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Energy levels and radiative rates for Ne-like ions from Cu to Ga

NARENDRA SINGH* and SUNNY AGGARWAL

Department of Physics, Shyamlal College (University of Delhi), G.T. Road, Shahdara, Delhi 110 032, India
*Corresponding author. E-mail: nsingh76@yahoo.co.in

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Abstract. Energy levels, lifetimes and wave function compositions are computed for 127 fine structural levels in Ne-like ions ($Z = 29-31$). Configuration interaction has been included among 51 configurations (generating 1016 levels) and multiconfigurational Dirac–Fock method is used to generate the wave functions. Similar calculations have also been performed using the fully relativistic flexible atomic code (FAC). Transition wavelength, oscillator strength, transition probabilities and line strength are reported for electric dipole (E1), electric quadrupole (E2), magnetic dipole (M1) and magnetic quadrupole (M2) transitions from the ground level. We compared our calculated results with the available data in the literature. The calculated results are found to be in close agreement with the previous results. Further, we predict some new atomic data which may be important for plasma diagnostics.

Keywords. Energy levels; oscillator strength; transition probability; GRASP.

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1. Introduction

The spectral lines for neon-like ions are useful in finding the abundance of their ionization states in laboratory and astrophysical [1,2] plasmas. Also, Ne-like ions are highly useful for the modelling of astrophysical, fusion and laser-generated plasmas. Further, because of their closed shell structure, we can estimate the importance of the contributions from relativistic, electron correlations and quantum electrodynamics (QED) effects for studying the energy level and radiative rates. Transitions between levels of $2p^5 3s$, 3p and 3d configurations produce prominent lines in the spectra of high-temperature light source in Ne-like ions [3,4]. Further, transitions between these levels were identified in solar flare, Z-pinch plasma etc. To obtain laser action, the 3s and 3p states have been utilized. Also, laser action is obtained in lighter elements [5] for Ne-like ions.

Ne-isoelectronic sequence ions have been studied both experimentally and theoretically. On the experimental side, a series of experiments has been performed to measure lifetimes of Ne-like ions using beam foil method [6–11]. As Ne-like ions of middle and high atomic numbers are present in tokamak, laser-produced plasma, electron beam ion trap (EBIT), solar atmosphere etc., the spectra of Ne-like ions have been observed [12–15]. Much work has been done on the theoretical side. Many authors have calculated the transition energies, oscillator strength, lifetimes and transition probabilities using Z-expansion method, configuration-interaction method, multiconfiguration Hartree–Fock (MCHF) method, multiconfiguration Dirac–Fock (MCDF) method and relativistic many-body perturbation theory (MBPT) for many Ne-like ions with $Z = 29-31$ [16–22]. Benchmark calculations for iron group ions have been performed by Ishikawa *et al* using a relativistic multireference Moller-Plesset method [23,24]. Recently, Jonsson *et al* [25] calculated energies, transition rates, oscillator strengths and lifetimes using relativistic configuration interaction method for Ne-like ions between Mg and Kr ($Z = 29-31$).

The aim of the present work is to extend the term analysis to more highly ionized ions and to upgrade the database for Ne-like ions with $Z = 29-31$. We have calculated results using the MCDF method employed in the GRASP code of Grant *et al* [26], revised by Norrington [27]. To the best of our knowledge, there do not appear to be any large-scale experimental measurement or theoretical calculations for the ions reported in the present work. Therefore, in this paper we have reported 127 fine structural level energies by taking into account Breit and QED effects along with the radiative rate data from the ground state. These calculations find

Table 1. Dirac–Coulomb (DC), Breit and quantum electrodynamics (QED) contributions to the MCDF energy (Ryd.) as a function of the orbital set Ne-like Cu. The sum (Total) is compared with FAC and NIST. All energies are relative to the ground-state MCDF energies (Ryd.), lifetimes (s) and mixing coefficients of levels in Ne-like Cu.

Level	Label	J	MCDF				Lifetime	Mixing coefficients	FAC	NIST
			DC	Breit	QED	Total				
1	$2s^22p^6\ {}^1S^e$	0	–	–	–	–	–	99.4	–	–
2	$2s^22p^53s\ {}^3P^o$	2	70.7492	−0.0638	0.00658	70.6919	1.47E−06	99.6	70.7705	70.8717
3	$2s^22p^53s\ {}^1P^o$	1	70.9215	−0.0628	0.00662	70.86534	5.54E−13	57.46 + 42.25(5)	70.9535	71.0392
4	$2s^22p^53s\ {}^3P^o$	0	72.3054	−0.0982	0.00945	72.21663	1.36E−05	99.6	72.2977	72.3906
5	$2s^22p^53s\ {}^3P^o$	1	72.4086	−0.101	0.00945	72.31716	7.25E−13	57.46 + 42.12(3)	72.4053	72.4918
6	$2s^22p^53p\ {}^3S^e$	1	73.4312	−0.0549	−0.00209	73.37423	2.15E−10	73.96 + 23.33(13)	73.4435	73.5454
7	$2s^22p^53p\ {}^3D^e$	2	73.696	−0.0547	−0.00209	73.63924	1.34E−10	56.4 + 30.58(14)	73.7184	73.7969
8	$2s^22p^53p\ {}^3D^e$	3	73.9511	−0.0655	−0.00152	73.88405	1.16E−10	99.8	73.9592	74.0458
9	$2s^22p^53p\ {}^1P^e$	1	74.0188	−0.0588	−0.00165	73.95833	1.29E−10	54.02 + 22.09(12)	74.0387	74.1171
10	$2s^22p^53p\ {}^3P^e$	2	74.2061	−0.06	−0.0015	74.14451	8.51E−11	67.4 + 32.26(14)	74.2258	74.3009
11	$2s^22p^53p\ {}^3P^e$	0	74.8264	−0.067	−0.00068	74.75876	7.58E−11	91.39	74.8408	
12	$2s^22p^53p\ {}^3D^e$	1	75.1978	−0.0924	0.000758	75.10613	1.69E−10	68.39 + 30.14(9)	75.1872	75.2641
13	$2s^22p^53p\ {}^3P^e$	1	75.5788	−0.0944	0.00121	75.48556	1.04E−10	60.53	75.5648	75.6456
14	$2s^22p^53p\ {}^1D^e$	2	75.6342	−0.101	0.00136	75.53433	9.43E−11	43.3 + 36.84(14) + 19.62(10)	75.6162	75.6925
15	$2s^22p^53p\ {}^1S^e$	0	76.7452	−0.0704	−8.10E−05	76.67466	2.76E−11	90.44	76.767	76.6093
16	$2s^22p^53d\ {}^3P^o$	0	77.4506	−0.0584	−0.00201	77.39013	6.92E−11	99.2	77.4471	77.5448
17	$2s^22p^53d\ {}^3P^o$	1	77.5573	−0.0669	−0.00194	77.48855	5.86E−12	89.3	77.5468	77.6474
18	$2s^22p^53d\ {}^3P^o$	2	77.7468	−0.0729	−0.00186	77.67212	7.17E−11	67.08 + 23.72(25)	77.7263	77.829
19	$2s^22p^53d\ {}^3F^o$	4	77.7525	−0.0787	−0.00186	77.67201	7.57E−11	99.8	77.7326	77.8231
20	$2s^22p^53d\ {}^3F^o$	3	77.7981	−0.0741	−0.00184	77.72222	6.23E−11	62.57 + 30.36(26)	77.7778	77.8681
21	$2s^22p^53d\ {}^1D^o$	2	77.9535	−0.0685	−0.00183	77.88322	6.04E−11	44.62 + 31.7(24) + 22.66(25)	77.9411	78.0302
22	$2s^22p^53d\ {}^3D^o$	3	78.0656	−0.0738	−0.00186	77.98998	6.76E−11	62.12 + 32.83(26)	78.0527	78.1367
23	$2s^22p^53d\ {}^3D^o$	1	78.5647	−0.0762	−0.00148	78.48702	6.85E−14	69.22 + 24.4(27)	78.5407	78.6105
24	$2s^22p^53d\ {}^3F^o$	2	79.3407	−0.108	0.001	79.23392	6.06E−11	65.77 + 26.94(21)	79.2971	79.3815
25	$2s^22p^53d\ {}^3D^o$	2	79.4218	−0.109	0.000877	79.31359	6.96E−11	47.2 + 30.69(18) + 19.8(21)	79.3733	7.9E+07
26	$2s^22p^53d\ {}^1F^o$	3	79.4885	−0.112	0.00101	79.37708	7.12E−11	36.48 + 35.28(20) + 27.98(22)	79.4361	79.5283
27	$2s^22p^53d\ {}^1P^o$	1	80.1066	−0.11	0.000425	79.99719	2.48E−14	74.48 + 20.79(23)	80.0433	80.0731
28	$2s2p^63s\ {}^3S^e$	1	82.7569	−0.0545	−0.0311	82.67141	5.37E−12	98.41	82.7901	
29	$2s2p^63s\ {}^1S^e$	0	83.3514	−0.0491	−0.0313	83.27094	8.02E−12	99.2	83.3917	
30	$2s2p^63p\ {}^3P^o$	0	85.6218	−0.0395	−0.0399	85.54236	5.83E−12	99	85.6516	
31	$2s2p^63p\ {}^3P^o$	1	85.6713	−0.0437	−0.0399	85.58776	8.02E−13	84.82	85.6984	85.5406
32	$2s2p^63p\ {}^3P^o$	2	85.9837	−0.0526	−0.0393	85.89174	5.69E−12	99	86.0002	
33	$2s2p^63p\ {}^1P^o$	1	86.1457	−0.0527	−0.0394	86.05359	1.61E−13	85.01	86.1689	85.9872

