

Oscillator strengths for transitions of astrophysical importance in *SIII*

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Abstract. Relativistic Quantum Defect Orbital (RQDO) calculations, with and without explicit account for core-valence correlation, have been performed on dipole-allowed transitions between the levels belonging to the $3s^2 3p^2$, $3s^2 3pnd$ ($n = 3, 4, 5$), $3s^2 3p ns$ ($n = 4, 5$) and $3s^2 3p 4p$ configurations of the Si-like ion SIII in the LS-coupling scheme. The present oscillator strengths, which are of considerable interest in astrophysics, are compared with other theoretical results and laboratory measurements, although the latter are extremely scarce for fine-structure transitions.

Key words: atomic data – atomic processes

1. Introduction

The importance of oscillator strengths in planetary atmosphere and stellar plasma modelling is broadly recognised. Several emission lines of some sulphur ions had been detected in the extreme ultraviolet spectrum of Jupiter (Broadfoot et al. 1979, 1981; Shemansky & Smith, 1981; Strobel & Davis, 1980). Recently, more observations have been made by the High-resolution Hopkins Ultraviolet Telescope on board ASTRO-1 (Morgan & Pilcher, 1982) and by the Goddard High Resolution Spectrograph on board the Hubble Space Telescope (Trauger et al. 1991). Moreover, the laboratory analysis of the spectra of the SIII by Johansson et al. (1992) has contributed to the research for SIII lines in the spectrum of the Jupiter satellite Io by the Extreme Ultraviolet Explorer (Hall et al. 1994). Ions of sulphur have an astrophysical importance, partly due to the high cosmic abundance of this element. The ultraviolet spectra of SIII is of considerable interest in temperature diagnostics of solar and stellar transition regions (Doscheck & Feldman 1987).

In a recent paper (Charro et al. 1997) we have reported oscillator strengths for a group of Si-like ions ($Z=19-54$), some of which have clear relevance in astrophysics. However, SIII was not included in our study and it is our aim here to supply f -values for several transition arrays in this ion, some of which have not been, to our knowledge, supplied by other authors. For

Table 1. Experimental Energy Levels in cm^{-1} reported by Johansson et al. (1992)

Level	Energy	Level	Energy	Level	Energy
$3s^2 3p^2$		$3s^2 3p 4s$		$3s^2 3p 5s$	
3P_0	0.0	$^3P_0^o$	146697.6	$^3P_0^o$	209775.1
3P_1	298.5	$^3P_1^o$	146737.7	$^3P_1^o$	209927.6
3P_2	833.1	$^3P_2^o$	147147.3	$^3P_2^o$	210699.6
1D_2	11323.8	$^1P_1^o$	148399.2	$^1P_1^o$	211329.2
1S_0	27162.5				
$3s^2 3p 3d$		$3s^2 3p 4p$		$3s^2 3p 4d$	
$^1D_2^o$	104159.6	3P_0	172632.9	$^1D_2^o$	205148.0
$^1F_3^o$	157610.5	3P_1	172787.4	$^1F_3^o$	211149.5
$^1P_1^o$	164141.1	3P_2	173193.3	$^1P_1^o$	213542.7
$^3P_0^o$	143097.3	3D_1	169771.6	$^3D_1^o$	206540.5
$^3P_1^o$	143116.7	3D_2	170068.9	$^3D_2^o$	206673.3
$^3P_2^o$	143125.5	3D_3	170650.7	$^3D_3^o$	206912.8
$^3F_2^o$	122118.7	3S_1	174037.9	$^3P_0^o$	208212.1
$^3F_3^o$	122404.2	1P_1	167553.4	$^3P_1^o$	208104.9
$^3F_4^o$	122798.8	1S_0	182759.3	$^3P_2^o$	207893.2
$^3D_1^o$	147551.8	1D_2	176984.6	$^3F_2^o$	204580.9
$^3D_2^o$	147692.4			$^3F_3^o$	205072.7
$^3D_3^o$	147745.9			$^3F_4^o$	205562.6
				$3s^2 3p 5d$	
				$^1P_1^o$	238195.5

most of the transitions object of the present work, few of the existing theoretical data have been obtained with methods that account for relativistic effects. Although SIII is not a heavy element ($Z=16$) the relativistic contributions to the wavefunctions and energies of the levels involved in the present transitions may not be negligible. We have consequently followed a theoretical method that gives explicit account of relativistic effects, The Relativistic Quantum Defect Orbital (RQDO) formalism (Martín & Karwowski, 1991, Karwowski & Martín 1991). This method has proved in a good number of cases (see, e.g., Charro et al 1996, 1997, Charro & Martín 1998, Biémont et al. 1998, and references therein) to be a simple and reliable procedure for predicting transition probability data. A special feature of the RQDO formalism is that the computational effort does not in-

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Table 2. Oscillator strengths for $3p^2 \rightarrow 3pnd$ fine-structure triplet-triplet transitions

