E2-TRANSITION PROBABILITIES FOR NIXVIII

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Abstract. Accurate theoretical data for the transition probabilities are highly demanding in astrophysics and in the study of plasma in astrophysical objects and fusion devices. Na-like highly stripped ions of iron group, specially NiXVIII is very important in this respect. A highly improved basis in a relativistic many-body coupled-cluster method (CCM) to include correlation properly is employed to calculate excitation energies, the electric quadrupole (E2) transition line strengths and transition probabilities for NiXVIII. The effect of correlation is studied thoroughly. The present improved data for different atomic/ionic properties are compared with the available theoretical and/or experimental data and they are in agreement. Some E2 transition data are reported for the first time.

Keywords: E2-transition, relativistic, stellar chemical composition, astrophysical plasma, fusion device

1. Introduction

The studies on forbidden lines in the spectrum is important for the study of astrophysical and fusion plasmas. Recent progress in stellar spectroscopy with the Hubble Space Telescope (HST) have urged both the theoretical and experimental studies. Particularly the chemically peculiar stars have very high abundances of heavy elements. Accurate theoretical data for the E2-transitions in Na-like highly stripped ions have a great demand (Tull et al., 1972; Charro et al., 2000; Ray, 2002a) even to search the basic physics. The studies on different iso-electronic and iso-nuclear sequences are essential for better understanding of underlying physics of atomic systems and for future progress.

The extremely hot environment of stars (for instance: the corona of the sun, planetary nebulae etc.) show abundances (Feldman, 1992) of highly stripped ions. To determine the abundances of heavy elements in the solar photospheres accurate knowledge of energy levels, transition probabilities or line strengths is of crucial importance. Many of the E2 lines arise from fine structure spectra whose observations are very important in determining atomic concentrations in astronomical and atmospheric sources and for determining the local physical conditions. In controlled thermonuclear reactions, atomic radiation is one of the primary loss mechanism. In laboratory tokamak plasmas and in various astronomical objects, suitably chosen E2-lines serve as a basis for reliable electron density and/or temperature diagnostic (Biemont et al., 1996). Many astrophysical phenomena like

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coronal heating, evolution of chemical composition in stellar envelopes, determination of the chemistry in the planetary nebulae precursor's envelope are believed to be explained largely by these forbidden lines. They can provide information on the thermal Doppler effect due to much longer wavelength when transition from metastable states occur in highly charged ion.

The first electric quadrupole transition calculations on NiXVIII were carried out by Tull et al. (1972) with a frozen core type Hartree-Fock (HF) orbitals. The detailed theoretical data of E2-transition probabilities for the Na-like iso-electronic highly stripped iron group ions were reported by Fuhr et al. (1988). To find the transition probabilities, it is essential to determine the term values very accurately since there is a fifth power dependence on these term values on transition probabilities. Tull et al. (1972) have reported non-relativistic line strength data and the term values with relativistic correction on their frozen core type Hartree-Fock orbitals through first order perturbation theory. Fuhr et al. (1988) have performed a relativistic calculation for E2-transition probabilities. A number of theoretical studies on electric and magnetic multipole transition rates performed in recent years using different approximations (Huang, 1985; Johnson et al., 1995; Safronova et al., 1999; Avgoustoglou et al., 1998; Beck 1998; Ishikawa et al., 2001) stressed on the importance of highly correlated wave functions to evaluate the transition rates accurately. For the electric-dipole forbidden transitions in high-Z ions, electric-quadrupole (E2) transition rates are dominant over magnetic-dipole (M1) rates. High precision calculation of transition energies as well as of wave functions are necessary. A relativistic description is necessary since the orbital electrons probe regions of space with high potential energy near the atomic nuclei; the primary effect of this relativistic description is to include changes in spatial and momentum distributions, spin-orbit interactions, quantum electrodynamic corrections such as Lamb shift and vacuum polarization whereas the secondary effect in many electron system is the modification of orbitals due to shielding of the other electrons in the penetrating orbits. Recently Charro et al. (2000) have employed a semi-empirical weakly correlated relativistic quantum defect orbital (RQDO) method to calculate the line strength for E2-transition for the same system.

We have used the Dirac-Hartree-Fock orbitals to consider the full relativistic effect. To include the effect of correlation, a many-body coupled-cluster method (CCM) is employed. This CCM theory is equivalent to an all order many-body perturbation theory.

An improved methodology (Majumder et al., 2001; Ray, 2002a,b,c) is used to generate the basis orbitals in the present prescription. The Dirac-Hartree-Fock method adapted in numerical MCDF GRASP-code by Parpia (1992) is able to generate only the bound orbitals due to the boundary conditions imposed to solve the differential equation; it creates convergence problem to generate higher orbitals. The Gaussian basis set expansion method is able to generate both the bound and continuum orbitals solving the Dirac-Hartree-Fock equation, but these orbitals are highly dependent on two arbitrary parameters, known in the literature as α_0 and β;

there is a great debate on the choice of these two parameters. In our calculation we have chosen a basis of total 98 orbitals with both bound and continuum; the continuum orbitals are confined within a maximum energy of 500 a.u. All the bound orbitals in our basis are obtained by using MCDF GRASP code (Parpia, 1992) and rest continuum orbitals from Gaussian code (Chaudhuri et al., 1999) choosing best values for α_0 and β. We have taken nine (9) s-orbitals upto 9s, eight (8) of each of $p_{1/2}$ and $p_{3/2}$ orbitals upto $9p_{1/2}$ and $9p_{3/2}$, seven (7) of each of $d_{3/2}$ and $d_{5/2}$ orbitals upto $9d_{3/2}$ and $9d_{5/2}$, five (5) of each of $f_{5/2}$ and $f_{7/2}$ orbitals upto 8 $f_{5/2}$ and 8 $f_{7/2}$, and three (3) of each of the $g_{7/2}$ and $g_{9/2}$ orbitals upto $7g_{7/2}$ and $7g_{9/2}$ as bound orbitals; the rest in our basis are virtual orbitals. These two different types of orbitals, bound and continuum are generated by two different codes, so they may not be orthogonal. We are considering that the MCDF GRASP orbitals are more closer to the accurate orbitals since they are obtained by imposing the proper physical boundary conditions. In our methodology, first we make the virtual orbitals orthogonal to the more accurate GRASP orbitals one by one following Schmidt orthogonalization procedure. These new orthogonal virtual orbitals are made normalized in the same Fock space. We have adapted a total of twelve (12) s-orbitals upto 12s; eleven (11) of each of the $p_{1/2}$, $p_{3/2}$, $d_{3/2}$, $d_{5/2}$, $f_{5/2}$; $f_{7/2}$ orbitals upto $12p_{1/2}$, $12p_{3/2}$, $13d_{3/2}$, $13d_{5/2}$, $14f_{5/2}$, $14f_{7/2}$; ten (10) of each of the $g_{7/2}$ and $g_{9/2}$ orbitals upto $14g_{7/2}$, $14g_{9/2}$. The motivation in choosing such an improved basis is to make the basis orbitals as close as possible to the accurate physical orbitals so that it can provide more accurate data in a finite set. However, the Slater determinant formed by these orbitals to represent the atomic state function (ASF) are deficient from the physical point of view due to the lack of correlation which is approximated by an equivalent single particle potential in the Dirac-Hartree-Fock theory. How the effect of correlation can be included properly in a many electron system is a great challenge to the quantum chemists, atomic and molecular physicists.