Table 1. *Continued.*

Level	Label	*J*	MCDF				Lifetime	Mixing coefficients	FAC	NIST
			DC	Breit	QED	Total				
34	$2s2p^63d\ ^3D^e$	1	89.6168	−0.0558	−0.0398	89.52122	6.97E−12	99.4	89.5967	
35	$2s2p^63d\ ^3D^e$	2	89.6414	−0.0614	−0.0398	89.54023	6.82E−12	99	89.6158	
36	$2s2p^63d\ ^3D^e$	3	89.6838	−0.0663	−0.0398	89.57768	6.70E−12	99.4	89.653	
37	$2s2p^63d\ ^1D^e$	2	90.1133	−0.0626	−0.0399	90.01088	5.49E−12	99.2	90.1029	
38	$2s^22p^54s\ ^3P^o$	2	95.5977	−0.0694	0.00103	95.52935	1.49E−12	99.8	95.58	
39	$2s^22p^54s\ ^1P^o$	1	95.6524	−0.069	0.00104	95.58446	7.54E−13	64.32 + 35.64(46)	95.6373	95.7195
40	$2s^22p^54p\ ^3S^e$	1	96.7161	−0.0652	−0.00192	96.64898	1.54E−12	59.44 + 37.09(56)	96.6972	
41	$2s^22p^54p\ ^3D^e$	2	96.7804	−0.0658	−0.00194	96.71266	1.51E−12	51.98 + 33.64(57)	96.7619	
42	$2s^22p^54p\ ^3D^e$	3	96.8874	−0.07	−0.00175	96.8157	1.59E−12	99.8	96.8639	
43	$2s^22p^54p\ ^1P^e$	1	96.9127	−0.0679	−0.00177	96.84298	1.54E−12	63.2	96.8919	
44	$2s^22p^54p\ ^3P^e$	2	96.9723	−0.068	−0.00173	96.90257	1.63E−12	68.23 + 31.7(57)	96.9524	
45	$2s^22p^54s\ ^3P^o$	0	97.1593	−0.106	0.00392	97.05704	1.48E−12	99.8	97.1121	
46	$2s^22p^54s\ ^3P^o$	1	97.187	−0.107	0.00391	97.08371	8.65E−13	64.16 + 35.4(39)	97.14	97.2049
47	$2s^22p^54p^3P^e$	0	97.3406	−0.0668	−0.00158	97.27222	1.73E−12	54.46 + 45.29(59)	97.3121	
48	$2s^22p^54d\ ^3P^o$	0	98.1976	−0.0676	−0.00186	98.12815	8.93E−13	99.8	98.1747	
49	$2s^22p^54d\ ^3P^o$	1	98.2418	−0.0702	−0.00185	98.16975	8.34E−13	82.81 + 16.56(71)	98.2154	98.2619
50	$2s^22p^54d\ ^3F^o$	4	98.3001	−0.0747	−0.00184	98.22359	8.96E−13	99.8	98.2687	
51	$2s^22p^54d\ ^3F^o$	3	98.313	−0.072	−0.00184	98.23914	9.02E−13	56.85 + 35.05(70)	98.2691	
52	$2s^22p^54d\ ^3P^o$	2	98.3151	−0.0728	−0.00184	98.24046	9.10E−13	53.14 + 38.32(69)	98.2832	
53	$2s^22p^54p\ ^3D^e$	1	98.3197	−0.104	0.000953	98.21687	1.48E−12	72.59 + 24.3(43)	98.2833	
54	$2s^22p^54d\ ^1D^o$	2	98.3716	−0.071	−0.00184	98.29877	9.17E−13	55.35 + 23.72(68) + 18.4(69)	98.3402	
55	$2s^22p^54d\ ^3D^o$	3	98.4135	−0.0727	−0.00184	98.33894	9.16E−13	68.06 + 30.25(70)	98.3796	
56	$2s^22p^54p\ ^3P^e$	1	98.4668	−0.105	0.00114	98.36274	1.61E−12	54.02 + 24.6(40)	98.4162	
57	$2s^22p^54p\ ^1D^e$	2	98.4895	−0.107	0.00116	98.38328	1.60E−12	47.75 + 34.46(57) + 17.64(44)	98.4372	
58	$2s^22p^54d\ ^1P^o$	1	98.6521	−0.0739	−0.00178	98.57646	8.16E−14	53.14 + 40.96(71)	98.6104	98.672
59	$2s^22p^54p\ ^1S^e$	0	98.6915	−0.0964	0.000806	98.59595	1.68E−12	54.17 + 45.56(47)	98.637	
60	$2s^22p^54f\ ^3D^e$	1	98.9916	−0.0736	−0.00192	98.91609	3.94E−13	99.8	98.9769	
61	$2s^22p^54f\ ^1G^e$	4	99.0019	−0.0762	−0.00184	98.92384	4.17E−13	50.84 + 48.58(73)	98.9864	
62	$2s^22p^54f\ ^3D^e$	2	99.0076	−0.0763	−0.00184	98.92947	4.16E−13	76.04 + 18.84(65)	98.991	
63	$2s^22p^54f\ ^3G^e$	5	99.0078	−0.0742	−0.00191	98.93163	4.02E−13	100.0	98.9943	
64	$2s^22p^54f\ ^3F^e$	3	99.0428	−0.0748	−0.00187	98.96611	4.07E−13	49.84 + 41.6(75)	99.0296	
65	$2s^22p^54f\ ^1D^e$	2	99.045	−0.0745	−0.00186	98.96866	4.23E−13	48.58 + 48.44(74)	99.0363	
66	$2s^22p^54f\ ^1F^e$	3	99.0522	−0.075	−0.00185	98.97538	4.16E−13	59.14 + 23.81(72)	99.0399	
67	$2s^22p^54f\ ^3F^e$	4	99.0624	−0.0754	−0.00184	98.98521	4.18E−13	72.93 + 16.32(61)	99.05	

Table 1. *Continued.*

Level	Label	J	MCDF DC	MCDF Breit	MCDF QED	MCDF Total	Lifetime	Mixing coefficients	FAC	NIST
68	$2s^22p^54d\ ^3F^o$	2	99.8637	−0.11	0.00105	99.75518	9.09E−13	72.25 + 22(54)	99.8037	
69	$2s^22p^54d\ ^3D^o$	2	99.8953	−0.11	0.00103	99.78608	9.04E−13	42.64 + 39.19(69)	99.8341	
70	$2s^22p^54d\ ^1F^o$	3	99.9249	−0.111	0.00105	99.81469	9.07E−13	41.47 + 34.57(70) + 23.91(55)	99.8615	
71	$2s^22p^54d\ ^3D^o$	1	100.091	−0.11	0.000973	99.98213	8.56E−14	46.1 + 42.25(71)	100.022	100.094
72	$2s^22p^54f\ ^3G^e$	3	100.582	−0.113	0.00105	100.4694	4.16E−13	72.76 + 18.06(66)	100.537	
73	$2s^22p^54f\ ^3G^e$	4	100.596	−0.113	0.00105	100.4834	4.18E−13	40.5(61) + 26.63(67)	100.551	
74	$2s^22p^54f\ ^3F^e$	2	100.599	−0.113	0.00103	100.4875	4.17E−13	46.51 + 32.49(65) + 20.93(62)	100.558	
75	$2s^22p^54f\ ^3D^e$	3	100.603	−0.113	0.00102	100.4906	4.06E−13	52.71 + 29.38(64) + 17.39(66)	100.558	
76	$2s^22p^55s\ ^3P^o$	2	106.349	−0.0726	−0.00055	106.2758	1.84E−12	99.8	106.331	
77	$2s^22p^55s\ ^1P^o$	1	106.377	−0.0723	−0.00052	106.3043	1.06E−12	65.29 + 34.46(95)	106.359	
78	$2s^22p^55p\ ^3S^e$	1	106.885	−0.0702	−0.00358	106.8108	1.67E−12	60.53 + 32.95(105)	106.865	
79	$2s^22p^55p\ ^3D^e$	2	106.941	−0.0707	−0.0019	106.868	1.84E−12	51.12 + 34.81(106)	106.921	
80	$2s^22p^55p\ ^3D^e$	3	106.994	−0.0728	−0.00181	106.9194	1.94E−12	100.0	106.973	
81	$2s^22p^55p\ ^1P^e$	1	107.003	−0.0714	−0.0021	106.929	1.83E−12	63.52	106.982	
82	$2s^22p^55p\ ^3P^e$	2	107.036	−0.0718	−0.00179	106.9625	1.99E−12	68.72 + 31.25(106)	107.015	
83	$2s^22p^55p\ ^1S^e$	0	107.221	−0.0702	−0.00242	107.1485	2.12E−12	56.4 + 41.86(107)	107.194	
84	$2s2p^64s\ ^3S^e$	1	107.545	−0.0588	−0.0346	107.452	1.23E−12	93.51	107.475	
85	$2s^22p^55d\ ^3P^o$	0	107.63	−0.0717	−0.002	107.5565	1.18E−12	99.2	107.617	
86	$2s^22p^55d\ ^3P^o$	1	107.653	−0.0729	−0.00195	107.5785	1.09E−12	81 + 17.98(115)	107.637	107.894
87	$2s^22p^55d\ ^3F^o$	4	107.684	−0.0751	−0.00184	107.6066	1.21E−12	100.0	107.648	
88	$2s^22p^55d\ ^3F^o$	0	107.69	−0.0737	−0.00189	107.6141	1.20E−12	55.8 + 35.64(114)	107.664	
89	$2s^22p^55d\ ^3P^o$	2	107.69	−0.0742	−0.00184	107.6138	1.22E−12	50.27 + 40.96(113)	107.669	
90	$2s^22p^55d\ ^1D^o$	2	107.717	−0.0733	−0.00184	107.6414	1.22E−12	57.15 + 22.37(112) + 17.89(113)	107.671	
91	$2s^12p^64s\ ^1S^e$	0	107.728	−0.0558	−0.0362	107.6356	1.19E−12	98.21	107.695	
92	$2s^22p^55d\ ^3D^o$	3	107.737	−0.0742	−0.00184	107.6611	1.22E−12	68.39 + 30.25(114)	107.714	
93	$2s^22p^55d\ ^1P^o$	1	107.848	−0.0823	−0.00139	107.7641	1.45E−13	51.7 + 31.26(115)	107.813	
94	$2s^22p^55s\ ^3P^o$	0	107.904	−0.109	0.00164	107.7971	1.79E−12	98.01	107.856	
95	$2s^22p^55s\ ^3P^o$	1	107.936	−0.102	0.00145	107.8348	5.42E−13	55.2 + 30.58(77)	107.89	
96	$2s^22p^55f\ ^3D^e$	1	108.016	−0.0744	−0.00194	107.94	7.54E−13	99.8	108.006	
97	$2s^22p^55f\ ^3D^e$	2	108.028	−0.0748	−0.00192	107.9508	7.66E−13	77.79	108.018	
98	$2s^22p^55f\ ^1G^e$	4	108.032	−0.0758	−0.00184	107.9545	7.86E−13	49.98 + 49.28(119)	108.022	
99	$2s^22p^55f\ ^3G^e$	5	108.034	−0.0759	−0.00184	107.9565	7.84E−13	100.0	108.024	
100	$2s^22p^55f\ ^3D^e$	3	108.048	−0.0752	−0.00188	107.971	7.69E−13	43.96 + 43.3(117)	108.039	