Transition	RQDO ^a	RQDO ^b	CI f_l ^c	CI f_v ^d	HFR ^e	MCDF ^f	O.P. ^g
$3p^2 \rightarrow 3p3d$							
$^3P_0 - ^3P_1^o$	0.494	0.461	0.774	0.789	0.102E+1	0.332	0.683E-1
$^3P_1 - ^3P_0^o$	0.165	0.154	0.252	0.256	0.306	0.219	0.227E-1
$^3P_1 - ^3P_1^o$	0.124	0.115	0.157	0.160	0.185	0.269	0.170E-1
$^3P_1 - ^3P_2^o$	0.206	0.192	0.354	0.358	0.473	0.673	0.285E-1
$^3P_2 - ^3P_1^o$	0.124	0.115	0.198	0.201	0.233	0.168	0.169E-1
$^3P_2 - ^3P_2^o$	0.371	0.346	0.513	0.521	0.617	0.278	0.511E-1
$^3P_0 - ^3D_1^o$	0.150E+1	0.140E+1	0.136E+1	0.132E+1	0.141E+1	0.191E+1	0.164E+1
$^3P_1 - ^3D_1^o$	0.374	0.349	0.447	0.438	0.381	0.300	0.409
$^3P_1 - ^3D_2^o$	0.112E+1	0.105E+1	0.326	0.312	0.820	0.120E+1	0.123E+1
$^3P_2 - ^3D_1^o$	0.149E-1	0.140E-1	0.286E-1	0.286E-1	0.182E-1	0.308E-2	0.163E-1
$^3P_2 - ^3D_2^o$	0.225	0.210	0.323	0.326	0.295	0.241	0.245
$^3P_2 - ^3D_3^o$	0.126E+1	0.118E+1	0.138E-1	0.135E+1	0.139E+1	0.131E+1	0.137E+1
$3p^2 \rightarrow 3p4d$							
$^3P_0 - ^3P_1^o$	0.355E-1	0.206E-1	0.787E-2	0.755E-2	–	–	0.179E-1
$^3P_1 - ^3P_0^o$	0.119E-1	0.696E-2	0.619E-2	0.594E-2	–	–	0.595E-2
$^3P_1 - ^3P_1^o$	0.882E-2	0.513E-2	0.806E-2	0.774E-2	–	–	0.446E-2
$^3P_1 - ^3P_2^o$	0.143E-1	0.826E-2	0.699E-3	0.695E-3	–	–	0.742E-2
$^3P_2 - ^3P_1^o$	0.874E-2	0.507E-2	0.502E-2	0.490E-2	–	–	0.445E-2
$^3P_2 - ^3P_2^o$	0.255E-1	0.147E-1	0.187E-1	0.183E-1	–	–	0.133E-1
$^3P_0 - ^3D_1^o$	0.863E-1	0.474E-1	0.814E-1	0.769E-1	–	–	0.578E-1
$^3P_1 - ^3D_1^o$	0.214E-1	0.118E-1	0.141E-1	0.134E-1	–	–	0.144E-1
$^3P_1 - ^3D_2^o$	0.656E-1	0.361E-1	0.573E-1	0.545E-1	–	–	0.434E-1
$^3P_2 - ^3D_1^o$	0.848E-3	0.464E-3	0.206E-3	0.197E-3	–	–	0.576E-3
$^3P_2 - ^3D_2^o$	0.130E-1	0.713E-2	0.495E-2	0.474E-2	–	–	0.865E-2
$^3P_2 - ^3D_3^o$	0.751E-1	0.417E-1	0.567E-1	0.547E-1	–	–	0.485E-1

^a Relativistic Quantum Defect Orbital Method, this work.

^b Relativistic Quantum Defect Orbital Method, with polarization, this work.

^c f -values in length form reported by Tayal (1997).

^d f -values in velocity form reported by Tayal (1997).

^e f -values reported by Fawcett (1987).

^f f -values reported by Huang (1985). ^g f -values reported by Verner et al. (1996)

crease as the atomic system becomes heavier. Also, the RQDO formalism, being an analytical method, is free from the convergence problems that often plague sophisticated self-consistent-field procedures.

In some of our recent studies (Charro et al. 1996, 1997, Charro & Martín 1998) on other atomic systems, we have also performed Multiconfiguration-Dirac-Fock (MCDF) using the GRASP code (Dyall et al. 1989). In many transitions the agreement between the MCDF and RQDO f -values was quite satisfactory and, hence, we have limited the present work to RQDO calculations.

2. Computational procedures

The Relativistic Quantum Defect Orbital (RQDO) method has been described in detail in previous papers (Karwowski & Martín 1991, Martín et al. 1993). Therefore, we shall only briefly summarise its most fundamental aspects.