One of the most advanced method for treating this problem is the coupled cluster method (Bishop et al., 1987). It is a quantum many-body method in which the wavefunction is decomposed in terms of amplitudes for exciting clusters of a finite number of particles. The development of this theory started in nuclear physics community by Coester and Kiimmel (Coester, 1958; Coester et al., 1960) and was later introduced in quantum chemistry by Cizek and coworkers (Paldus et al., 1978; Paldus, 1983) which was applicable mainly to the closed shell systems. Subsequent development of this theory using the idea of complete model spaces (Lindgren, 1978; Ey, 1978; Mukherjee, 1986; Lindgren et al., 1987) and a Hermitian formulation (Lindgren, 1991) of the coupled cluster method has lead to connected cluster operators and an effective Hamiltonian, even for an incomplete model space.

The idea of the coupled cluster method (CCM) is as follows: Two particles in the filled Fermi sea interact with each other and lift themselves out of the Fermi sea, so that after the interaction both particles are in orbitals that in the previous simplified picture were unoccupied. This process may be described by a quantum

mechanical operator S_2 which acts on the Fermi sea wavefunction (say $\mid \Phi\rangle$) to produce the wavefunction $S_2 \mid \Phi\rangle$), which describes two particles outside the Fermi sea and consequently two holes inside it and all remaining N-2 particles are in their previous orbitals, where N is the total number of electrons present in the atom.

It may also happen that two pairs of particles do this completely independently. This process may be described by applying this operator S_2 twice and so on, with the proviso that we must include the proper weighting factor. By the principle of linear superposition, the total amplitude for excitation of an arbitrary number (s) 'm' (including zero) of independent pairs is

$$\sum_{m=0}^{\infty} \frac{1}{m!} s_2^m \mid \Phi\rangle = e^{S_2} \mid \Phi\rangle \tag{1.1}$$

Simultaneous excitation of three particles can be described by a contribution $S_3 \mid \Phi\rangle$ to the exact wavefunction and the simultaneous excitation of 'n' independent triplets will be $(1/n!)S_3^n \mid \Phi\rangle$. We must count also the possibility of simultaneous excitation of pairs and triplets. Again by linear superposition, the amplitude for simultaneous excitation of 'm' pairs and 'n' triplets from the Fermi sea is $(1/m!n!)S_2^m S_3^n \mid \Phi\rangle$. Here S_2 and S_3 are independent processes, so they commute and we need not worry about their ordering. Summing over all possible values of 'm' and 'n' leads to the amplitude $e^{(S_2+S_3)} \mid \Phi\rangle$ for the total effect of all pair and triplet excitations. Proceeding in this way with the excitation of clusters of 4, 5, ..., N particles we arrive at a wavefunction

$$\mid \Psi\rangle = e^S \mid \Phi\rangle \tag{1.2}$$

where

$$S = \sum_{n=1}^{N} S_n \tag{1.3}$$

Here S_n indicates excitation of n-particles at a time. John Hubbard (1957) noticed first that the operator generating the wavefunction of a quantum many-body system has an exponential form. This exponential representation may be regarded as an expansion of the exact wavefunction in a complete orthonormal basis. But we have to keep always in mind the arguments we have used. Such an interpretation of the wavefunction is very useful in practical application of coupled cluster method (CCM). It has a wide range of applicability in different fields of many-body systems of both bosons and fermions, quite regardless of the type and range of interaction and it can yield high-precision results for the ground state as well as low-energy excited states.

The CCM equations for the matrix elements of S_n are easily obtained by projecting the Schrödinger equation

$$e^{-S} H e^S \mid \Phi\rangle = E \mid \Phi\rangle \tag{1.4}$$

onto the complete N-body space spanned by the Fermi sea states and those states obtained by creating 'n' general particle-hole excitations out of it. This yields a series of coupled equations, each of which contains a finite number of terms. The first equation in this series yields an expression for E. Due to the special form of the above Schrödinger equation, the remaining equations do not involve the energy E or other macroscopic terms, and represent a truly microscopic decomposition of the Schrödinger equation into a set of coupled equations that describe the dynamics of the n-body clusters. These equations are intrinsically nonlinear. We consider all the single (S_1), double (S_2) and partial triple ($S_1 \times S_2$) excitations from the core in the present calculation.

The excitation operators can be written as:

$$S_1 = \sum_{i,a} s_i^a a^+ i \tag{1.5}$$

$$S_2 = \sum_{i,j,a,b} s_{ij}^{ab} a^+ i b^+ j \tag{1.6}$$

and so on. Here i, j are the hole annihilation; a^+, b^+ are the particle creation operators; s_i^a and s_{ij}^{ab} are the amplitudes for single-particle, two-particle excitations repectively.

2. Theory

2.1. Matrix element for electric quadrupole transition

The matrix element for electric quadrupole transitions is

$$\hat{Q}_{fi} = \langle \Psi_f \mid \hat{Q} \mid \Psi_i \rangle \tag{2.1}$$

where $\mid \Psi \rangle$ and $\mid \Psi_f \rangle$ denote respectively the initial and final atomic state functions. Here electric quadrupole operator $\hat{Q}$ is a rank two tensor and may be written as

$$\hat{Q} = er^2 C_q^2(\hat{r}) \tag{2.2}$$

The line strength is defined as

$$S_{fi} = \sum_{M_f, M_i} \mid \langle \Psi_f \mid \hat{Q} \mid \Psi_i \rangle \mid^2 \tag{2.3}$$

Applying the Wigner-Eckart theorem, the above expression transforms to

$$S_{fi} = \sum_{M_f, M_i} \sum_q (2J_f + 1) \begin{pmatrix} J_f & 2 & J_i \\ -M_f & q & M_i \end{pmatrix}^2$$

$$\mid \langle \Psi_f \mid\mid \hat{Q} \mid\mid \Psi_i \rangle \mid^2 \tag{2.4}$$

The transition probability (in s^{-1}) for present E2 transition is related with the line strength (in atomic or $e^2a_0^4$ unit) by the relation

$$A = (1.11995 \times 10^{18}/g_f\lambda^5)S_{fi} \tag{2.5}$$

Here λ is the wavelength in Å of the associated electromagnetic radiation, 'A' is the transition probability and g_f is the degeneracy of the final state.

The expression for the present E2 transition using CCM is

$$\langle \Psi_f \mid \hat{Q} \mid \Psi_i \rangle = \langle \Phi_f^0 \mid \{e^{s_f^\dagger}\}\bar{Q}\{e^{S_i}\} \mid \Phi_i^0 \rangle \tag{2.6}$$

with

$$\bar{Q} = e^{T^\dagger}\hat{Q}e^T \tag{2.7}$$

where T, S_i and S_f are the cluster operators for excitations from the core and the valence orbitals in the initial and final states respectively. The connected parts of Eq. (2.6) and Eq. (2.7) will contribute and hence we compute only those parts in our quadrupole matrix elements calculation. Here $\mid \Phi_i^0\rangle$ and $\mid \Phi_f^0\rangle$ are the Slater determinants obtained by using the Dirac Hartree Fock single particle orbitals.