Table 1. *Continued.*

Level	Label	J	MCDF DC	MCDF Breit	MCDF QED	MCDF Total	Lifetime	Mixing coefficients	FAC	NIST
101	$2s^22p^55f\ ^1D^e$	2	108.055	−0.075	−0.00185	107.9778	8.06E−13	52.29 + 46.1(118)	108.04	
102	$2s^22p^55f\ ^1F^e$	3	108.056	−0.0752	−0.00184	107.9792	7.80E−13	53.88 + 24.8(116) + 19.36(117)	108.044	
103	$2s^22p^55f\ ^3F^e$	4	108.062	−0.0754	−0.00184	107.9848	7.83E−13	73.44 + 16.89(98)	108.047	
104	$2s^22p^55p\ ^3D^e$	1	108.494	−0.109	0.000911	108.3864	1.81E−12	75.52 + 21.53(81)	108.048	
105	$2s^22p^55p\ ^3P^e$	1	108.577	−0.11	0.00104	108.4674	1.94E−12	51.12 + 28.41(78)	108.053	
106	$2s^22p^55p\ ^1D^e$	2	108.577	−0.109	0.000778	108.4687	2.01E−12	48.72 + 33.87(106) + 17.22(82)	108.055	
107	$2s^22p^55p\ ^3P^e$	0	108.653	−0.105	0.000808	108.5485	1.91E−12	56.7 + 42.77(83)	108.058	
108	$2s2p^64p\ ^3P^o$	0	108.703	−0.0532	−0.0391	108.6111	1.24E−12	97.81	108.061	
109	$2s2p^64p\ ^3P^o$	1	108.71	−0.0543	−0.0395	108.6158	5.12E−13	77.7 + 20.79(111)	108.063	108.486
110	$2s2p^64p\ ^3P^o$	2	108.831	−0.0576	−0.0393	108.7342	1.24E−12	98.6	108.069	
111	$2s2p^64p\ ^1P^o$	1	108.889	−0.0577	−0.0395	108.7914	2.54E−13	78.5 + 20.52(109)	108.072	108.678
112	$2s^22p^55d\ ^3F^o$	2	109.247	−0.112	0.00104	109.1362	1.22E−12	74.48 + 19.71(90)	108.443	
113	$2s^22p^55d\ ^3D^o$	2	109.266	−0.111	0.000725	109.1553	1.23E−12	45.83 + 36.12(113)	108.525	
114	$2s^22p^55d\ ^1F^o$	3	109.277	−0.112	0.00105	109.1658	1.21E−12	42.9 + 33.99(114) + 23.04(92)	108.526	
115	$2s^22p^55d\ ^3D^o$	1	109.351	−0.111	0.000857	109.241	2.09E−13	45.97 + 33.69(93)	108.6	109.37
116	$2s^22p^55f\ ^3G^e$	3	109.603	−0.113	0.000689	109.4909	7.80E−13	60.68 + 28.73(102)	108.63	
117	$2s^22p^55f\ ^3F^e$	3	109.605	−0.113	0.000835	109.4927	7.79E−13	43.56 + 36.48(117)	108.635	
118	$2s^22p^55f\ ^3F^e$	2	109.609	−0.113	0.000746	109.4972	7.95E−13	45.29 + 32.95(101) + 21.07(97)	108.754	
119	$2s^22p^55f\ ^3G^e$	4	109.612	−0.113	0.00105	109.4997	7.86E−13	41.09 + 33.18(98) + 25.81(103)	108.81	
120	$2s2p^64d\ ^3D^e$	1	110.203	−0.0583	−0.0397	110.1045	7.86E−13	99.4	109.197	
121	$2s2p^64d\ ^3D^e$	2	110.215	−0.0605	−0.0395	110.1152	7.77E−13	98.21	109.216	
122	$2s2p^64d\ ^3D^e$	3	110.237	−0.0626	−0.0393	110.1349	7.66E−13	98.41	109.225	
123	$2s2p^64d\ ^1D^e$	2	110.381	−0.0603	−0.0398	110.2809	8.00E−13	98.8	109.294	
124	$2s2p^64f\ ^3F^o$	2	110.895	−0.0624	−0.04	110.7921	3.91E−13	100.0	109.563	
125	$2s2p^64f\ ^3F^o$	3	110.898	−0.0635	−0.04	110.7941	3.91E−13	92.35	109.565	
126	$2s2p^64f\ ^3F^o$	4	110.906	−0.0639	−0.04	110.8017	3.91E−13	100.0	109.571	
127	$2s2p^64f\ ^1F^o$	3	110.919	−0.0631	−0.04	110.8157	3.97E−13	92.35	109.572	

Table 2. Dirac–Coulomb (DC), Breit and quantum electrodynamics (QED) contributions to the MCDF energy (Ryd.) as a function of the orbital set Ne-like Zn. The sum (total) is compared with FAC and NIST. All energies are relative to the ground-state MCDF energies (Ryd.), lifetimes (s) and mixing coefficients of levels in Ne-like Zn.