The relativistic quantum defect orbitals are determined by solving analytically the quasi-relativistic second-order Dirac-like equation

$$\left[-\frac{d^2}{dr^2} + \frac{\Lambda(\Lambda+1)}{r^2} - \frac{2Z'_{net}}{r} \right] \psi_k^{RD} = 2e^{RD} \psi_k^{RD} \quad (2.1)$$

$$\Lambda = \eta - n + l - \delta' + c \quad (2.2)$$

$$Z'_{net} = Z_{net}(1 + \alpha^2 E^x) \quad (2.3)$$

$$e^{RD} = -\frac{(Z'_{net})^2}{2(\eta - \delta')^2} - E^x \frac{(1 + \alpha^2 E^x/2)}{(1 + \alpha^2 E^x)^2} \quad (2.4)$$

η is the relativistic principal quantum number, n and l are the principal and orbital angular momentum quantum numbers, δ' is the relativistic quantum defect, c is an integer chosen to ensure the normalizability of the wavefunction and its correct nodal structure; Z'_{net} is the nuclear charge acting on the valence electrons at large radial distances; E^x is the experimentally measured energy, and α is the fine structure constant. Atomic units

Table 3. Oscillator strengths for the $3pnl \rightarrow 3p4p$ fine-structure triplet-triplet transitions

Transition	RQDO ^a	RQDO ^b	CI f_l^c	CI f_v^d	C.A. ^e
$3p4s \rightarrow 3p4p$					
$^3P_0^o - ^3P_1$	0.130	0.124	0.107	0.108	0.37
$^3P_1^o - ^3P_0$	0.434E-1	0.413E-1	0.120E-1	0.146E-1	0.12
$^3P_1^o - ^3P_1$	0.326E-1	0.310E-1	0.619E-1	0.554E-2	0.92E-1
$^3P_1^o - ^3P_2$	0.546E-1	0.520E-1	0.237E-1	0.240E-1	0.16
$^3P_2^o - ^3P_1$	0.325E-1	0.309E-1	0.188	0.953E-2	0.92E-1
$^3P_2^o - ^3P_2$	0.979E-1	0.932E-1	0.821E-1	0.663E-1	0.28
$^3P_0^o - ^3D_1$	0.209	0.197	0.311	0.281	0.54
$^3P_1^o - ^3D_1$	0.523E-1	0.492E-1	0.588E-1	0.508E-1	0.14
$^3P_1^o - ^3D_2$	0.158	0.149	0.196	0.175	0.41
$^3P_1^o - ^3D_1$	0.210E-2	0.200E-2	0.800E-2	0.601E-2	0.53E-2
$^3P_2^o - ^3D_2$	0.313E-1	0.295E-1	0.499E-1	0.391E-1	0.81E-1
$^3P_2^o - ^3D_3$	0.177	0.167	0.845E-1	0.760E-1	0.47
$^3P_0^o - ^3S_1$	0.100	0.914E-1	0.122	0.938E-1	0.13
$^3P_1^o - ^3S_1$	0.100	0.914E-1	0.117	0.926E-1	0.13
$^3P_2^o - ^3S_1$	0.996E-1	0.909E-1	0.647E-1	0.570E-1	0.13
$3p3d \rightarrow 3p4p$					
$^3F_2^o - ^3D_1$	0.128	0.124	0.112	0.118	–
$^3F_2^o - ^3D_2$	0.236E-1	0.229E-1	0.208E-1	0.219E-1	–
$^3F_2^o - ^3D_3$	0.666E-3	0.585E-3	0.585E-3	0.619E-3	–
$^3F_3^o - ^3D_2$	0.135	0.131	0.121	0.126	–
$^3F_3^o - ^3D_3$	0.167E-1	0.162E-1	0.149E-1	0.156E-1	–
$^3F_4^o - ^3D_3$	0.151	0.146	0.137	0.142	–
$^3D_1^o - ^3P_0$	0.646E-1	0.614E-1	0.521E-1	0.360E-1	0.54E-1
$^3D_1^o - ^3P_1$	0.485E-1	0.461E-1	0.198E-1	0.114E-1	0.41E-1
$^3D_1^o - ^3P_2$	0.330E-2	0.310E-2	0.103E-2	0.443E-3	0.27E-2
$^3D_2^o - ^3P_1$	0.872E-1	0.829E-1	0.335E-1	0.238E-1	0.73E-1
$^3D_2^o - ^3P_2$	0.292E-1	0.278E-1	0.317E-2	0.568E-2	0.25E-1
$^3D_3^o - ^3P_2$	0.117	0.111	0.774E-1	0.498E-1	0.98E-1

^a Relativistic Quantum Defect Orbital Method, this work.^b Relativistic Quantum Defect Orbital Method, with polarization, this work.^c f -values in the length form reported by Tayal (1997).^d f -values in the velocity form reported by Tayal (1997).^e f -values from a critical compilation (Wiese et al. 1969).

are used throughout. Since the effective Hamiltonian in Eq. (2.1) includes a screening term, the quantum defect orbitals are approximately valid in the core region of space. The relativistic quantum defect orbitals lead to close-form analytical expressions for the transition integrals. This allows us to calculate transition probabilities and oscillator strengths by simple algebra and with little computational effort.