3. Results and Discussion

We present the theoretical data for term values, E2-transition line strengths and transition probabilities which are far more accurate than the previous theoretical results. Firstly, we have used fully relativistic Dirac-Hartree-Fock (DHF) orbitals and secondly, we have included the effect of Coulomb correlation through an ab-initio all order many-body coupled-cluster theory. It should be noted that the present coupled-cluster theory is equivalent to an all order many-body perturbation theory. We have included all the single (S_1), double (S_2) and partially triple ($S_1 \times S_2$) excitations from the atomic core in our calculation. In Table I (a), we have compared our term values obtained by using CCM with fully relativistic Dirac-Hartree Fock orbitals, with the corresponding available experimental data of Feldman (1971) and the theoretical data of Tull et al. (1972). In their calculation of term values, Tull et al. have included the relativistic effect through first order perturbation theory on the non-relativistic frozen core type Hartree-Fock orbitals. The percentage errors with respect to the observed values are presented in the same table for both the theoretical results and the simple Dirac-Hartree-Fock (DHF) term values. A negative sign before the percentage error indicates that the experimental values are lower than the theoretical values and vice versa. The effect of the Coulomb correlation interaction can be understood by comparing rows *a* and *b* in Table I (a). All our theoretical results indicate the importance of correlation in such system. The effect of correlation is more in low lying states and in all the p-orbitals. Again it should be noted that the effect of correlation has changed all the errors to

TABLE I(a)
Term values of NiXVIII in cm^{-1}

Levels	Multiplicity	DHF$_a$	CCM$_b$	Tull et al.$_c$	Observed	% error$_a$	% error$_b$	% error$_c$
3s	1/2	0	0	0	0	0		
3p	1/2	313143	312158	311900	311860	–0.411	–0.095	–0.013
	3/2	344286	343433	340330	342460	–0.533	–0.284	0.622
3d	3/2	768810	767369	766680	765550	–0.426	–0.237	–0.148
	5/2	773807	772478	771880	770200	–0.468	–0.296	–0.218
4s	1/2	2299570	2302847	2300760	2301630	0.089	–0.053	0.038
4p	1/2	2424615	2427557	2425350	2426120	0.062	–0.059	0.032
	3/2	2436914	2439845	2436600	2438130	0.050	–0.070	0.063
4d	3/2	2593328	259658	2593770	2594350	0.039	–0.081	0.022
	5/2	2595583	2598752	2596000	2596490	0.035	–0.087	0.019
4f	5/2	2664120	2668204	2665880	2666150	0.076	–0.077	0.010
	7/2	2664921	2669012	2666690	2667010	0.078	–0.075	0.012
5s	1/2	3259617	3291032	3288210				
5p	1/2	3324793	3352741	3349860	3352440	0.825	–0.009	0.077
	3/2	3354612	3358811	3355440	3358070	0.103	–0.022	0.078
5d	3/2	3430231	3434578	3431440	3433540	0.096	–0.030	0.061
	5/2	3431407	3435773	3432590	3434600	0.093	–0.093	0.058
5f	5/2	3465837	3470567	3467650	3468980	0.091	–0.046	0.038
	7/2	3466250	3470984	3468070	3469300	0.088	–0.048	0.035
5g	7/2	3469520	3474872					
	9/2	3469765	3475118					
6s	1/2	3556532	3805457	3802310				
6p	1/2	3661489	3840354	3837180	3839360	4.633	–0.026	0.057
	3/2	3839044	3843789	3840340	3843200	0.108	–0.015	0.074
6d	3/2	3881446	3886285	3882960	3885590	0.107	–0.018	0.068
	5/2	3882130	3886981	3883630	3886050	0.101	–0.024	0.062
6f	5/2	3901817	3906850	3903670	3905760	0.101	–0.028	0.054
	7/2	3902057	3907093	3903910	3905980	0.100	–0.028	0.053
6g	7/2	3904211	3909605					
	9/2	3904353	3909747					
7s	1/2	3886037	4107115	4103800				
7p	1/2	3974221	4128729	4125400				
	3/2	4152017	4130859	4127360				
7d	3/2	4125839	4157098	4153680	4155060	0.703	–0.049	0.033
	5/2	4152449	4157537	4154090	4156630	0.101	–0.022	0.061
7f	5/2	4164748	4169942	4166620	4168880	0.099	–0.025	0.05
	7/2	4164900	4170096	4166770	4169020	0.099	–0.026	0.054
8s	1/2	4096351	4299064	4295650				

TABLE I(a)
Continued

Levels	Multiplicity	DHF$_a$	CCM$_b$	Tull et al.$_c$	Observed	% error$_a$	% error$_b$	% error$_c$
8p	1/2	4173434	4313362	4309940				
	3/2	4309601	4314774		4311240			
8d	3/2	4326902	4332116	4328630	4330990	0.094	–0.026	0.054
	5/2	4327192	4332411	4328910	4331290	0.095	–0.026	0.055
8f	5/2	4335386	4340671	4337260	4339530	0.095	–0.026	0.052
	7/2	4335487	4340774	4337360	4339330	0.088	–0.033	0.045
9s	1/2	4241971	4428723	4425240				
9p	1/2	4311875	4438668	4435180				
	3/2	4434390	4439651	4436090				
9d	3/2	4446422	4451712	4448190				
	5/2	4446626	4451919	4448380				
9f	5/2	4335386	4480474	4454220				
	7/2	4335487	4480653	4454290				

TABLE I(b)

Comparison of present line strength in a.u. with available theoretical data (Tull et al., 1972; Charro et al., 2000)

Transition	Line strength Present calculation			Line strength Charro et al.			Line strength Tull et al.
$n'l' \rightarrow$nl	**l**-1/2	**1**+1/2	Sum	**l**-1/2	**1**+1/2	Sum	Non-realitivistic
3s→3d	0.076	0.115	0.191	0.076	0.114	0.191	0.184
3s→4d	0.057	0.084	0.142	0.052	0.078	0.130	0.144
3s→5d	0.007	0.011	0.018	0.007	0.10	0.017	0.018
4s→4d	1.178	1.177	2.949	1.14	1.17	2.85	2.83
4s→5d	0.388	0.577	0.965	0.355	0.530	0.885	0.983
3p(1/2)→4f	0.204			0.207			
3p(3/2)→4f	0.060	0.361	0.625	0.061	0.365	0.633	0.603
3p(1/2)→4p		0.039		0.038	0.000		
3p(3/2)→4p	0.043	0.041	0.123	0.042	0.040	0.120	0.118
3d(3/2)→4d	0.038	0.016		0.038	0.016		
3d(5/2)→4d	0.017	0.066	0.137	0.016	0.658	0.137	0.131
4f(5/2)→5f	0.507	0.085		0.482	0.080		
4f(7/2)→5f	0.085	0.705	1.381	0.081	0.671	1.32	1.31

