. This has been done by making the assumption that the cascades, mainly originating from the few levels having a strong branch decaying toward the observed level, could be taken into account. For that purpose we used theoretical and predicted values for estimating their contributions and thus for deriving a reliable lifetime value for the primary component.

For the $3s3p\ ^1\mathrm{P}^\mathrm{o}$ level, the cascades are mainly due to $3s3d\ ^1\mathrm{D}$ ($\lambda = 44.1$ nm , $\tau = 0.05$ ns, according to the present HFR calculation with core-polarization included: see Sect. 3), $3s4d\ ^1\mathrm{D}$ ($\lambda = 17.2$ nm , $\tau = 0.07$ ns) and $3s4s\ ^1\mathrm{S}$ ($\lambda = 22.1$ nm, $\tau = 0.03$ ns).

Two more cascading levels arise from levels of the displaced term $3p^2$, that is $^1\mathrm{S}_0$ and $^1\mathrm{D}_2$. Neither decay was observed in this study, but these two levels have given rise to much discussion in other ions of the same isoelectronic sequence. The $3p^2\ ^1\mathrm{D}_2$ level is relatively long lived and the associated cascade component is generally easily identified in a multiexponential fit. A problem for the evaluation of the $3s3p\ ^1\mathrm{P}^\mathrm{o}$ level decay arises from the $3p^2\ ^1\mathrm{S}_0$ level, the lifetime of which is predicted [47] to be only a little longer (by some 30 to 50%) than that of the level of interest. Because the statistical weight of the $J = 0$ level is low, the associated decay does not stand out in our spectra (in fact, this single-line identification is not yet quoted in the NIST database) and, even if that line was measured in Ca [47], it was not recognized here. This lead us to the assumption that, although it could cause a systematic error in the lifetime evaluation, this potential uncertainty remains small and is well accounted in our error estimate.

Assuming for the cascading level an effective mean growing in lifetime of ≈0.05 ns, we obtained a lifetime of 0.12 ns for the $3s3p\ ^1\mathrm{P}^\mathrm{o}$ level. This value is in agreement with the theoretical estimates and justifies *a posteriori* our assumptions.

4.2 $3p^2\ ^3\mathrm{P}$

The lifetime has been estimated from the analysis of the 56.5 nm multiplet (unresolved). At this wavelength, no blending is expected from other ionisation stages. The line intensity ratio between 1.7 and 0.8 MeV beam energy is 9. Ten curves have been recorded. The lifetime was deduced by fitting to the observed curves a multi-exponential decay convoluted with the resolution function of the apparatus.

4.3 $3s3d\ ^3\mathrm{D}$

This level has been observed from the multiplet at $\lambda =$ 42.25 nm. A K V line (at 42.22 nm) might interfere with our measurement. However, we have checked that the strong K V multiplet at 42.5 nm, which should be twice stronger than the K V line, is very weak, specially at 1.7 MeV beam energy. Between 1.7 and 0.8 MeV, the 42.25 nm line intensity decreases by a factor of 5.3 whereas the intensity of the lines at 42.5 nm decreases only by a factor of 2.6 confirming that the 42.25 nm line is not strongly blended with K V. Seven curves have been recorded. The lifetime was deduced by fitting a multi-exponential decay convoluted with the resolution function of the apparatus to the observed curves and a direct fitting of a sum of exponentials to the decay portion of the curve.

4.4 $3s3d\ ^1\mathrm{D}$

The feature observed at $\lambda = 44.13$ nm is asymmetric and appears very weakly at 0.8 MeV. We have recorded decay curves on each side of the line and strong differences did appear, confirming a blend which is due to the $3p^2\ ^3\mathrm{P}$–$3p3d\ ^3\mathrm{P}^\mathrm{o}$ K VIII multiplet at 44.09 nm. The lifetime deduced from the curves recorded on the long wavelength side of the line is very short and has been attributed to the $3s3d\ ^1\mathrm{D}$ level. Five decay curves were recorded and analysed by direct fitting.

5 Results and discussion

The theoretical and experimental lifetimes obtained in this study are reported in Table 3. It is seen that the three sets of results are in very close agreement. Moreover,

Table 4. Oscillator strengths for $n = 3$ transitions in K VIII. The wavelengths are given in nm.