The electric dipole oscillator strength for a transition between two states within the LS coupling, is given by the equation

$$f_{ij} = \frac{2}{3} \frac{l_m}{2J+1} \Delta E (D_{line})^2 (D_{mult})^2 (-1)^{l-l_m} \times | \langle R_{nl} | Q(r) | R_{n'l'} \rangle |^2 \quad (2.5)$$

where l_m is the greatest orbital angular-momentum quantum number of those of the states involved in the transition, $(2J+1)$ is the degeneracy of initial level and J is the total angular

Table 4. Oscillator strengths for the $3p4p \rightarrow 3p4d$ fine-structure triplet-triplet transitions

Transition	RQDO ^a	RQDO ^b	CI f_l^c	CI f_v^d	C.A. ^e
$^3P_0 - ^3D_0^o$	0.977	0.915	0.975	0.887	0.88
$^3P_1 - ^3D_1^o$	0.244	0.229	0.187	0.171	0.22
$^3P_1 - ^3D_2^o$	0.733	0.687	0.730	0.663	0.66
$^3P_2 - ^3D_1^o$	0.980E-2	0.920E-2	0.273E-2	0.266E-2	0.88E-2
$^3P_2 - ^3D_2^o$	0.147	0.138	0.641E-1	0.594E-1	0.13
$^3D_2 - ^3D_3^o$	0.824	0.772	0.672	0.612	0.74
$^3D_1 - ^3F_2^o$	0.793	0.706	0.793	0.606	0.97
$^3D_2 - ^3F_2^o$	0.879E-1	0.782E-1	0.895E-1	0.681E-1	0.86
$^3D_2 - ^3F_3^o$	0.711	0.634E-1	0.992	0.754	0.87
$^3D_3 - ^3F_2^o$	0.178E-2	0.159E-2	0.995E-3	0.846E-3	0.22E-2
$^3D_3 - ^3F_3^o$	0.631E-1	0.563E-1	0.546E-1	0.407E-1	0.77E-1
$^3D_3 - ^3F_4^o$	0.739	0.660	0.988	0.745	0.90
$^3D_1 - ^3P_0^o$	0.764E-2	0.707E-2	0.782E-2	0.703E-2	–
$^3D_1 - ^3P_1^o$	0.571E-2	0.528E-2	0.124E-2	0.157E-2	–
$^3D_1 - ^3P_2^o$	0.379E-3	0.350E-3	0.168E-3	0.501E-3	–
$^3D_2 - ^3P_1^o$	0.102E-1	0.948E-2	0.160E-1	0.277E-2	–
$^3D_2 - ^3P_2^o$	0.339E-2	0.314E-2	0.116E-3	0.554E-3	–
$^3D_3 - ^3P_2^o$	0.135E-1	0.125E-1	0.286E-1	0.696E-2	–
$^3P_0 - ^3P_1^o$	0.241	0.227	0.140	0.119	–
$^3P_1 - ^3P_0^o$	0.805E-1	0.758E-1	0.553E-1	0.450E-1	–
$^3P_1 - ^3P_1^o$	0.604E-1	0.569E-1	0.433E-1	0.372E-1	–
$^3P_1 - ^3P_2^o$	0.101	0.950E-1	0.901E-1	0.786E-1	–
$^3P_2 - ^3P_1^o$	0.606E-1	0.570E-1	0.838E-1	0.708E-1	–
$^3P_2 - ^3P_2^o$	0.182	0.172	0.287	0.253	–
$^3D_1 - ^3D_1^o$	0.145	0.135	0.116	0.899E-1	0.13
$^3D_1 - ^3D_2^o$	0.482E-1	0.451E-1	0.119E-1	0.111E-1	0.43E-1
$^3D_2 - ^3D_1^o$	0.290E-1	0.271E-1	0.187E-1	0.181E-1	0.26E-1
$^3D_2 - ^3D_2^o$	0.134	0.126	0.141	0.108	0.12
$^3D_2 - ^3D_3^o$	0.301E-1	0.282E-1	0.712E-2	0.727E-2	0.27E-1
$^3D_3 - ^3D_2^o$	0.215E-1	0.202E-1	0.114E-1	0.131E-1	0.19E-1
$^3D_3 - ^3D_3^o$	0.172	0.161	0.188	0.154	0.16
$^3S_1 - ^3P_0^o$	0.110	0.986E-1	0.175	0.161	–
$^3S_1 - ^3P_1^o$	0.328	0.295	0.451	0.422	–
$^3S_1 - ^3P_2^o$	0.545	0.489	0.540	0.508	–

See footnotes to Table 3.

momentum quantum number of that state, ΔE is the transition energy in Hartrees, D_{line} is the line factor, D_{mult} is the multiplet factor and $Q(r)$ is the standard dipole-length transition operator.