TABLE I(c)

Comparison of present transition probabilities with the available theoretical data by Fuhr et al. (1988) in units of $10^8 s^{-1}$. The quantities within third brackets indicate the powers of 10

Transition	Present E2-transition probabilities			E2-transition probabilities Fuhr et al.		
$n'l' \rightarrow$nl	**l**-1/2	**1**+1/2	Sum	**l**-1/2	**1**+1/2	Sum
3s→3d	8.03[-3]	8.36[-3]	1.64[-2]	8.2[-3]	8.4[-3]	1.66[-2]
3s→4d	2.67[0]	2.66[0]	5.33[0]	2.9[0]	2.8[0]	5.7[0]
3s→5d	1.40[0]	1.40[0]	2.80[0]		1.5[0]	
4s→4d	1.02[-3]	1.06[-3]	2.08[-3]	1.02[-3]	1.06[-3]	2.08[-3]
4s→5d	2.85[-1]	2.84[-1]	5.69[-1]	3.07[-1]	3.1[-1]	6.08[-1]
3p(1/2)→4f	3.91[0]			4.07[0]		
3p(3/2)→4f	1.08[0]	4.86[0]	9.85[0]	1.1[0]	4.92[0]	1.01[+1]
3p(1/2)→4p		6.73[-1]			7.1[-1]	
3p(3/2)→4p	1.33[0]	6.61[-1]	2.66[0]	1.3[0]	6.6[-1]	2.67[0]
3d(3/2)→4d	3.11[-1]	8.95[-2]		3.2[-1]	9.2[-2]	
3d(5/2)→4d	1.34[-1]	3.54[-1]	8.88[-1]	1.4[-1]	3.6[-1]	9.12[-1]
4f(5/2)→5f	4.45[-2]	5.59[-3]		4.48[-2]	5.60[-3]	
4f(7/2)→5f	7.43[-3]	4.63[-2]	1.04[-1]	7.40[-3]	4.70[-2]	1.05[-1]

negative which means that the improved term values are slightly higher than the observed values. The low lying p(3/2) and d(3/2,5/2) deviate more strongly. The percentage error is $\sim 10^{-1}$ whereas in other cases it is $\sim 10^{-2}$. In Table I (b), a few of our line strength data are compared with the existing non-relativistic data of Tull et al. (1972) and a quasi-relativistic RQDO-data of Charro et al. (2000). Similarly in Table I (c), a few of our transition probability data are compared with the relativistic E2-transition probability data of Fuhr et al. (1988). All the present data are in consistency with other theoretical values. In Table II, the present detailed data for E2-transition line strengths and transition probabilities for NiXVIII are reported with both the experimental and the theoretical transition energies. All line strength results are in close agreement with the relativistic results of Charro et al. (2000) and the non-relativistic results of Tull et al. (1972). Our line strength data in Table II need a multiplicative factor of $1/\sqrt{2}$ to compare with others. All our transition probality data are also in agreement with Fuhr et al. (1988). Some of the data reported here are completely new.

TABLE II

Line strength in a.u. and transition probability in s^{-1} in general E-format

Transition (f→i)	Line strength	Transition probability
3s(1/2)→3d(3/2)	0.10777E+00	0.803E+06
3s(1/2)→4d(3/2)	0.80853E-01	0.267E+09
3x(1/2)→5d(3/2)	0.10475E-01	0.140E+09
3s(1/2)→6d(3/2)	0.31256E-02	0.776E+08
3s(1/2)→7d(3/2)	0.13451E-02	0.468E+08
3s(1/2)→8d(3/2)	0.69812E-03	0.298E+08
3s(1/2)→9d(3/2)	0.35168E-03	0.172E+08
3s(1/2)→3d(5/2)	0.16287E+00	0.836E+06
3s(1/2)→4d(5/2)	0.12033E+00	0.266E+09
3s(1/2)→5d(5/2)	0.15671E-01	0.140E+09
3s(1/2)→6d(5/2)	0.46817E-02	0.775E+08
3s(1/2)→7d(5/2)	0.20160E-02	0.467E+08
3s(1/2)→8d(5/2)	0.10465E-02	0.298E+08
3s(1/2)→9d(5/2)	0.52691E-03	0.172E+08
4s(1/2)→4d(3/2)	0.16654E+01	0.102E+06
4s(1/2)→5d(3/2)	0.54860E+00	0.285E+08
4s(1/2)→6d(3/2)	0.71668E-01	0.200E+08
4s(1/2)→7d(3/2)	0.21256E-01	0.130E+08
4s(1/2)→8d(3/2)	0.90267E-02	0.870E+07
4s(1/2)→9d(3/2)	0.42047E-02	0.539E+07
4s(1/2)→4d(5/2)	0.25047E+01	0.106E+06
4s(1/2)→5d(5/2)	0.81598E+00	0.284E+08
4s(1/2)→6d(5/2)	0.10736E+00	0.200E+08
4s(1/2)→7d(5/2)	0.31943E-01	0.131E+08
4s(1/2)→8d(5/2)	0.13591E-01	0.874E+07
4s(1/2)→9d(5/2)	0.63379E-02	0.542E+07
5s(1/2)→5d(3/2)	0.11872E+02	0.203E+05
5s(1/2)→6d(3/2)	0.24842E+01	0.520E+07
5s(1/2)→7d(3/2)	0.31698E+00	0.432E+07
5s(1/2)→8d(3/2)	0.91848E-01	0.315E+07
5s(1/2)→9d(3/2)	0.36113E-01	0.213E+07
5s(1/2)→5d(5/2)	0.17840E+02	0.212E+05
5s(1/2)→6d(5/2)	0.36881E+01	0.517E+07
5s(1/2)→7d(5/2)	0.47383E+00	0.432E+07
5s(1/2)→8d(5/2)	0.13770E+00	0.315E+07
5s(1/2)→9d(5/2)	0.54221E-01	0.213E+07