Transition	Levels	$\lambda^a_{\rm exp}$	$\lambda^b_{\rm calc}$	log gf^b
$3s^2$–$3s3p$	$^1S_0$–$^1P^o_1$	51.9372	51.9378	0.044
$3s3p$–$3p^2$	$^3P^o_2$–$^3P_2$	56.4462	56.4474	0.131
	$^3P^o_2$–$^3P_1$	57.2790	57.2810	−0.340
	$^3P^o_1$–$^3P_2$	55.7029	55.7032	−0.345
	$^3P^o_1$–$^3P_1$	56.5112	56.5148	−0.555
	$^3P^o_1$–$^3P_0$	56.9479	56.9520	−0.434
	$^3P^o_0$–$^3P_1$	56.1593	56.1593	−0.427
	$^1P^o_1$–$^1D_2$	92.7213	92.7211	−0.464
	$^1P^o_1$–$^1S_0$	60.561	60.5619	−0.398
$3s3p$–$3s3d$	$^3P^o_2$–$^3D_3$	42.2414	42.2414	0.326
	$^3P^o_2$–$^3D_2$	42.2643	42.2640	−0.422
	$^3P^o_2$–$^3D_1$	42.2788*	42.2789	−1.598
	$^3P^o_1$–$^3D_2$	41.8456	41.8454	0.059
	$^3P^o_1$–$^3D_1$	41.8582	41.8601	−0.418
	$^3P^o_0$–$^3D_1$	41.6654	41.6647	−0.291
	$^1P^o_1$–$^1D_2$	44.1379	44.1379	0.465
$3p^2$–$3p3d$	$^3P_2$–$^3D^o_3$	43.401	43.4071	0.486
	$^3P_2$–$^3D^o_2$	43.5140*	43.5099	0.013
	$^3P_2$–$^3D^o_1$		43.6407	−0.796
	$^3P_1$–$^3D^o_2$	43.031	43.0272	0.061
	$^3P_1$–$^3D^o_1$		43.1551	−0.116
	$^3P_0$–$^3D^o_1$		42.9037	−0.439
	$^3P_2$–$^3P^o_2$	44.1324*	44.1269	−0.286
	$^3P_2$–$^3P^o_1$		44.0592	−0.694
	$^3P_1$–$^3P^o_2$	43.6361*	43.6306	−0.040
	$^3P_1$–$^3P^o_1$		43.5644	−1.846
	$^3P_1$–$^3P^o_0$		43.4445	−0.567
	$^3P_0$–$^3P^o_1$		43.3081	−0.169
	$^1D_2$–$^1F^o_3$		38.9830	0.270
	$^1D_2$–$^1D^o_2$	47.483	47.4720	0.157
	$^1D_2$–$^1P^o_1$	39.4893*	39.4892	−2.013
	$^1S_0$–$^1P^o_1$	51.0308	51.0299	−0.010
$3s3d$–$3p3d$	$^3D_3$–$^3F^o_4$	72.14	72.1260	0.103
	$^3D_3$–$^3F^o_3$	73.0620*	73.0525	−0.907
	$^3D_3$–$^3F^o_2$	73.8171*	73.8352	−2.492
	$^3D_2$–$^3F^o_3$	72.99	72.9852	−0.070
	$^3D_2$–$^3F^o_2$	73.7458*	73.7665	−0.940
	$^3D_1$–$^3F^o_2$	73.72	73.7209	−0.255
	$^3D_3$–$^3D^o_3$	58.525	58.5484	0.080
	$^3D_3$–$^3D^o_2$	58.7441*	58.7357	−2.384
	$^3D_2$–$^3D^o_3$	58.4860*	58.5052	−0.763
	$^3D_2$–$^3D^o_2$	58.6989*	58.6922	−0.083
	$^3D_2$–$^3D^o_1$		58.9304	−2.374
	$^3D_1$–$^3D^o_2$	58.6717*	58.6633	−0.768
	$^3D_1$–$^3D^o_1$		58.9013	−0.223
	$^3D_3$–$^3P^o_2$	59.8767*	59.8657	0.047
	$^3D_2$–$^3P^o_2$	59.8297*	59.8206	−1.661
	$^3D_2$–$^3P^o_1$		59.6962	−0.182
	$^3D_1$–$^3P^o_2$	59.8015*	59.7906	−3.351
	$^3D_1$–$^3P^o_1$		59.6663	−1.795
	$^3D_1$–$^3P^o_0$		59.4417	−0.633
	$^1D_2$–$^1F^o_3$		72.5638	0.360
	$^1D_2$–$^1D^o_2$	108.8258*	108.7691	−0.677
	$^1D_2$–$^1P^o_1$	74.3384*	74.3377	−0.106

[a] From [1].
[b] Present work (HFR + CP results; see text).
* Wavelength calculated from the experimental levels.

the MCDF Babushkin and Coulomb gauge results agree quite well. The quoted experimental errors (scattering between 14 and 25%) are conservative and represent two standard deviations. In this table, we compare also our values with the previous theoretical data. As expected, our results agree rather well with the HXR calculations by Fawcett [1] who used a similar method, the differences between the two sets of data being due to the inclusion of CP effects in our calculations. As a consequence, our results are expected to be more accurate. It is worth noting the excellent agreement between our MCDF value and the MCDF + CP result of Stanec *et al.* [4] which is due to the fact that both methods are similar, *i.e.* both are MCDF models with the inclusion of core-valence effects.

HFR + CP transition probabilities have been calculated for 54 $n = 3$ transitions depopulating the $3s3p$ $^1P^o$, $3p^2$ ^3P, ^1D, ^1S, $3s3d$ ^1D, ^3D and $3p3d$ $^3P^o$, $^3D^o$, $^3F^o$, $^1F^o$, $^1D^o$, $^1P^o$ levels, including 14 not yet observed transitions. These results are reported in Table 4.

6 Conclusions

The agreement observed between HFR + CP and MCDF lifetime values and between these two sets of results and experiment (within the error bars) gives strong support to the theoretical results reported in the present paper. Experimental branching fractions for some transitions would be welcome to definitely assess the reliability of the f values reported in the present work which are nevertheless expected to be accurate within a few percent.

The authors are grateful to E. Träbert for constructive conversations. Financial support from the Belgian National Fund for Scientific Research (FNRS) and from the Institut Interuniversitaire des Sciences Nucléaires (IISN) is acknowledged.

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