One aspect of the computational procedure which has to be investigated is how to correct the transition operator for the neglect of explicit core-valence correlation in the quantum defect orbitals. It is well known that core-valence correlation significantly contributes to certain transition matrix elements. Laughlin (1989) has pointed out that when matrix elements are calculated with wavefunctions obtained from a valence-electron equation, core-polarization corrections introduced in the transition operator are especially adequate. Different forms for these corrections can be found in the literature. As in some of our previous computations we have adopted (Bielińska-Wąz D., 1992)

$$Q(r) = r \left[1 - \frac{\alpha'}{r^3} [1 - \exp(-r/r_c)]^3 \right], \quad (2.6)$$

Table 5. Oscillator strengths for the $3pnp \rightarrow 3p5s$ fine structure triplet-triplet transitions

Transition	RQDO ^a	RQDO ^b	C.A. ^c	O.P. ^d
$3p^2 \rightarrow 3p5s$				
$^3P_0 - ^3P_1^o$	0.180E-1	0.222E-1	–	0.270E-1
$^3P_1 - ^3P_0^o$	0.636E-2	0.777E-2	–	0.898E-2
$^3P_1 - ^3P_1^o$	0.456E-2	0.562E-2	–	0.674E-2
$^3P_1 - ^3P_2^o$	0.589E-2	0.766E-2	–	0.113E-1
$^3P_2 - ^3P_1^o$	0.469E-2	0.574E-2	–	0.672E-2
$^3P_2 - ^3P_2^o$	0.109E-1	0.141E-1	–	0.202E-1
$3p4p \rightarrow 3p5s$				
$^3P_0 - ^3P_1^o$	0.200	0.203	0.20	–
$^3P_1 - ^3P_0^o$	0.680E-1	0.690E-1	0.68E-1	–
$^3P_1 - ^3P_1^o$	0.502E-1	0.510E-1	0.50E-1	–
$^3P_1 - ^3P_2^o$	0.776E-1	0.792E-1	0.79E-1	–
$^3P_2 - ^3P_1^o$	0.511E-1	0.518E-1	0.51E-1	–
$^3P_2 - ^3P_2^o$	0.142	0.145	0.15	–
$^3D_1 - ^3P_0^o$	0.100	0.102	0.97E-1	–
$^3D_1 - ^3P_1^o$	0.738E-1	0.756E-1	0.72E-1	–
$^3D_1 - ^3P_2^o$	0.451E-2	0.465E-2	0.45E-2	–
$^3D_2 - ^3P_1^o$	0.135	0.138	0.13	–
$^3D_2 - ^3P_2^o$	0.411E-1	0.424E-1	0.41E-1	–
$^3D_3 - ^3P_2^o$	0.169	0.174	0.17	–
$^3S_1 - ^3P_0^o$	0.235E-1	0.238E-1	0.24E-1	–
$^3S_1 - ^3P_1^o$	0.583E-1	0.597E-1	0.71E-1	–
$^3S_1 - ^3P_2^o$	0.890E-1	0.918E-1	0.11	–

^a Relativistic Quantum Defect Orbital Method, this work.^b Relativistic Quantum Defect Orbital Method, with polarization, this work.^c f -values from a critical compilation (Wiese et al. 1969).^d f -values reported by Verner et al. (1996)

where α' is the core polarizability and r_c is a cut-off radius. This expression offers the great advantage, unlike the one formerly proposed by Caves & Dalgano (1972), of retaining total analyticity in the RQDO transition integrals.

3. Results and analysis

In the RQDO procedure, atomic energy level data are required. We have adopted the most recent ones available (Johansson et al. 1992) on S III, which are also considered by other authors as the most reliable energy data for this ion (Tayal, 1995, 1997). These are collected in Table 1. When core polarization effects have been explicitly included in the transition operator, the core polarizability of S III has been taken from Fraga et al. (1976). Since there is no analytical expression for the cut-off radius, we have employed a value of the order of magnitude of the core outermost electron's mean radial distance. In the RQDO calculations where the standard dipole-length transition operator has been employed, core-valence polarization is always accounted for implicitly the semiempirical parameter of the model Hamiltonian.