TABLE II
Continued

Transition (f→i)	Line strength	Transition probability
6s(1/2)→6d(3/2)	0.56168E+02	0.543E+04
6s(1/2)→7d(3/2)	0.87229E+01	0.131E+07
6s(1/2)→8d(3/2)	0.10777E+01	0.122E+07
6s(1/2)→9d(3/2)	0.29452E+00	0.930E+06
7s(1/2)→7d(3/2)	0.20438E+03	0.179E+04
7s(1/2)→8d(3/2)	0.25633E+02	0.414E+06
7s(1/2)→9d(3/2)	0.30190E+01	0.411E+06
8s(1/2)→8d(3/2)	0.61860E+03	0.683E+03
8s(1/2)→9d(3/2)	0.65586E+02	0.152E+06
9s(1/2)→9d(3/2)	0.16374E+04	0.294E+03
6s(1/2)→6d(5/2)	0.84346E+02	0.567E+04
6s(1/2)→7d(5/2)	0.12936E+02	0.131E+07
6s(1/2)→Sd(5/2)	0.16093E+01	0.122E+07
6s(1/2)→9d(5/2)	0.44100E+00	0.929E+06
7s(1/2)→7d(5/2)	0.30679E+03	0.187E+04
7s(1/2)→8d(5/2)	0.37984E+02	0.412E+06
7s(1/2)→9d(5/2)	0.45037E+01	0.410E+06
8s(1/2)→8d(5/2)	0.92824E+03	0.714E+03
8s(1/2)→9d(5/2)	0.97123E+02	0.151E+06
9s(1/2)→9d(5/2)	0.24564E+04	0.308E+03
3d(3/2)→4s(1/2)	0.39249E-01	0.188E+08
3d(3/2)→5s(1/2)	0.16822E-02	0.964E+07
3d(3/2)→6s(1/2)	0.39110E-03	0.567E+07
3d(3/2)→7s(1/21	0.15453E-03	0.360E+07
3d(3/2)→8s(1/2)	0.78836E-04	0.243E+07
3d(3/2)→9s(1/2)	0.48334E-04	0.178E+07
4d(3/2)→5s(1/2)	0.58703E+00	0.531E+07
4d(3/2)→6s(1/2)	0.21319E-01	0.308E+07
4d(3/2)→7s(1/2)	0.45187E-02	0.199E+07
4d(3/2)→8s(1/2)	0.16835E-02	0.135E+07
4d(3/2)→9s(1/2)	0.81476E-03	0.942E+06
5d(3/2)→6s(1/2)	0.41234E+01	0.162E+07
5d(3/2)→7s(1/2)	0.13130E+00	0.101E+07
5d(3/2)→8x(1/2)	0.25690E-01	0.695E+06
5d(3/2)→9s(1/2)	0.89285E-02	0.486E+06
6d(3/2)→7s(1/2)	0.19337E+02	0.569E+06
6d(3/2)→8s(1/2)	0.55471E+00	0.372E+06

TABLE II
Continued

Transition (f→i)	Line strength	Transition probability
6d(3/2)→9s(1/2)	0.10033E+00	0.264E+06
7d(3/2)→8s(1/2)	0.69935E+02	0.226E+06
7d(3/2)→9s(1/2)	0.18326E+01	0.152E+06
8d(3/2)→9s(1/2)	0.21034E+03	0.991E+05
3p(1/2)→3p(3/2)	0.13686E+00	0.115E+00
3p(1/2)→4p(3/2)	0.55094E-01	0.673E+08
3p(1/2)→5p(3/2)	0.50379E-02	0.370E+08
3p(1/2)→6p(3/2)	0.14136E-02	0.217E+08
3p(1/2)→7p(3/2)	0.60172E-03	0.137E+08
3p(1/2)→8p(3/2)	0.31406E-03	0.903E+07
3p(1/2)→9p(3/2)	0.17697E-03	0.594E+07
4p(1/2)→4p(3/2)	0.18051E+01	0.142E-01
4p(1/2)→5p(3/2)	0.54305E+00	0.106E+08
4p(1/2)→6p(3/2)	0.43413E-01	0.693E+07
4p(1/2)→7p(3/2)	0.11251E-01	0.452E+07
4p(1/2)→8p(3/2)	0.45276E-02	0.303E+07
4p(1/2)→9p(3/2)	0.21408E-02	0.198E+07
5p(1/2)→5p(3/2)	0.12367E+02	0.285E-02
5p(1/2)→6p(3/2)	0.31105E+01	0.249E+07
5p(1/2)→7p(3/2)	0.22660E+00	0.181E+07
5p(1/2)→8p(3/2)	0.55033E-01	0.127E+07
5p(1/2)→9p(3/2)	0.20250E-01	0.860E+06
6p(1/2)→6p(3/2)	0.57799E+02	0.775E-03
6p(1/2)→7p(3/2)	0.12875E+02	0.746E+06
6p(1/2)→8p(3/2)	0.87320E+00	0.588E+06
6p(1/2)→9p(3/2)	0.19619E+00	0.425E+06
7p(1/2)→7p(3/2)	0.20969E+03	0.258E-03
7p(1/2)→Sp(3/2)	0.42758E+02	0.267E+06
7p(1/2)→9p(3/2)	0.27069E+01	0.220E+06
8p(1/2)→8p(3/2)	0.63508E+03	0.997E-04
8p(1/2)→9p(3/2)	0.12057E+03	0.108E+06
9p(1/2)→9p(3/2)	0.16851E+04	0.433E-04
3p(3/2)→3p(1/2)	0.13729E+00	0.230E+00
3p(3/2)→4p(1/2)	0.60621E-01	0.133E+09
3p(3/2)→5p(1/2)	0.52254E-02	0.722E+08
3p(3/2)→6p(1/2)	0.14381E-02	0.421E+08
3p(3/2)→7p(1/2)	0.60619E-03	0.264E+08

TABLE II
Continued

Transition (f→i)	Line strength	Transition probability
3p(3/2)→8p(1/2)	0.31399E-03	0.173E+08
4p(3/2)→4p(1/2)	0.18137E+01	0.285E-01
4p(3/2)→5p(1/2)	0.59471E+00	0.211E+08
4p(3/2)→6p(1/2)	0.44634E-01	0.135E+08
4p(3/2)→7p(1/2)	0.11303E-01	0.870E+07
4p(3/2)→8p(1/2)	0.44884E-02	0.580E+07
5p(3/2)→5p(1/2)	0.12423E+02	0.573E-02
5p(3/2i→6p(1/2)	0.34017E+01	0.493E+07
5p(3/2)→7p(1 2)	0.23250E+00	0.352E+07
5p(3/2)→8p(1/2)	0.55103E-01	0.245E+07
6p(3/2)→6p(1/2)	0.58047E+02	0.156E-02
6p(3/2)→7p(1/2)	0.14070E+02	0.148E+07
6p(3/2)→8p(1/2)	0.89457E+00	0.114E+07
7p(3/2)→7p(1/2)	0.21057E+03	0.518E-03
7p(3/2)→8p(1/2)	0.46694E+02	0.529E+06
8p(3/2)→8p(1/2)	0.63780E+03	0.200E-03
3p(3/2)→4p(3/2)	0.58277E-01	0.661E+08
3p(3/2)→5p(3/2)	0.512589-02	0.358E+08
3p(3/2)→6p(3/2)	0.14178E-02	0.209E+08
3p(3/2)→7p(3/2)	0.59875E-03	0.131E+08
3p(3/2)→8p(3/2)	0.31068E-03	0.859E+07
3p(3/2)→9p(3/2)	0.17292E-03	0.558E+07
4p(3/2)→4p(3/2)	0.18247E+01	0.000E+00
4p(3/2)→5p(3/2)	0.57064E+00	0.105E+08
4p(3/2)→6p(3/2)	0.43734E-01	0.668E+07
4p(3/2)→7p(3/2)	0.11142E-01	0.431E+07
4p(3/2)→8p(3/2)	0.44386E-02	0.288E+07
4p(3/2)→9p(3/2)	0.20786E-02	0.186E+07
5p(3/2)→5p(3/2)	0.12473E+02	0.000E+00
5p(3/2)→6p(3/2)	0.32572E+01	0.245E+07
5p(3/2)→7p(3/2)	0.22703E+00	0.174E+07
5p(3/2)→8p(3/2)	0.54088E-01	0.121E+07
5p(3/2)→9p(3/2)	0.19659E-01	0.812E+06
6p(3/2)→6p(3/2)	0.58208E+02	0.000E+00
6p(3/2)→7p(3/2)	0.13453E+02	0.734E+06
6p(3/2)→8p(3/2)	0.87171E+00	0.566E+06
6p(3/2)→9p(3/2)	0.19185E+00	0.403E+06