Level	Label	J	MCDF				Lifetime	Mixing coefficients	FAC	NIST
			DC	Breit	QED	Total				
1	$2s^22p^6\ ^1S_e$	0				–	–	99.6		
2	$2s^22p^53s\ ^3P_o$	2	77.1474	−0.0721	0.00755	77.08288	1.05E−06	99.6	77.1622	
3	$2s^22p^53s\ ^1P_o$	1	77.3289	−0.0708	0.00758	77.26568	4.63E−13	58.37 + 41.22(5)	77.3546	77.4295
4	$2s^22p^53s\ ^3P_o$	0	78.9613	−0.111	0.0109	78.86139	8.43E−06	99.6	78.9435	
5	$2s^22p^53s\ ^3P_o$	1	79.0679	−0.114	0.0109	78.96488	6.25E−13	58.37 + 41.22(3)	79.0539	79.1308
6	$2s^22p^53p\ ^3S_e$	1	79.983	−0.061	−0.00247	79.91958	1.97E−10	71.06 + 25.81(13)	79.9897	
7	$2s^22p^53p\ ^3D_e$	2	80.2445	−0.0616	−0.00246	80.18044	1.21E−10	55.65 + 30.91(14)	80.2601	
8	$2s^22p^53p\ ^3D_e$	3	80.5585	−0.074	−0.00179	80.48276	1.05E−10	99.8	80.5583	
9	$2s^22p^53p\ ^1P_e$	1	80.6203	−0.0668	−0.00193	80.5515	1.17E−10	55.20 + 20.88(12)	80.6322	
10	$2s^22p^53p\ ^3P_e$	2	80.8259	−0.0677	−0.00177	80.7564	7.55E−11	67.4 + 32.38(14)	80.8381	80.9296
11	$2s^22p^53p\ ^3P_e$	0	81.5214	−0.0744	−0.0009	81.44612	6.61E−11	89.49	81.5289	
12	$2s^22p^53p\ ^3D_e$	1	81.9988	−0.104	0.000854	81.89555	1.59E−10	68.72 + 29.48(9)	81.9773	
13	$2s^22p^53p\ ^3P_e$	1	82.442	−0.107	0.0014	82.33664	9.42E−11	59.75 + 16.56(6)	82.4164	
14	$2s^22p^53p\ ^1D_e$	2	82.5047	−0.114	0.00157	82.39204	8.31E−11	43.96 + 36.48(14) + 19.27(10)	82.4746	82.5681
15	$2s^22p^53p\ ^1S_e$	0	83.5772	−0.0805	$-3.90E-05$	83.49667	2.61E−11	88.74	83.5888	83.4529
16	$2s^22p^53d\ ^3P_o$	0	84.2259	−0.0656	−0.00236	84.15789	6.43E−11	99.2	84.2146	
17	$2s^22p^53d\ ^3P_o$	1	84.3435	−0.0751	−0.00229	84.26607	5.09E−12	88.55	84.324	84.4079
18	$2s^22p^53d\ ^3P_o$	2	84.551	−0.0817	−0.00221	84.4671	6.69E−11	65.12 + 25.91(25)	84.5172	
19	$2s^22p^53d\ ^3F_o$	4	84.5541	−0.0888	−0.0022	84.46309	7.17E−11	99.8	84.5274	
20	$2s^22p^53d\ ^3F_o$	3	84.5935	−0.0834	−0.00218	84.50794	5.77E−11	61.78 + 31.02(26)	84.5635	
21	$2s^22p^53d\ ^1D_o$	2	84.7604	−0.0771	−0.00217	84.68108	5.64E−11	46.38 + 30.47(24) + 21.9(25)	84.7391	
22	$2s^22p^53d\ ^3D_o$	3	84.8854	−0.0831	−0.0022	84.80002	6.39E−11	65.61 + 32.38(26)	84.8627	
23	$2s^22p^53d\ ^3D_o$	1	85.4331	−0.0855	−0.00183	85.34573	5.19E−14	66.26 + 27.25(27)	85.3986	85.4605
24	$2s^22p^53d\ ^3F_o$	2	86.3902	−0.121	0.00114	86.26982	5.62E−11	66.75 + 26.52(21)	86.3332	
25	$2s^22p^53d\ ^3D_o$	2	86.4832	−0.123	0.001	86.36098	6.60E−11	46.38 + 32.15(18) + 18.92(21)	86.4209	
26	$2s^22p^53d\ ^1F_o$	3	86.5574	−0.127	0.00115	86.43167	6.74E−11	36.24 + 36.12(20) + 27.35(22)	86.4909	
27	$2s^22p^53d\ ^1P_o$	1	87.1822	−0.124	0.000537	87.05831	2.15E−14	71.57 + 23.14(23)	87.1054	87.3358
28	$2s2p^63s\ ^3S_e$	1	89.869	−0.0614	−0.0352	89.77233	4.95E−12	98.41	89.8922	
29	$2s2p^63s\ ^1S_e$	0	90.4923	−0.0554	−0.0355	90.40134	7.34E−12	99.2	90.523	
30	$2s2p^63p\ ^3P_o$	0	92.8799	−0.0444	−0.0454	92.79003	5.38E−12	99.2	92.9003	
31	$2s2p^63p\ ^3P_o$	1	92.9339	−0.0491	−0.0454	92.83946	6.29E−13	83.54	92.9512	92.8399
32	$2s2p^63p\ ^3P_o$	2	93.3065	−0.0593	−0.0447	93.20247	5.24E−12	99.2	93.3119	
33	$2s2p^63p\ ^1P_o$	1	93.4739	−0.0595	−0.0448	93.36959	1.37E−13	83.72	93.4859	93.3502
34	$2s2p^63d\ ^3D_e$	1	97.1183	−0.0627	−0.0453	97.01026	6.36E−12	99.4	97.0861	
35	$2s2p^63d\ ^3D_e$	2	97.1476	−0.069	−0.0453	97.03318	6.21E−12	98.8	97.1092	

Table 2. *Continued.*

Level	Label	J	MCDF				Lifetime	Mixing coefficients	FAC	NIST
			DC	Breit	QED	Total				
36	$2s2p^63d\ ^3D_e$	3	97.1991	−0.0747	−0.0453	97.07901	6.11E−12	99.4	97.1547	
37	$2s2p^63d\ ^1D_e$	2	97.6518	−0.0704	−0.0454	97.53599	4.92E−12	99	97.6286	
38	$2s^22p^54s\ ^3P_o$	2	104.305	−0.0786	0.00116	104.2275	1.25E−12	99.8	104.279	
39	$2s^22p^54s\ ^1P_o$	1	104.363	−0.0781	0.00118	104.2857	6.35E−13	64.48 + 35.4(47)	104.339	104.477
40	$2s^22p^54p\ ^3S_e$	1	105.487	−0.0736	−0.00227	105.4109	1.27E−12	57.3 + 38.69(57)	105.46	
41	$2s^22p^54p\ ^3D_e$	2	105.551	−0.0744	−0.00229	105.4742	1.24E−12	51.84 + 33.76(58)	105.524	
42	$2s^22p^54p\ ^3D_e$	3	105.682	−0.0792	−0.00206	105.6007	1.32E−12	99.8	105.65	
43	$2s^22p^54p\ ^1P_e$	1	105.706	−0.0771	−0.00208	105.6269	1.28E−12	63.2	105.676	
44	$2s^22p^54p\ ^3P_e$	2	105.772	−0.077	−0.00204	105.6926	1.35E−12	68.06 + 31.81(58)	105.743	
45	$2s^22p^54s\ ^3P_o$	0	106.125	−0.12	0.00453	106.0096	1.25E−12	99.8	106.066	
46	$2s^22p^54p\ ^3P_e$	0	106.154	−0.121	0.00452	106.0372	7.17E−13	52.27 + 47.61(59)	106.095	
47	$2s^22p^54s\ ^3P_o$	1	106.164	−0.0751	−0.0019	106.0873	1.44E−12	64.48 + 35.16(39)	106.127	106.236
48	$2s^22p^54d\ ^3F_o$	0	107.058	−0.0764	−0.0022	106.9794	7.32E−13	99.8	107.027	
49	$2s^22p^54d\ ^3P_o$	1	107.106	−0.0794	−0.00219	107.0244	6.88E−13	82.26 + 17.14(71)	107.071	
50	$2s^22p^54d\ ^3F_o$	4	107.171	−0.0846	−0.00218	107.0839	7.34E−13	99.8	107.13	
51	$2s^22p^54d\ ^3F_o$	3	107.182	−0.0824	−0.00218	107.0977	7.45E−13	56.55 + 35.28(70)	107.141	
52	$2s^22p^54d\ ^3P_o$	2	107.183	−0.0814	−0.00218	107.0998	7.39E−13	51.7 + 40.7(69)	107.145	
53	$2s^22p^54d\ ^1D_o$	2	107.243	−0.0804	−0.00218	107.1607	7.51E−13	57.15 + 23.14(68) + 16.32(69)	107.203	
54	$2s^22p^54d\ ^3D_o$	3	107.29	−0.0824	−0.00218	107.2059	7.50E−13	68.23 + 30.14(70)	107.247	
55	$2s^22p^54d\ ^1D_e$	1	107.347	−0.117	0.00108	107.2311	1.22E−12	72.76 + 24.11(43)	107.284	107.183
56	$2s^22p^54d\ ^1P_o$	1	107.52	−0.119	0.0013	107.4028	1.34E−12	54.32 + 39.69(71)	107.457	107.621
57	$2s^22p^54p\ ^3P_e$	1	107.545	−0.121	0.00132	107.4247	1.32E−12	53.73 + 25(40)	107.48	
58	$2s^22p^54p\ ^1D_e$	2	107.545	−0.0836	−0.00212	107.4593	6.69E−14	48.02 + 34.34(58) + 17.56(44)	107.494	
59	$2s^22p^54p\ ^1S_e$	0	107.728	−0.11	0.000939	107.6192	1.37E−12	51.98 + 47.75(46)	107.662	
60	$2s^22p^54f\ ^3D_e$	1	107.905	−0.0833	−0.00225	107.8197	3.26E−13	99.8	107.881	
61	$2s^22p^54f\ ^1G_e$	4	107.918	−0.0864	−0.00218	107.8297	3.44E−13	50.69 + 48.86(73)	107.893	
62	$2s^22p^54f\ ^3D_e$	2	107.924	−0.0841	−0.00224	107.8378	3.32E−13	76.56 + 17.39(65)	107.899	
63	$2s^22p^54f\ ^3G_e$	5	107.926	−0.0864	−0.00218	107.8372	3.43E−13	100	107.901	
64	$2s^22p^54p\ ^3D_e$	3	107.962	−0.0848	−0.00221	107.8752	3.37E−13	52.42 + 39.94(75)	107.939	
65	$2s^22p^54f\ ^1D_e$	2	107.965	−0.0844	−0.0022	107.8781	3.49E−13	49.98 + 47.89(74)	107.947	
66	$2s^22p^54p\ ^3P_e$	3	107.972	−0.0849	−0.00219	107.8853	3.43E−13	61 + 22.75(72)	107.951	
67	$2s^22p^54f\ ^1F_e$	4	107.984	−0.0854	−0.00218	107.8969	3.45E−13	72.93 + 16.48(61)	107.962	
68	$2s^22p^54d\ ^3F_o$	2	108.988	−0.124	0.00118	108.8657	7.45E−13	72.42 + 21.9(53)	108.916	
69	$2s^22p^54d\ ^3D_o$	2	109.026	−0.125	0.00117	108.9023	7.39E−13	43.16 + 38.94(69)	108.952	
70	$2s^22p^54d\ ^1F_o$	3	109.058	−0.126	0.00119	108.9329	7.42E−13	41.73 + 34.46(70) + 23.72(54)	108.981	