In Table 2 the oscillator strengths for the fine-structure triplet-triplet transitions corresponding to the $3p^2 \rightarrow 3pnd$ ($n = 3, 4$) complex are collected. In addition to the two sets of RQDO f -values, we have included those existing in the literature, that have been obtained with quite more complex theoretical procedures. These comprise those of the very extensive configuration interaction (CI) length and velocity calculations by Tayal (1997), who has incorporated relativistic effects by means of the Breit-Pauli Hamiltonian, and has made some adjustments so that the energy splittings are as close as possible as the experimental values of Johansson et al. (1992); the relativistic Hartree-Fock (HFR) f -values by Fawcett (1987), who carried out an optimization of Slater parameters previously calculated *ab initio* with an HFR programme package which includes configuration interaction; the MCDF oscillator strengths obtained by Huang (1985) with the code by Desclaux (1975); the Opacity Project (OP) oscillator strengths reported first by Nahar & Pradhan (1993), who performed extensive close-coupling (CC) approximation and R-matrix calculations, and claim to have obtained good theoretical energies as compared to the observed ones from different sources. More recently, Verner et al. (1996) assigned the multiplet OP f -values to individual lines using a compilation of experimental energy levels. These authors remark that the OP f -values cannot be used for spectroscopic applications as they correspond to multiplets only. The exceptionally low magnitude of the oscillator strengths reported by Verner et al. (1996) for the $^3P - ^3P^o$ transitions may perhaps be due to a typographical error in their tables. No experimental data are available, to our knowledge, in the literature.

An inspection of Table 2 reveals some dispersion between the oscillator strengths from the different sources for the $3p^2\ ^3P \rightarrow 3p\ 3d\ ^3P^o$ transitions, which greatly diminishes for the $^3P - ^3D^o$ lines. One possible explanation to this fact is the remark by Tayal (1997) concerning a mixing of the $3s^2\ 3p\ 3d\ ^3P^o$ level with others of the same symmetry such as $3s\ 3p^3$ and $3s^2\ 3p\ 4s$. Expect when cancellation effects seem to be present ($^3P^o - ^3D$), a good general accord is found between the RQDO, HFR (Fawcett 1987), MCDF (Huang 1985) and OP (Verner et al 1996) oscillator strengths for the $3p^2\ ^3P^o \rightarrow 3p\ 3d\ ^3D$ transitions. For the $3p^2 \rightarrow 3p\ 4d$ fine-structure transitions, the RQDO oscillator strengths calculated with explicit inclusion of core polarization conform reasonably well with those by Verner et al (1996) for both $^3P - ^3P^o$ and $^3P - ^3D^o$ groups. In this and the remaining tables, unless otherwise specified, the oscillator strengths have been obtained with the dipole-length form of the transition operator.

In Table 3, where the transitions correspond to the excitation of either a $4s$ or a $3d$ electron to a $4p$ orbital, the f -values by Tayal (1997) that have been included have not been corrected for relativistic effects. It is apparent that the RQDO oscillator strengths conform generally better with the CI (Tayal 1997) f -values than with those of Coulomb Approximation (CA) compiled critically by Wiese et al. (1969) for the $3p\ 4s \rightarrow 3p\ 4p$ transitions. However, for the $3p\ 3d\ ^3D^o \rightarrow 3p\ 4p\ ^3P$ transitions, the RQDO and CA values appear to agree reasonably well, whilst

Table 6. Oscillator strengths for singlet-singlet transitions

Transition	RQDO ^a	RQDO ^b	O.P. ^c	CI f_l/f_v ^d	Others
$3p^2\ ^1D_2 \rightarrow 3p4s\ ^1P_1^o$	0.167	0.159	0.94E-1/0.94E-1	0.142/0.142	0.10/0.14 ^e 0.7E-1±0.4E-1 ^f
$3p^2\ ^1D_2 \rightarrow 3p3d\ ^1D_2^o$	0.856	0.795	0.102E+1/0.982	0.759E-1/0.109	0.107/0.27E-1 ^e
$3p^2\ ^1D_2 \rightarrow 3p3d\ ^1F_3^o$	0.124E+1	0.116E+1	0.136E+1/0.135E+1	0.133E+1/0.128E+1	0.154E+1/0.160E+1 ^e
$3p^2\ ^1D_2 \rightarrow 3p4d\ ^1F_3^o$	0.102	0.631E-1	–	0.959E-1/0.100	–
$3p^2\ ^1S_0 \rightarrow 3p4d\ ^1P_1^o$	0.104	0.664E-1	–	0.132/0.172	–
$3p^2\ ^1S_0 \rightarrow 3p5s\ ^1P_1^o$	0.704E-1	0.701E-1	–	–	–
$3p^2\ ^1D_2 \rightarrow 3p5s\ ^1P_1^o$	0.266E-1	0.249E-1	–	–	–
$3p^2\ ^1D_2 \rightarrow 3p5d\ ^1P_1^o$	0.384E-1	0.225E-1	–	–	–
$3p^2\ ^1S_0 \rightarrow 3p5d\ ^1P_1^o$	0.531E-1	0.299E-1	–	–	–
$3p3d\ ^1F_3^o \rightarrow 3p4p\ ^1D_2$	0.102	0.979E-1	0.106	0.129/0.103	–
$3p4s\ ^1P_1^o \rightarrow 3p4p\ ^1P_1$	0.269	0.241	–	0.279/0.267	–
$3p4s\ ^1P_1^o \rightarrow 3p4p\ ^1D_2$	0.430	0.384	0.580	0.557/0.516	–
$3p4p\ ^1D_2 \rightarrow 3p4d\ ^1F_3^o$	0.919	0.868	0.900	0.834/0.920	–
$3p4p\ ^1P_1 \rightarrow 3p4d\ ^1D_2^o$	0.327	0.330	0.827	0.686/0.485	–
$3p4p\ ^1P_1 \rightarrow 3p4d\ ^1P_1^o$	0.197	0.211	0.315	0.298/0.188	–
$3p4p\ ^1S_0 \rightarrow 3p4d\ ^1P_1^o$	0.100E+1	0.102E+1	0.807	0.941/0.109E+1	–
$3p4p\ ^1P_1 \rightarrow 3p5s\ ^1P_1^o$	0.133	0.139	–	–	–
$3p4p\ ^1S_0 \rightarrow 3p5s\ ^1P_1^o$	0.766	0.767	–	–	–
$3p4p\ ^1D_2 \rightarrow 3p5s\ ^1P_1^o$	0.125	0.127	–	–	–
$3p4p\ ^1S_0 \rightarrow 3p5d\ ^1P_1^o$	0.213	0.179	–	–	–
$3p4p\ ^1P_1 \rightarrow 3p5d\ ^1P_1^o$	0.126	0.113	–	–	–
$3p4p\ ^1D_2 \rightarrow 3p5d\ ^1P_1^o$	0.597E-1	0.518E-1	–	–	–