TABLE II
Continued

Transition (f→i)	Line strength	Transition probability
7p(3/2)→8p(3/2)	0.44612E+02	0.263E+06
7p(3/2)→9p(3/2)	0.26959E-01	0.212E+06
8p(3/2)→9p(3/2)	0.12567E+03	0.107E+06
3p(1/2)→4f(5/2)	0.28831E+00	0.391E+09
3p(1/2)→5f(5/2)	0.10785E-01	0.633E+08
3p(1/2)→6f(5/2)	0.13048E-02	0.146E+08
3p(1/2)→7f(5/2)	0.26286E-03	0.419E+07
3p(1/2)→8f(5/2)	0.68666E-04	0.136E+07
3p(1/2)→9f(5/2)	0.91041E-05	0.214E+06
4p(1/2)→4f(5/2)	0.15625E+01	0.235E+05
4p(1/2)→5f(5/2)	0.19632E+01	0.452E+08
4p(1/2)→6f(5/2)	0.14274E+00	0.189E+08
4p(1/2)→7f(5/2)	0.29173E-01	0.874E+07
4p(1/2)→8f(5/2)	0.95643E-02	0.458E+07
4p(1/2)→9f(5/2)	0.33325E-02	0.227E+07
5p(1/2)→5f(5/2)	0.14923E+02	0.633E+04
5p(1/2)→6f(5/2)	0.84163E+01	0.821E+07
5p(1/2)→7f(5/2)	0.73047E+00	0.497E+07
5p(1/2)→8f(5/2)	0.16708E+00	0.293E+07
5p(1/2)→9f(5/2)	0.47035E-01	0.160E+07
6p(1/2)→6f(5/2)	0.78625E+02	0.191E+04
6p(1/2)→7f(5/2)	0.27993E+02	0.203E+07
6p(1/2)→8f(5/2)	0.25850E+01	0.151E+07
6p(1/2)→9f(5/2)	0.46329E+00	0.929E+06
7p(1/2)→7f(5/2)	0.30121E+03	0.669E+03
7p(1/2)→8f(5/2)	0.78489E+02	0.627E+06
7p(1/2)→9f(5/2)	0.54158E+01	0.544E+06
8p(1/2)→8f(5/2)	0.93765E+03	0.266E+03
8p(1/2)→9f(5/2)	0.14543E+03	0.354E+06
9p(1/2)→9f(5/2)	0.26975E+04	0.643E+04
3p(3/2)→4f(5/2)	0.84978E-01	0.108E+09
3p(3/2)→5f(5/2)	0.29535E-02	0.165E+08
3p(3/2)→6f(5/2)	0.33221E-03	0.356E+07
3p(3/2)→7f(5/2)	0.61133E-04	0.936E+06

TABLE II
Continued

Transition (f→i)	Line strength	Transition probability
3p(3/2)→8f(5/2)	0.14083E-04	0.268E+06
4p(3/2)→4f(5/2)	0.44716E+00	0.518E+04
4p(3/2)→5f(5/2)	0.58302E+00	0.127E+08
4p(3/2)→6f(5/2)	0.40413E-01	0.513E+07
4p(3/2)→7f(5/2)	0.80295E-02	0.232E+07
4p(3/2)→8f(5/2)	0.25775E-02	0.119E+07
4p(3/2)→9f(5/2)	0.86244E-03	0.570E+06
5p(3/2)→5f(5/2)	0.42750E+01	0.139E+04
5p(3/2)→6f(5/2)	0.25128E+01	0.232E+07
5p(3/2)→7f(5/2)	0.20937E+00	0.137E+07
5p(3/2)→8f(5/2)	0.46895E-01	0.799E+06
5p(3/2)→9f(5/2)	0.12896E-01	0.427E+06
6p(3/2)→6f(5/2)	0.22539E+02	0.420E+03
6p(3/2)→7f(5/2)	0.83884E+01	0.578E+06
6p(3/2)→8f(5/2)	0.74592E+00	0.422E+06
6p(3/2)→9f(5/2)	0.13067E+00	0.255E+06
7p(3/2)→7f(5/2)	0.86386E+02	0.147E+03
7p(3/2)→8f(5/2)	0.23586E+02	0.179E+06
7p(3/2)→9f(5/2)	0.15676E+01	0.153E+06
8p(3/2)→8f(5/2)	0.26902E+03	0.585E+02
8p(3/2)→9f(5/2)	0.43850E+02	0.102E+06
9p(3/2)→9f(5/2)	0.77903E+03	0.165E+04
3p(3/2)→4f(7/2)	0.51043E+00	0.486E+09
3p(3/2)→5f(7/2)	0.17891E-01	0.750E+08
3p(3/2)→6f(7/2)	0.20321E-02	0.164E+08
3p(3/2)→7f(7/2)	0.37897E-03	0.435E+07
3p(3/2)→8f(7/2)	0.89048E-04	0.127E+07
3p(3/2)→9f(7/2)	0.61839E-05	0.105E+06
4p(3/2)→4f(7/2)	0.26876E+01	0.238E+05
4p(3/2)→5f(7/2)	0.34943E+01	0.570E+08
4p(3/2)→6f(7/2)	0.24319E+00	0.232E+08
4p(3/2)→7f(7/2)	0.48437E-01	0.105E+08
4p(3/2)→8f(7/2)	0.15577E-01	0.541E+07
4p(3/2)→9f(7/2)	0.52563E-02	0.260E+07
5p(3/2)→5f(7/2)	0.25680E+02	0.638E+04
5p(3/2)→6f(7/2)	0.15046E+02	0.104E+08
5p(3/2)→7f(7/2)	0.12579E+01	0.619E+07