Table 2. *Continued.*

Level	Label	*J*	MCDF				Lifetime	Mixing coefficients	FAC	NIST
			DC	Breit	QED	Total				
71	$2s^22p^54d\ ^3D_o$	1	109.225	−0.125	0.00111	109.1018	7.39E−14	44.89 + 43.03(71)	109.143	109.261
72	$2s^22p^54f\ ^3G_e$	3	109.758	−0.128	0.00119	109.6309	3.43E−13	72.93 + 18.15(66)	109.7	
73	$2s^22p^54f\ ^3F_e$	4	109.775	−0.128	0.00119	109.6476	3.45E−13	40.58 + 32.83(61) + 26.52(67)	109.717	
74	$2s^22p^54f\ ^3F_e$	2	109.776	−0.128	0.00117	109.6499	3.44E−13	46.38 + 32.6(65) + 21.07(62)	109.722	
75	$2s^22p^54f\ ^3D_e$	3	109.781	−0.128	0.00116	109.6543	3.36E−13	52.85 + 29.59(64) + 17.06(66)	109.723	
76	$2s^22p^55s\ ^3P_o$	2	116.086	−0.0822	−0.0007	116.0031	1.54E−12	99.8	116.059	
77	$2s^22p^55s\ ^1P_o$	1	116.116	−0.0819	−0.00066	116.0333	8.82E−13	65.29 + 34.34(103)	116.09	
78	$2s^22p^55p\ ^3S_e$	1	116.617	−0.0777	−0.00981	116.5293	1.22E−12	54.32 + 25.91(109) + 17.81(84)	116.58	
79	$2s^22p^55p\ ^3D_e$	2	116.711	−0.0801	−0.00226	116.6284	1.52E−12	50.98 + 34.69(110)	116.682	
80	$2s^22p^55p\ ^1P_e$	1	116.776	−0.0801	−0.00356	116.692	1.49E−12	59.14 + 18.58(109) + 16.24(108)	116.745	
81	$2s^22p^55p\ ^3D_e$	3	116.776	−0.0825	−0.00215	116.6915	1.61E−12	100	116.746	
82	$2s^22p^55p\ ^3P_e$	2	116.821	−0.0813	−0.00212	116.7372	1.65E−12	68.56 + 31.36(110)	116.791	
83	$2s^22p^55p\ ^1S_e$	0	116.99	−0.0776	−0.00946	116.9031	1.73E−12	49.98 + 34.11(111)	116.937	
84	$2s2p^64s\ ^3S_e$	1	117.01	−0.0688	−0.0328	116.9081	1.21E−12	78.15	116.946	
85	$2s2p^64s\ ^1S_e$	0	117.178	−0.0648	−0.0346	117.0788	1.02E−12	84.09	117.096	
86	$2s^22p^55d\ ^3P_o$	0	117.443	−0.0809	−0.00258	117.3596	9.58E−13	99	117.421	
87	$2s^22p^55d\ ^3P_o$	1	117.469	−0.0824	−0.00245	117.3839	9.03E−13	80.46 + 18.4(115)	117.444	
88	$2s^22p^55d\ ^3F_o$	4	117.504	−0.0851	−0.00218	117.4162	9.93E−13	100	117.475	
89	$2s^22p^55d\ ^3F_o$	3	117.508	−0.084	−0.00218	117.4217	9.99E−13	55.5 + 35.88(114)	117.478	
90	$2s^22p^55d\ ^3P_o$	2	117.509	−0.0834	−0.00228	117.4232	9.83E−13	49.14 + 43.03(113)	117.481	
91	$2s^22p^55d\ ^3P_o$	2	117.537	−0.0831	−0.00219	117.4517	1.00E−12	58.68 + 21.9(112)	117.507	
92	$2s^22p^55d\ ^3D_o$	3	117.56	−0.084	−0.00218	117.4739	1.00E−12	68.56 + 30.14(114)	117.528	
93	$2s^22p^55d\ ^1P_o$	1	117.685	−0.0857	−0.00229	117.5966	9.97E−14	58.68 + 34.11(115)	117.643	117.763
94	$2s^22p^55f\ ^3D_e$	1	117.856	−0.0842	−0.00233	117.7695	6.25E−13	99.6	117.81	
95	$2s^22p^55f\ ^3D_e$	2	117.869	−0.0847	−0.0023	117.7819	6.34E−13	77.97	117.837	
96	$2s^22p^55f\ ^1G_e$	4	117.872	−0.117	−0.00334	117.7517	1.41E−12	49.7 + 49.56(119)	117.847	
97	$2s^22p^55f\ ^3G_e$	5	117.875	−0.0859	−0.00218	117.7864	6.49E−13	100	117.85	
98	$2s^22p^55s\ ^3P_e$	0	117.877	−0.086	−0.00218	117.7893	6.47E−13	88.17	117.855	
99	$2s^22p^55f\ ^3D_e$	3	117.891	−0.0851	−0.00225	117.804	6.36E−13	45.02 + 43.3(116)	117.858	
100	$2s^22p^55f\ ^3F_e$	2	117.899	−0.0849	−0.0022	117.8117	6.65E−13	54.17 + 45.29(117)	117.872	

Table 2. *Continued.*

Level	Label	J	MCDF DC	MCDF Breit	MCDF QED	MCDF Total	Lifetime	Mixing coefficients	FAC	NIST
101	$2s^22p^55f\ ^1F_e$	3	117.9	−0.0852	−0.00218	117.8129	6.44E−13	55.35 + 24.4(118) + 17.72(99)	117.876	
102	$2s^22p^55f\ ^3F_e$	4	117.907	−0.0854	−0.00218	117.8195	6.46E−13	73.44 + 17.14(96)	117.88	
103	$2s^22p^55s\ ^3P_e$	1	117.909	−0.12	−0.00061	117.7886	1.44E−12	58.98 + 32.49(77)	117.882	
104	$2s2p^64p\ ^3P_e$	1	118.2	−0.0635	−0.043	118.0939	4.21E−13	70.22 + 25(107)	117.883	118.164
105	$2s2p^64p\ ^3P_o$	0	118.211	−0.0663	−0.039	118.106	1.12E−12	87.8	117.889	
106	$2s2p^64p\ ^3P_o$	2	118.338	−0.0648	−0.045	118.2282	1.07E−12	99.2	117.892	
107	$2s2p^64p\ ^1P_o$	1	118.402	−0.0663	−0.0439	118.2918	2.50E−13	74.3 + 22.85(104)	117.896	118.21
108	$2s^22p^55p\ ^3D_e$	1	118.521	−0.123	0.000967	118.3992	1.49E−12	74.82 + 21.9(80)	117.898	
109	$2s^22p^55p\ ^3P_e$	1	118.616	−0.124	0.00108	118.4932	1.65E−12	51.41 + 28.3(78)	117.901	
110	$2s^22p^55p\ ^1D_e$	2	118.618	−0.125	0.00109	118.494	1.60E−12	48.72 + 33.76(110) + 17.14(82)	117.908	
111	$2s^22p^55p\ ^3P_e$	0	118.685	−0.12	0.00103	118.5667	1.59E−12	57.91 + 41.73(83)	117.911	
112	$2s^22p^55d\ ^3F_o$	2	119.323	−0.126	0.00119	119.1983	1.00E−12	74.13 + 20.43(91)	118.115	
113	$2s^22p^55d\ ^3D_o$	2	119.344	−0.126	0.00111	119.2183	1.00E−12	45.83 + 36.84(113)	118.129	
114	$2s^22p^55d\ ^1F_o$	3	119.358	−0.127	0.00118	119.2316	9.96E−13	43.03 + 33.99(114) + 22.94(92)	118.248	
115	$2s^22p^55d\ ^3D_o$	1	119.431	−0.126	0.00112	119.3062	1.67E−13	46.51 + 39.06(93)	118.312	119.513
116	$2s^22p^55f\ ^3D_e$	3	119.67	−0.116	−0.0104	119.5431	6.72E−13	42.38 + 20.88(99) + 19.01(122)	118.458	
117	$2s^22p^55f\ ^3F_e$	2	119.687	−0.119	−0.00887	119.5597	6.77E−13	39.31 + 28.52(100) + 16.97(95)	118.552	
118	$2s^22p^55f\ ^3G_e$	3	119.706	−0.128	0.00118	119.579	6.45E−13	74.13	118.553	
119	$2s^22p^55f\ ^3G_e$	4	119.715	−0.128	0.00119	119.5881	6.49E−13	41.09 + 33.18(96) + 25.7(102)	118.62	
120	$2s2p^64d\ ^3D_e$	1	119.778	−0.0662	−0.0451	119.6672	6.52E−13	99.2	119.261	
121	$2s2p^64d\ ^3D_e$	2	119.815	−0.0771	−0.0356	119.7023	6.29E−13	84.46	119.281	
122	$2s2p^64d\ ^3D_e$	3	119.853	−0.0818	−0.0337	119.7378	6.09E−13	80.64	119.293	
123	$2s2p^64d\ ^1D_e$	2	119.969	−0.0687	−0.0449	119.8555	6.61E−13	98.21	119.362	
124	$2s2p^64f\ ^3F_o$	2	120.516	−0.0708	−0.0455	120.3999	3.24E−13	100	119.603	
125	$2s2p^64f\ ^3F_o$	3	120.52	−0.0721	−0.0455	120.4023	3.24E−13	91.2	119.622	
126	$2s2p^64f\ ^3F_o$	4	120.53	−0.0724	−0.0455	120.4117	3.24E−13	100	119.653	
127	$2s2p^64f\ ^1F_o$	3	120.544	−0.0716	−0.0455	120.4269	3.29E−13	91.2	119.662	

Table 3. Dirac–Coulomb (DC), Breit, and quantum electrodynamics (QED) contributions to the MCDF energy (Ryd.) as a function of the orbital set Ne-like Ga. The sum (total) is compared with FAC and NIST. All energies are relative to the ground-state MCDF energies (Ryd.), lifetimes (s) and mixing coefficients of levels in Ne-like Ga.