^a Relativistic Quantum Defect Orbital Method, this work.

^b Relativistic Quantum Defect Orbital Method, with polarization, this work.

^c f -values in the length and velocity forms reported by Nahar & Pradhan (1993).

^d f -values in the length and velocity forms reported by Tayal (1997).

^e f -values in the length and velocity forms reported by Ho & Henry (1984,1987).

^f Experimental f -values reported by Ryan et al. (1989).

the length and velocity CI oscillator strengths are in much worse agreement than in previous transitions.

The RQDO $3p4p \rightarrow 3p4d$ fine-structure oscillator strengths displayed in Table 4 are, again, in better agreement with the CA values than with the CI ones, although great similarities between the RQDO and the latter are apparent in some of the transitions, as it appeared in the preceding tables. It is well known that the Coulomb Approximation yields quite good transition probabilities when the region that most largely contributes to the transition integrals is the one corresponding to large radial distances (Wiese et al. 1969).

For the $3p^2 \rightarrow 3p5s$ transitions only OP f -values (Verner et al. 1996) have been found as comparative data. They clearly agree much better with the RQDO results explicitly corrected for core polarization than with the other RQDO set (see Table 5). However, for the $3p4p \rightarrow 3p5s$ transitions, for which OP values are not available, the CA oscillator strengths conform better with the RQDO f -values non-corrected for polarization than with the corrected ones, except for the $^3S - ^3P^o$ lines.

Oscillator strengths corresponding to singlet-singlet different types of transitions are collected in Table 6, and those for triplet-triplet transitions in Table 7. For a good number of the former, only RQDO f -values are available. Apart from the OP

(Nahar & Pradhan 1993) and CI (Tayal 1995,1997) comparative values, the CI results by Ho & Henry (1984,1987) obtained with the CIV3 code of Hibbert (1975) are also available for a few transitions, as well as the beam-foil measurement by Ryan et al (1989). According to Tayal (1995) the disagreement between his CI f -values and those of the OP (Nahar & Pradhan 1993) is mainly caused by the wrong classification of the $3s^2 3p3d\ ^1D_2^o$ and $3s3p^3\ ^1D_2^o$ energy levels in the OP calculation. This author (Tayal 1995) also claims that the configuration interaction carried out by Ho & Henry (1984, 1987) involves an inadequate representation of the mixing between the levels of $^3P_0^o$ symmetry.

We find a fairly good agreement between the RQDO f -values (mainly those non-corrected for polarization) and the CI ones by Tayal (1997) for most of the singlet-singlet transitions (Table 6), as well as with the OP f -values (Nahar & Pradhan 1993) for the others. The same feature is observed for the triplet-triplet transitions (Table 7), where the general accord of the RQDO oscillator strengths that include polarization is much better with the OP results than with the CA f -values (Wiese et al. 1969) when discrepancies appear between these two sets of calculations. The experimental oscillator strengths (Ryan et al 1989) have lower magnitude than all the theoretical data.