TABLE II
Continued

Transition (f→i)	Line strength	Transition probability
5p(3/2)→8f(7/2)	0.28226E+00	0.361E+07
5p(3/2)→9f(7/2)	0.78140E-01	0.194E+07
6p(3/2)→6f(7/2)	0.13535E+03	0.193E+04
6p(3/2)→7f(7/2)	0.50198E+02	0.260E+07
6p(3/2)→8f(7/2)	0.44776E+01	0.190E+07
6p(3/2)→9f(7/2)	0.78890E+00	0.116E+07
7p(3/2)→7f(7/2)	0.51865E+03	0.675E+03
7p(3/2)→8f(7/2)	0.14108E+03	0.805E+06
7p(3/2)→9f(7/2)	0.94318E+01	0.691E+06
8p(3/2)→8f(7/2)	0.16149E+04	0.269E+03
8p(3/2)→9f(7/2)	0.26262E+03	0.462E+06
9p(3/2)→9f(7/2)	0.46697E+04	0.758E+04
4f(5/2)→5f(5/2)	0.71681E+00	0.445E+07
4f(5/2)→6f(5/2)	0.40050E-01	0.218E+07
4f(5/2)→7f(5/2)	0.85517E-02	0.122E+07
4f(5/2)→8f(5/2)	0.29926E-02	0.731E+06
4f(5/2)→9f(5/2)	0.79253E-03	0.289E+06
5f(5/2)→6f(5/2)	0.52275E+01	0.154E+07
5f(5/2)→7f(5/2)	0.30062E+00	0.939E+06
5f(5/2)→8f(5/2)	0.63538E-01	0.591E+06
5f(5/2)→9f(5/2)	0.15644E-01	0.307E+06
6f(5/2)→7f(5/2)	0.23366E+02	0.550E+06
6f(5/2)→8f(5/2)	0.13283E+01	0.381E+06
6f(5/2)→9f(5/2)	0.19794E+00	0.229E+06
4f(7/2)→5f(5/2)	0.12034E+00	0.743E+06
4f(7/2)→6f(5/2)	0.67322E-02	0.365E+06
4f(7/2)→7f(5/2)	0.14410E-02	0.205E+06
4f(7/2)→8f(5/2)	0.50581E-03	0.123E+06
4f(7/2)→9f(5/2)	0.13557E-03	0.494E+05
5f(7/2)→6f(5/2)	0.87909E+00	0.258E+06
5f(7/2)→7f(5/2)	0.50705E-01	0.158E+06
5f(7/2)→8f(5/2)	0.10762E-01	0.999E+05
5f(7/2)→9f(5/2)	0.26800E-02	0.524E+05
6f(7/2)→7f(5/2)	0.39331E+01	0.921E+05
6f(7/2)→8f(5/2)	0.22450E+00	0.642E+05
6f(7/2)→9f(5/2)	0.33832E-01	0.391E+05
7f(7/2)→8f(5/2)	0.13483E+02	0.363E+05

TABLE II
Continued

Transition (f→i)	Line strength	Transition probability
7f(7/2)→9f(5/2)	0.54587E+00	0.293E+05
8f(7/2)→9f(5/2)	0.29714E+02	0.295E+05
4f(5/2)→4f(7/2)	0.27572E+00	0.133E-08
4f(5/2)→5f(7/2)	0.11974E+00	0.559E+06
4f(5/2)→6f(7/2)	0.67428E-02	0.275E+06
4f(5/2)→7f(7/2)	0.14468E-02	0.155E+06
4f(5/2)→8f(7/2)	0.50817E-03	0.931E+05
4f(5/2)→9f(7/2)	0.13746E-03	0.376E+05
5f(5/2)→5f(7/2)	0.27039E+01	0.479E-09
5f(5/2)→6f(7/2)	0.87396E+00	0.194E+06
5f(5/2)→7f(7/2)	0.50732E-01	0.119E+06
5f(5/2)→8f(7/2)	0.10791E-01	0.754E+05
5f(5/2)→9f(7/2)	0.27060E-02	0.398E+05
6f(5/2)→6f(7/2)	0.14599E+02	0.173E-09
6f(5/2)→7f(7/2)	0.39086E+01	0.692E+05
6f(5/2)→8f(7/2)	0.22449E+00	0.483E+05
6f(5/2)→9f(7/2)	0.34051E-01	0.297E+05
7f(5/2)→7f(7/2)	0.56863E+02	0.677E-10
7f(5/2)→8f(7/2)	0.13395E+02	0.273E+05
7f(5/2)→9f(7/2)	0.54707E+00	0.222E+05
8f(5/2)→8f(7/2)	0.17911E+03	0.291E-10
8f(5/2)→9f(7/2)	0.29546E+02	0.222E+05
9f(5/2)→9f(7/2)	0.85237E+03	0.223E-08
4f(7/2)→5f(7/2)	0.99666E+00	0.463E+07
4f(7/2)→6f(7/2)	0.55693E-01	0.227E+07
4f(7/2)→7f(7/2)	0.11894E-01	0.127E+07
4f(7/2)→8f(7/2)	0.41658E-02	0.762E+06
4f(7/2)→9f(7/2)	0.11159E-02	0.305E+06
5f(7/2)→6f(7/2)	0.72664E+01	0.160E+07
5f(7/2)→7f(7/2)	0.41792E+00	0.977E+06
5f(7/2)→8f(7/2)	0.88359E-01	0.616E+06
5f(7/2)→9f(7/2)	0.21907E-01	0.322E+06
6f(7/2)→7f(7/2)	0.32474E+02	0.572E+06
6f(7/2)→8f(1/2)	0.18463E+01	0.397E+06
6f(7/2)→9f(r/2)	0.27643E+00	0.240E+06
7f(7/2)→8f(7/2)	0.11123E+03	0.226E+06
7f(7/2)→9f(7/2)	0.44772E+01	0.181E+06

TABLE II
Continued

Transition (f→i)	Line strength	Transition probability
8f(7/2)→9f(7/2)	0.24511E+03	0.184E+06
3d(3/2)→5g(7/2)	0.17494E+00	0.356E+09
3d(3/2)→6g(7/2)	0.63284E-01	0.271E+09
4d(3/2)→5g(7/2)	0.58146E+01	0.426E+08
4d(3/2)→6g(7/2)	0.90417E-03	0.494E+05
5d(3/2)→5g(7/2)	0.11622E+02	0.173E+02
5d(3/2)→6g(7/2)	0.30751E+02	0.104E+08
6d(3/2)→6g(7/2)	0.89285E-02	0.862E+01
3d(5/2)→5g(7/2)	0.19598E-01	0.395E+08
3d(5/2)→6g(7/2)	0.70725E-02	0.301E+08
4d(5/2)→5g(7/2)	0.64858E+00	0.469E+07
4d(5/2)→6g(7/2)	0.13046E-03	0.707E+04
5d(5/2)→5g(7/2)	0.12896E+01	0.165E+01
5d(5/2)→6g(7/2)	0.34355E+01	0.115E+07
6d(5/2)→6g(7/2)	0.99100E+01	0.822E+00
5g(7/2)→6d(3/2)	0.67098E+00	0.221E+06
5g(7/2)→7d(3/2)	0.36147E-01	0.150E+06
5g(7/2)→8d(3/2)	0.76403E-02	0.990E+05
5g(7/2)→9d(3/2)	0.27832E-02	0.693E+05
6g(7/2)→7d(3/2)	0.62066E+01	0.161E+06
6g(7/2)→8d(3/2)	0.32109E+00	0.121E+06
6g(7/2)→9d(3/2)	0.66742E-01	0.875E+05
5g(9/2)→6d(5/2)	0.92278E+00	0.204E+06
5g(9/2)→7d(5/2)	0.49924E-01	0.138E+06
5g(9/2)→8d(5/2)	0.10563E-01	0.913E+05
5g(9/2)→9d(5/2)	0.38493E-02	0.639E+05
6g(9/2)→7d(5/2)	0.85386E+01	0.149E+06
6g(9/2)→8d(5/2)	0.44377E+00	0.112E+06
6g(9/2)→9d(5/2)	0.92353E-01	0.808E+05
3d(3/2)→4d(3/2)	0.54208E-01	0.311E+08
3d(3/2)→5d(3/2)	0.38570E-02	0.146E+08
3d(3/2)→6d(3/2)	0.96249E-03	0.795E+07
3d(3/2)→7d(3/2)	0.38529E-03	0.483E+07
3d(3/2)→8d(3/2)	0.19649E-03	0.317E+07
3d(3/2)→9d(3/2)	0.12120E-03	0.230E+07
4d(3/2)→5d(3/2)	0.59724E+00	0.692E+07
4d(3/2)→6d(3/2)	0.40812E-01	0.408E+07