			MCDF							
S. No.	Label	J	DC	Breit	QED	Total	Lifetimes	Mixing coefficients	FAC	NIST
1	$2s^22p^6\ ^1S^e$	0	–	–	–	–	–	99.6		
2	$2s^22p^53s\ ^3P^o$	2	83.815	−0.081	0.0086	83.74263	7.64E−07	99.8	83.8227	
3	$2s^22p^53s\ ^1P^o$	1	84.0056	−0.0794	0.00863	83.93475	3.90E−13	59.3 + 40.4(5)	84.0246	84.0917
4	$2s^22p^53s\ ^3P^o$	0	85.9177	−0.124	0.0125	85.80575	5.34E−06	99.6	85.889	
5	$2s^22p^53s\ ^3P^o$	1	86.0278	−0.128	0.0125	85.91224	5.41E−13	59.3 + 40.3(3)	86.0023	86.0965
6	$2s^22p^53p\ ^3S^e$	1	86.8053	−0.0675	−0.00291	86.73491	1.81E−10	68.4 + 28.2(13)	86.8059	
7	$2s^22p^53p\ ^3D^e$	2	87.063	−0.069	−0.00289	86.99111	1.09E−10	55.1 + 31.2(14)	87.0714	
8	$2s^22p^53p\ ^3D^e$	3	87.4444	−0.0831	−0.00209	87.35922	9.45E−11	99.8	87.4354	
9	$2s^22p^53p\ ^1P^e$	1	87.5	−0.0756	−0.00225	87.42211	1.07E−10	56.1 + 19.7(12)	87.5033	
10	$2s^22p^53p\ ^3P^e$	2	87.7242	−0.076	−0.00207	87.64609	6.69E−11	67.4 + 32.4(14)	87.7284	87.786
11	$2s^22p^53p\ ^3P^e$	0	88.4979	−0.0822	−0.00116	88.41457	5.75E−11	87.6	88.4982	
12	$2s^22p^53p\ ^3D^e$	1	89.1012	−0.117	0.000955	88.98526	1.50E−10	69.2 + 28.9(9)	89.0679	
13	$2s^22p^53p\ ^3P^e$	1	89.6148	−0.12	0.00161	89.49636	8.55E−11	59 + 17.5(6)	89.5769	
14	$2s^22p^53p\ ^1D^e$	2	89.6849	−0.128	0.00179	89.55834	7.32E−11	44.6 + 36.2 + 19(11)	89.6419	89.7252
15	$2s^22p^53p\ ^1S^e$	0	90.7077	−0.0916	1.74E−05	90.61607	2.48E−11	86.9	90.7082	
16	$2s^22p^53d\ ^3P^o$	0	91.2797	−0.0734	−0.00276	91.20359	5.97E−11	99.2	91.2602	
17	$2s^22p^53d\ ^3P^o$	1	91.4085	−0.084	−0.00269	91.32185	4.50E−12	87.8	91.3798	91.473
18	$2s^22p^53d\ ^3P^o$	2	91.6349	−0.0912	−0.00261	91.54109	6.23E−11	63.4 + 28.2(25)	91.5879	
19	$2s^22p^53d\ ^3F^o$	4	91.6361	−0.0997	−0.00259	91.53383	6.80E−11	99.8	91.6013	
20	$2s^22p^53d\ ^3F^o$	3	91.6674	−0.0935	−0.00257	91.57134	5.36E−11	61.2 + 31.7(26)	91.627	
21	$2s^22p^53d\ ^1D^o$	2	91.8465	−0.0866	−0.00256	91.75736	5.28E−11	48.2 + 29.4 + 20.9(25)	91.8157	
22	$2s^22p^53d\ ^3D^o$	3	91.9856	−0.0933	−0.00258	91.88975	6.05E−11	65.9 + 32(26)	91.9525	
23	$2s^22p^53d\ ^3D^o$	1	92.5825	−0.0957	−0.00222	92.48462	4.01E−14	63.2 + 30.1(27)	92.537	92.585
24	$2s^22p^53d\ ^3F^o$	2	93.7494	−0.136	0.00128	93.61434	5.22E−11	67.4 + 26.1(21)	93.678	
25	$2s^22p^53d\ ^3D^o$	2	93.8564	−0.139	0.00113	93.71901	6.26E−11	45.6 + 33.5 + 18.2(21)	93.7793	
26	$2s^22p^53d\ ^1F^o$	3	93.938	−0.143	0.00129	93.79681	6.39E−11	36.8 + 36.1 + 26.8(22)	93.8564	
27	$2s^22p^53d\ ^1P^o$	1	94.5665	−0.14	0.00066	94.427	1.88E−14	68.9 + 25.3(23)	94.4753	94.498
28	$2s^12p^63s\ ^3S^e$	1	97.2843	−0.069	−0.0397	97.17558	4.56E−12	98.4	97.2969	
29	$2s^12p^63s\ ^1S^e$	0	97.9367	−0.0623	−0.0401	97.83435	6.71E−12	99.4	97.9571	
30	$2s^12p^63p\ ^3P^o$	0	100.442	−0.0497	−0.0515	100.3409	4.95E−12	99.2	100.452	
31	$2s^12p^63p\ ^3P^o$	1	100.501	−0.055	−0.0514	100.3943	5.00E−13	82.3 + 16.8(33)	100.507	100.358

Table 3. *Continued.*

S. No.	Label	J	MCDF				Lifetimes	Mixing coefficients	FAC	NIST
			DC	Breit	QED	Total				
32	$2s^12p^63p\ ^3P^o$	2	100.942	−0.0665	−0.0506	100.8246	4.82E−12	99.2	100.935	
33	$2s^12p^63p\ ^1P^o$	1	101.115	−0.0668	−0.0507	100.997	1.17E−13	82.4 + 16.9(31)	101.114	100.959
34	$2s^12p^63d\ ^3D^e$	1	104.932	−0.0701	−0.0513	104.8107	5.80E−12	99.4	104.887	
35	$2s^12p^63d\ ^3D^e$	2	104.967	−0.0774	−0.0514	104.838	5.66E−12	98.8	104.915	
36	$2s^12p^63d\ ^3D^e$	3	105.029	−0.0838	−0.0514	104.8936	5.58E−12	99.4	104.97	
37	$2s^12p^63d\ ^1D^e$	2	105.504	−0.0789	−0.0514	105.3738	4.40E−12	99	105.467	
38	$2s^22p^54s\ ^3P^o$	2	113.386	−0.0885	0.00131	113.2984	1.06E−12	99.8	113.351	
39	$2s^22p^54s\ ^1P^o$	1	113.446	−0.088	0.00132	113.3597	5.39E−13	64.6 + 35.2(47)	113.414	113.48
40	$2s^22p^54p\ ^3S^e$	1	114.631	−0.0826	−0.00267	114.546	1.05E−12	55.2 + 40.1(57)	114.596	
41	$2s^22p^54p\ ^3D^e$	2	114.695	−0.0838	−0.00269	114.6088	1.03E−12	51.7 + 33.8(58)	114.659	
42	$2s^22p^54p\ ^3D^e$	3	114.854	−0.0892	−0.00241	114.7622	1.10E−12	99.8	114.812	
43	$2s^22p^54p\ ^1P^e$	1	114.877	−0.087	−0.00244	114.7872	1.07E−12	63.2 + 16(40)	114.838	
44	$2s^22p^54p\ ^3P^e$	2	114.948	−0.0867	−0.0024	114.8591	1.13E−12	68.1 + 31.9(58)	114.91	
45	$2s^22p^54p\ ^3P^e$	0	115.365	−0.0841	−0.00227	115.2783	1.20E−12	50.3 + 49.4(59)	115.318	
46	$2s^22p^54s\ ^3P^o$	0	115.496	−0.135	0.0052	115.3657	1.06E−12	99.8	115.423	
47	$2s^22p^54s\ ^3P^o$	1	115.525	−0.136	0.00518	115.3941	5.94E−13	64.6 + 34.9(39)	115.453	115.631
48	$2s^22p^54d\ ^3P^o$	0	116.296	−0.086	−0.00258	116.2073	6.05E−13	99.8	116.256	
49	$2s^22p^54d\ ^3P^o$	1	116.348	−0.0894	−0.00257	116.2556	5.74E−13	81.7 + 17.6(71)	116.303	116.916
50	$2s^22p^54d\ ^3F^o$	4	116.419	−0.0953	−0.00257	116.3215	6.07E−13	99.8	116.368	
51	$2s^22p^54d\ ^3F^o$	3	116.427	−0.0928	−0.00257	116.3313	6.16E−13	56.4 + 35.6(70)	116.376	
52	$2s^22p^54d\ ^3P^o$	2	116.432	−0.0915	−0.00257	116.3374	6.12E−13	50 + 43.3(69)	116.383	
53	$2s^22p^54d\ ^1D^o$	2	116.493	−0.0907	−0.00257	116.3996	6.20E−13	58.8 + 22.4(68)	116.443	
54	$2s^22p^54d\ ^3D^o$	3	116.546	−0.0928	−0.00257	116.4501	6.20E−13	68.4 + 29.9(70)	116.492	
55	$2s^22p^54p\ ^3D^e$	1	116.78	−0.132	0.0012	116.6492	1.02E−12	72.8 + 24(43)	116.704	
56	$2s^22p^54d\ ^1P^o$	1	116.816	−0.0941	−0.0025	116.7194	5.56E−14	55.4 + 38.4(71)	116.754	
57	$2s^22p^54p\ ^3P^e$	1	116.983	−0.134	0.00147	116.8501	1.12E−12	53.3 + 25.4(40)	116.906	
58	$2s^22p^54p\ ^1D^e$	2	117.009	−0.137	0.00149	116.8734	1.10E−12	48.2 + 34.2 + 17.5(44)	116.93	
59	$2s^22p^54p\ ^1S^e$	0	117.17	−0.124	0.00108	117.0469	1.13E−12	50.1 + 49.7(45)	117.091	
60	$2s^22p^54f\ ^3D^e$	1	117.197	−0.0938	−0.00263	117.1009	2.72E−13	99.8	117.163	
61	$2s^22p^54f\ ^1G^e$	4	117.213	−0.0974	−0.00257	117.1128	2.86E−13	50.4 + 49(74)	117.177	
62	$2s^22p^54f\ ^3D^e$	2	117.219	−0.0947	−0.00262	117.1216	2.77E−13	77.1 + 16(65)	117.186	
63	$2s^22p^54f\ ^3G^e$	5	117.223	−0.0974	−0.00257	117.1226	2.86E−13	100	117.186	
64	$2s^22p^54f\ ^3F^e$	3	117.26	−0.0955	−0.00259	117.1618	2.81E−13	55.1 + 37.6(75)	117.227	