Table 7. Oscillator strengths for the multiplet transitions

Transition	RQDO ^a	RQDO ^b	O.P. ^c	CI f_l/f_v ^e	Others
$3p^2\ ^3P \rightarrow 3p\ 3d\ ^3D^o$	0.150E+1	0.140E+1	0.164E+1 ^d 0.167/0.163	0.166E+1/0.162E+1	0.186E+1/0.162E+1 ^h 0.96±0.19 ^g
$3p^2\ ^3P \rightarrow 3p\ 3d\ ^3P^o$	0.494	0.461	0.681E-1 ^d 0.780/0.760	0.785/0.763	0.39/0.30 ^h
$3p^2\ ^3P \rightarrow 3p\ 4d\ ^3P^o$	0.347E-1	0.201E-1	0.178E-1 ^d	0.16E-1/0.17E-1	–
$3p^2\ ^3P \rightarrow 3p\ 4d\ ^3D^o$	0.880E-1	0.486E-1	0.577E-1 ^d	0.63E-1/0.64E-1	–
$3p^2\ ^3P \rightarrow 3p\ 5s\ ^3P^o$	0.163E-1	0.205E-1	0.269E-1 ^d	–	–
$3p\ 3d\ ^3P^o \rightarrow 3p\ 4p\ ^3S$	0.193	0.159	0.160	0.5E-2/0.2E-2	0.70E-1 ^f
$3p\ 3d\ ^3D^o \rightarrow 3p\ 4p\ ^3P$	0.117	0.111	0.71E-1	0.73E-1/0.72E-1	0.10 ^f
$3p\ 3d\ ^3D^o \rightarrow 3p\ 4p\ ^3D$	0.373E-1	0.352E-1	0.38E-1	0.24E-1/0.19E-1	0.31E-1 ^f
$3p\ 3d\ ^3F^o \rightarrow 3p\ 4p\ ^3D$	0.152	0.147	0.137	0.140/0.127	–
$3p\ 3d\ ^3P^o \rightarrow 3p\ 4p\ ^3P$	0.896E-1	0.823E-1	0.83E-1	0.325/0.284	0.53E-1 ^f
$3p\ 4s\ ^3P^o \rightarrow 3p\ 4p\ ^3P$	0.130	0.124	0.313	0.89E-1/0.79E-1	0.38 ^f
$3p\ 4s\ ^3P^o \rightarrow 3p\ 4p\ ^3D$	0.210	0.198	0.236	0.317/0.316	0.55 ^f
$3p\ 4s\ ^3P \rightarrow 3p\ 4p\ ^3S^o$	0.998E-1	0.911E-1	0.5E-2	0.166/0.149	–
$3p\ 4p\ ^3P \rightarrow 3p\ 4d\ ^3P^o$	0.242	0.228	0.296	0.286/0.247	–
$3p\ 4p\ ^3P \rightarrow 3p\ 4d\ ^3D^o$	0.979	0.917	0.788	0.833/0.749	0.88 ^f
$3p\ 4p\ ^3D \rightarrow 3p\ 4d\ ^3D^o$	0.194	0.181	0.166	0.176/0.161	0.18 ^f
$3p\ 4p\ ^3D \rightarrow 3p\ 4d\ ^3P^o$	0.136E-1	0.126E-1	0.6E-2	0.16E-1/0.10E-1	–
$3p\ 4p\ ^3D \rightarrow 3p\ 4d\ ^3F^o$	0.800	0.713	0.947/0.880	0.105E+1/0.885	0.99 ^f
$3p\ 4p\ ^3S \rightarrow 3p\ 4d\ ^3P^o$	0.983	0.883	0.108E+1	0.118E+1/0.105E+1	–
$3p\ 4p\ ^3S \rightarrow 3p\ 5s\ ^3P^o$	0.171	0.175	–	–	–
$3p\ 4p\ ^3P \rightarrow 3p\ 5s\ ^3P^o$	0.195	0.198	–	–	–
$3p\ 4p\ ^3D \rightarrow 3p\ 5s\ ^3P^o$	0.173	0.178	–	–	–

^a Relativistic Quantum Defect Orbital Method, this work.

^b Relativistic Quantum Defect Orbital Method, with polarization, this work.

^c f -values in the length and velocity forms reported by Nahar & Pradhan (1993).

^d f -values in the length and velocity forms reported by Verner et al. (1996).

^e f -values in the length and velocity forms reported by Tayal (1995).

^f f -values from a critical compilation (Wiese et al. 1969).

^g Experimental f -values reported by Ryan et al. (1989).

^h f -values in the length and velocity forms reported by Ho & Henry (1984,1987).

This may be due to possible cascade effects that are frequent in beam-foil measurements.

4. Concluding remarks

We can conclude that the RQDO method can yield reasonable f -values for complex atoms, that in many cases are close in magnitude to those of much more complex theoretical procedures. Although the explicit inclusion of core polarization is difficult to assess when there are no comparative data available that accounts for these effects, as a general rule we are in favour of its inclusion in our calculations. Given the importance of some lines in astrophysics, we are presently in the process of modifying our codes in order to be able to deal with spin-forbidden transitions.

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