TABLE II
Continued

Transition (f→i)	Line strength	Transition probability
4d(3/2)→7d(3/2)	0.97747E-02	0.253E+07
4d(3/2)→8d(3/2)	0.37848E-02	0.167E+07
4d(3/2)→9d(3/2)	0.18671E-02	0.115E+07
5d(3/2)→6d(3/2)	0.34972E+01	0.184E+07
5d(3/2)→7d(3/2)	0.22662E+00	0.125E+07
5d(3/2)→8d(3/2)	0.51919E-01	0.847E+06
5d(3/2)→9d(3/2)	0.19107E-01	0.582E+06
6d(3/2)→7d(3/2)	0.14523E+02	0.592E+06
6d(3/2)→8d(3/2)	0.89542E+00	0.442E+06
6d(3/2)→9d(3/2)	0.19439E+00	0.315E+06
7d(3/2)→8d(3/2)	0.48126E+02	0.221E+06
7d(3/2)→9d(3/2)	0.28193E+01	0.175E+06
8d(3/2)→9d(3/2)	0.13533E+03	0.927E+05
3d(3/2)→3d(5/2)	0.40370E-01	0.262E-05
3d(3/2)→4d(5/2)	0.23274E-01	0.895E+07
3d(3/2)→5d(5/2)	0.16821E-02	0.425E+07
3d(3/2)→6d(5/2)	0.42363E-03	0.234E+07
3d(3/2)→7d(5/2)	0.17059E-03	0.143E+07
3d(3/2)→8d(5/2)	0.87349E-04	0.939E+06
3d(3/2)→9d(5/2)	0.54012E-04	0.685E+06
4d(3/2)→4d(5/2)	0.70598E+00	0.838E-06
4d(3/2)→5d(5/2)	0.25607E+00	0.199E+07
4d(3/2)→6d(5/2)	0.17764E-01	0.119E+07
4d(3/2)→7d(5/2)	0.42882E-02	0.742E+06
4d(3/2)→8d(5/2)	0.16688E-02	0.491E+06
4d(3/2)→9d(5/2)	0.82622E-03	0.339E+06
5d(3/2)→5d(5/2)	0.52635E+01	0.239E-06
5d(3/2)→6d(5/2)	0.14994E+01	0.530E+06
5d(3/2)→7d(5/2)	0.98752E-01	0.364E+06
5d(3/2)→8d(5/2)	0.22834E-01	0.249E+06
5d(3/2)→9d(5/2)	0.84580E-02	0.172E+06
6d(3/2)→6d(5/2)	0.25433E+02	0.773E-07
6d(3/2)→7d(5/2)	0.62272E+01	0.171E+06
6d(3/2)→8d(5/2)	0.39069E+00	0.129E+06
6d(3/2)→9d(5/2)	0.85727E-01	0.926E+05
3d(5/2)→4d(3/2)	0.23636E-01	0.134E+08
3d(5/2)→5d(3/2)	0.16760E-02	0.627E+07

TABLE II
Continued

Transition (f→i)	Line strength	Transition probability
3d(5/2)→6d(3/2)	0.41858E-03	0.343E+07
3d(5/2)→7d(3/2)	0.16772E-03	0.209E+07
3d(5/2)→8d(3/2)	0.85599E-04	0.137E+07
3d(5/2)→9d(3/2)	0.52641E-04	0.994E+06
4d(5/2)→5d(3/2)	0.26078E+00	0.298E+07
4d(5/2)→6d(3/2)	0.17784E-01	0.176E+07
4d(5/2)→7d(3/2)	0.42651E-02	0.110E+07
4d(5/2)→8d(3/2)	0.16539E-02	0.725E+06
4d(5/2)→9d(3/2)	0.81657E-03	0.499E+06
5d(5/2)→6d(3/2)	0.15291E+01	0.795E+06
5d(5/2)→7d(3/2)	0.99073E-01	0.542E+06
5d(5/2)→8d(3/2)	0.22772E-01	0.369E+06
5d(5/2)→9d(3/2)	0.84110E-02	0.255E+06
6d(5/2)→7d(3/2)	0.63536E+01	0.256E+06
6d(5/2)→8d(3/2)	0.39215E+00	0.192E+06
6d(5/2)→9d(3/2)	0.85559E-01	0.138E+06
3d(5/2)→4d(5/2)	0.93380E-01	0.354E+08
3d(5/2)→5d(5/2)	0.66420E-02	0.166E+08
3d(5/2)→6d(5/2)	0.16580E-02	0.907E+07
3d(5/2)→7d(5/2)	0.663598-03	0.551E+07
3d(5/2)→8d(5/2)	0.33831E-03	0.361E+07
3d(5/2)→9d(5/2)	0.20807E-03	0.262E+07
4d(5/2)→5d(5/2)	0.10280E+01	0.788E+07
4d(5/2)→6d(5/2)	0.70258E-01	0.465E+07
4d(5/2)→7d(5/2)	0.16829E-01	0.289E+07
4d(5/2)→8d(5/2)	0.65166E-02	0.190E+07
4d(5/2)→9d(5/2)	0.32136E-02	0.131E+07
5d(5/2)→6d(5/2)	0.60154E+01	0.210E+07
5d(5/2)→7d(5/2)	0.38987E+00	0.143E+07
5d(5/2)→8d(5/2)	0.89342E-01	0.966E+06
5d(5/2)→9d(5/2)	0.32894E-01	0.665E+06
6d(5/2)→7d(5/2)	0.24967E+02	0.676E+06
6d(5/2)→8d(5/2)	0.15398E+01	0.504E+06
6d(5/2)→9d(5/2)	0.33447E+00	0.359E+06
7d(5/2)→8d(5/2)	0.82709E+02	0.252E+06
7d(5/2)→9d(5/2)	0.48475E+01	0.200E+06
8d(5/2)→9d(5/2)	0.23254E+03	0.106E+06

4. Conclusion

The continuing developments in astrophysical and astronomical observations demand accurate theoretical transition data to determine the stellar chemical composition. The most improved present theoretical values obtained from the highly correlated many-body coupled-cluster method using fully relativistic Dirac-Fock orbitals generated by an improved methodology of forming basis sets, are definitely very accurate for the highly stripped Na-like iron group ion NiXVIII and can partially meet the present requirement. The variation of the percentage errors of different theories from the observed term values in the same atom can provide information to understand the basic physics and at the same time it can provide hints for future improvement. The variation of the properties like orbital energies, term-values, transition probabilities, line-strengths along different iso-electronic and iso-nuclear sequences can be useful to assure the underlying physics and for future progress.

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