Table 3. *Continued.*

S. No.	Label	*J*	MCDF				Lifetimes	Mixing coefficients	FAC	NIST
			DC	Breit	QED	Total				
65	$2s^22p^54f\ ^1D^e$	2	117.263	−0.095	−0.00259	117.1651	2.91E−13	51.3 + 47.1(73)	117.235	
66	$2s^22p^54f\ ^1F^e$	3	117.271	−0.0957	−0.00257	117.1727	2.85E−13	62.7 + 21.4(72)	117.239	
67	$2s^22p^54f\ ^3F^e$	4	117.285	−0.0962	−0.00257	117.1862	2.87E−13	73.1 + 16.6(61)	117.253	
68	$2s^22p^54d\ ^3F^o$	2	118.522	−0.139	0.00133	118.3836	6.16E−13	72.6 + 21.7(53)	118.435	
69	$2s^22p^54d\ ^3D^o$	2	118.566	−0.14	0.00131	118.4268	6.11E−13	53.6 + 38.7(69)	118.478	
70	$2s^22p^54d\ ^1F^o$	3	118.6	−0.142	0.00133	118.4592	6.14E−13	42 + 34.3 + 23.6(54)	118.509	
71	$2s^22p^54d\ ^3D^o$	1	118.768	−0.14	0.00126	118.6287	6.41E−14	43.8 + 43.8(71)	118.671	118.775
72	$2s^22p^54f\ ^3G^e$	3	119.343	−0.144	0.00133	119.2006	2.85E−13	72.9 + 18.3(66)	119.271	
73	$2s^22p^54f\ ^3F^e$	2	119.363	−0.144	0.00131	119.2205	2.86E−13	46.2 + 32.6 + 21.2(62)	119.291	
74	$2s^22p^54f\ ^3G^e$	4	119.363	−0.144	0.00133	119.2203	2.87E−13	40.7 + 32.9 + 26.4(67)	119.294	
75	$2s^22p^54f\ ^3D^e$	3	119.369	−0.144	0.0013	119.2266	2.80E−13	52.9 + 29.7 + 16.7(66)	119.297	
76	$2s^22p^55s\ ^3P^o$	2	126.244	−0.0926	−0.00089	126.1503	1.30E−12	99.6	126.208	
77	$2s^22p^55s\ ^1P^o$	1	126.275	−0.0922	−0.00084	126.1823	7.38E−13	65.4 + 34.2(107)	126.24	
78	$2s^12p^64s\ ^3S^e$	1	126.645	−0.0793	−0.034	126.5311	8.20E−13	69.1 + 22.6(109)	126.566	
79	$2s^22p^55p\ ^3D^e$	2	126.902	−0.0902	−0.00266	126.809	1.27E−12	50.8 + 34.6(110)	126.857	
80	$2s^22p^55p\ ^3P^e$	1	126.942	−0.0871	−0.00813	126.8464	1.28E−12	41 + 22.9(84)	126.864	
81	$2s^12p^64s\ ^1S^e$	0	126.955	−0.0734	−0.0445	126.8375	9.68E−13	94.5	126.897	
82	$2s^22p^55p\ ^3D^e$	3	126.981	−0.0929	−0.00253	126.8857	1.34E−12	99.8	126.941	
83	$2s^22p^55p\ ^3P^e$	2	127.028	−0.0916	−0.00249	126.934	1.38E−12	68.4 + 31.5(110)	126.987	
84	$2s^22p^55p\ ^1P^e$	1	127.036	−0.0888	−0.0104	126.9367	1.36E−12	41.6 + 35 + 17.9(78)	126.989	
85	$2s^22p^55p\ ^1S^e$	0	127.262	−0.0871	−0.00547	127.1699	1.25E−12	54.9 + 39.4(111)	127.212	
86	$2s^22p^55d\ ^3P^o$	0	127.674	−0.0904	−0.00435	127.5796	7.76E−13	96.6	127.641	
87	$2s^22p^55d\ ^3P^o$	1	127.704	−0.0924	−0.0037	127.608	7.54E−13	79 + 18.3(118)	127.669	
88	$2s^22p^55d\ ^3F^o$	4	127.747	−0.0959	−0.00257	127.6485	8.24E−13	100	127.709	
89	$2s^22p^55d\ ^3F^o$	3	127.749	−0.0946	−0.00257	127.6517	8.28E−13	55.4 + 36.1(117)	127.709	
90	$2s^22p^55d\ ^3P^o$	2	127.75	−0.0938	−0.00289	127.6537	8.11E−13	17.7 + 44.8(116)	127.713	
91	$2s^22p^55d\ ^1D^o$	2	127.781	−0.0936	−0.0026	127.6843	8.29E−13	60.1 + 21.3(115)	127.741	
92	$2s^22p^55d\ ^3D^o$	3	127.807	−0.0946	−0.00257	127.7093	8.29E−13	68.7 + 29.9(117)	127.765	
93	$2s^22p^55d\ ^1P^o$	1	127.937	−0.0956	−0.00335	127.8377	8.03E−14	59.3 + 33.6(118)	127.884	127.988
94	$2s^12p^64p\ ^3P^o$	0	128.019	−0.0769	−0.0441	127.8976	9.01E−13	85.9	127.926	
95	$2s^12p^64p\ ^3P^o$	1	128.063	−0.0736	−0.0477	127.9415	4.55E−13	77.6	127.966	127.988
96	$2s^22p^55f\ ^3D^e$	1	128.119	−0.0949	−0.00282	128.0211	5.23E−13	99.6	128.089	
97	$2s^22p^55f\ ^3D^e$	2	128.133	−0.0954	−0.00277	128.0352	5.30E−13	78	128.104	
98	$2s^22p^55f\ ^3G^e$	4	128.14	−0.0968	−0.00257	128.0408	5.40E−13	49.7 + 49.4(121)	128.111	
99	$2s^22p^55f\ ^3G^e$	5	128.144	−0.0969	−0.00257	128.0448	5.39E−13	100	128.114	

Table 3. *Continued.*

S. No.	Label	J	MCDF				Lifetimes	Mixing coefficients	FAC	NIST
			DC	Breit	QED	Total				
100	$2s^22p^55f\ ^3F^e$	3	128.158	−0.0959	−0.00267	128.0595	5.31E−13	46.6 + 42.6(123)	128.129	
101	$2s^22p^55f\ ^1D^e$	2	128.167	−0.0957	−0.00259	128.0683	5.54E−13	55.2 + 44.6(122)	128.133	
102	$2s^22p^55f\ ^1F^e$	3	128.168	−0.096	−0.00257	128.0692	5.36E−13	56.9 + 24 + 16.1(100)	128.139	
103	$2s^22p^55f\ ^3F^e$	4	128.176	−0.0963	−0.00257	128.077	5.38E−13	73.4 + 17.3(121)	128.139	
104	$2s^12p^64p\ ^3P^o$	2	128.256	−0.0732	−0.0507	128.132	9.25E−13	98.8	128.14	
105	$2s^12p^64p\ ^1P^o$	1	128.268	−0.0929	−0.0382	128.1372	2.60E−13	68.1 + 16.3(107)	128.147	129.99
106	$2s^22p^55s\ ^3P^o$	0	128.406	−0.131	−0.00247	128.273	1.33E−12	89.3	128.153	
107	$2s^22p^55s\ ^3P^o$	1	128.44	−0.116	−0.0117	128.3123	6.28E−13	46.5 + 24(77)	128.153	
108	$2s^22p^55p\ ^3D^e$	1	128.998	−0.138	0.000738	128.8614	1.23E−12	74.5 + 21.8(84)	128.157	
109	$2s^22p^55p\ ^3S^e$	1	129.11	−0.139	0.00125	128.9718	1.38E−12	51.4 + 28.4(109)	128.158	
110	$2s^22p^55p\ ^1D^e$	2	129.111	−0.14	0.000844	128.9715	1.32E−12	48.4 + 33.5 + 17.4(83)	128.162	
111	$2s^22p^55p\ ^3P^e$	0	129.171	−0.135	0.0012	129.0372	1.32E−12	59 + 40.8(85)	128.169	
112	$2s^12p^64d\ ^3D^e$	1	129.768	−0.0751	−0.0506	129.6426	5.47E−13	98.4	128.173	
113	$2s^12p^64d\ ^3D^e$	2	129.772	−0.0782	−0.0503	129.6433	5.53E−13	95.5	128.174	
114	$2s^12p^64d\ ^3D^e$	3	129.785	−0.0812	−0.0498	129.6544	5.57E−13	96.8	128.329	
115	$2s^22p^55d\ ^3F^o$	2	129.854	−0.142	0.00133	129.7133	8.29E−13	74 + 20.6(91)	128.357	
116	$2s^22p^55d\ ^3D^o$	2	129.878	−0.142	0.0013	129.7363	8.27E−13	46 + 36.8(116)	128.921	
117	$2s^22p^55d\ ^1F^o$	3	129.893	−0.143	0.0013	129.7509	8.25E−13	43.2 + 33.9 + 22.8(92)	129.032	
118	$2s^22p^55d\ ^3D^o$	1	129.965	−0.0776	−0.0509	129.8364	5.61E−13	56.9 + 38.6(93)	129.033	129.99
119	$2s^12p^64d\ ^1D^e$	2	129.966	−0.142	0.00129	129.8254	1.41E−13	96.6	129.093	
120	$2s^22p^55f\ ^3G^e$	3	130.262	−0.144	0.00133	130.1195	5.37E−13	74.1 + 16.3(102)	129.658	
121	$2s^22p^55f\ ^1G^e$	4	130.273	−0.144	0.00133	130.1302	5.41E−13	41.2 + 33.2 + 25.7(103)	129.66	
122	$2s^22p^55f\ ^3F^e$	2	130.281	−0.143	0.000436	130.1389	5.29E−13	44.2 + 32.6 + 21.5(97)	129.672	
123	$2s^22p^55f\ ^3D^e$	3	130.288	−0.142	−0.00018	130.1457	5.12E−13	53.3 + 26.6 + 17.1(102)	129.778	
124	$2s^12p^64f\ ^3F^o$	2	130.55	−0.0799	−0.0515	130.4188	2.71E−13	100	129.801	
125	$2s^12p^64f\ ^3F^o$	3	130.554	−0.0813	−0.0515	130.4215	2.71E−13	90.1	129.814	
126	$2s^12p^64f\ ^3F^o$	4	130.566	−0.0817	−0.0515	130.4331	2.71E−13	100	129.843	
127	$2s^12p^64f\ ^1F^o$	3	130.582	−0.0808	−0.0515	130.4497	2.76E−13	90.1	129.883	

Table 4. Energies (in Ryd.) are compared with other results.

	Ne-like Ga		Ne-like Cu		Ne-like Zn	
Level	Calculated value	Ref. [41]	Calculated value	Ref. [41]	Calculated value	Ref. [42]
$2s^22p^6\ ^1S_0$	–	–	–	–	0	0
$2s^22p^53s\ ^3P_2$	–	–	–	–	77.083	77.481
$2s^22p^53s\ ^1P_1$	83.93	84.12	70.86	71.04	77.266	79.337
$2s^22p^53s\ ^3P_0$	–	–	–	–	78.861	79.236
$2s^22p^53s\ ^3P_1$	–	–	–	–	78.965	77.656
$2s^22p^53p\ ^3P_1$	–	–	–	–	82.337	82.687
$2s^22p^53p\ ^1D_2$	–	–	–	–	82.392	82.731
$2s^22p^53p\ ^3D_3$	–	–	–	–	80.483	80.845
$2s^22p^53p\ ^3S_1$	–	–	–	–	79.919	80.353
$2s^22p^53p\ ^3P_2$	–	–	–	–	80.756	81.104
$2s^22p^53p\ ^3P_0$	–	–	–	–	81.446	81.788
$2s^22p^53p\ ^1P_1$	–	–	–	–	80.552	82.249
$2s^22p^53p\ ^3D_1$	–	–	–	–	81.896	80.917
$2s^22p^53p\ ^3D_2$	–	–	–	–	80.180	80.551
$2s^22p^53p\ ^1S_0$	–	–	–	–	83.497	83.826
$2s^22p^53d\ ^3P_0$	–	–	–	–	84.158	84.559
$2s^22p^53d\ ^3P_1$	–	–	–	–	84.266	84.672
$2s^22p^53d\ ^3F_4$	–	–	–	–	84.463	84.862
$2s^22p^53d\ ^3F_3$	–	–	–	–	84.508	84.886
$2s^22p^53d\ ^3P_2$	–	–	–	–	84.467	84.876
$2s^22p^53d\ ^3D_2$	–	–	–	–	86.361	86.744
$2s^22p^53d\ ^3D_3$	–	–	–	–	84.800	86.806
$2s^22p^53d\ ^3D_1$	–	–	–	–	85.346	85.735
$2s^22p^53d\ ^3F_2$	–	–	–	–	86.269	85.056
$2s^22p^53d\ ^1D_2$	–	–	–	–	84.681	86.615
$2s^22p^53d\ ^1F_3$	–	–	–	–	86.432	85.196
$2s^22p^53d\ ^1P_1$	–	–	–	–	87.058	87.464

applications in analysing new data from different plasma and astrophysical sources.

2. Theoretical method

For reliable calculations, we have performed calculations by taking two different methods, namely MCDF method and flexible atomic code (FAC). Both methods being fully relativistic, give comparable results. We have obtained results using the MCDF method employed in the GRASP code of Grant *et al* [26] and revised by Norrington [27]. In the MCDF approach, Hamiltonian for an N-electron atom or ion Dirac–Coulomb Hamiltonian is given by

$$\hat{H}^{\mathrm{DC}} = \sum_{i=1}^{N} \hat{H}_i + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left|\hat{r}_i - \hat{r}_j\right|^{-1}, \tag{1}$$

where

$$\hat{H} = c\,\alpha_i \cdot p_i + \beta c^2 + V_{\mathrm{nuc}}(r) \tag{2}$$

is the single-particle Hamiltonian consisting of kinetic energy and its interaction with the nucleus. In eq. (2), α and β represent 4×4 Dirac matrices whereas c is the speed of light. The N-electron wave function is constructed from central-field Dirac orbitals given by

$$\phi_{nkm} = \frac{1}{r} \begin{pmatrix} P_{nk}(r) & \chi_{km}(\theta,\phi,\sigma) \\ -i\,Q_{nk}(r) & \chi_{-km}(\theta,\phi,\sigma) \end{pmatrix}, \tag{3}$$

where k is the Dirac angular quantum number, $k = \pm(j+1/2)$ for $l = j \pm 1/2$. So $j = k - 1/2$, m is the projection of the angular momentum j, and P_{nk}, Q_{nk} are radial functions. The spin angular momentum $\chi_{km}(\theta,\phi)$ is a two-component function defined by

$$\chi_{km}(\theta,\phi) = \sum_{\sigma=\pm 1/2} \left\langle lm - \sigma \frac{1}{2}\sigma \,\middle|\, l\frac{1}{2}jm \right\rangle Y_l^{m-\sigma}(\theta,\phi)\,\phi^{\sigma}\,. \tag{4}$$

An atomic state function (ASF) now formed for the N-electron system with the given total angular momentum

Table 5. Transition data for E1, E2, M1 and M2 transitions from ground levels and $2J$ for lower level I, upper level k, wavelength λ (Å), line strength S (length form), oscillator strength f (length form), transition rate A_{ji} (length form) calculated using MCDF for Ne-like Cu. Results are compared with NIST.

S. No.	I	J	λ (Å) MCDF	λ (Å) NIST	A_{ji} (s^{-1}) (MCDF)	f_{ij} (MCDF)	S_{ij} (a.u.) (MCDF)	Velocity/length	Type
1	$2s^22p^6\ ^1S_0$	$2s^22p^53s\ ^3P_2$	12.891		6.81E+05	8.48E−08	8.13E−02		M2
2	$2s^22p^6\ ^1S_0$	$2s^22p^53s\ ^1P_1$	12.859	12.827	1.80E+12	1.34E−01	5.68E−03	0.95	E1
3	$2s^22p^6\ ^1S_0$	$2s^22p^53s\ ^3P_1$	12.601	12.570	1.38E+12	9.85E−02	4.09E−03	0.95	E1
4	$2s^22p^6\ ^1S_0$	$2s^22p^53s\ ^3S_1$	12.42		7.99E+05	5.54E−08	1.70E−04		M1
5	$2s^22p^6\ ^1S_0$	$2s^22p^53p\ ^3D_2$	12.375		1.28E+09	1.47E−04	1.66E−03	0.97	E2
6	$2s^22p^6\ ^1S_0$	$2s^22p^53p\ ^1P_1$	12.321		1.94E+03	1.33E−10	4.05E−07		M1
7	$2s^22p^6\ ^1S_0$	$2s^22p^53p\ ^3P_2$	12.291		1.33E+09	1.51E−04	1.67E−03	0.97	E2
8	$2s^22p^6\ ^1S_0$	$2s^22p^53p\ ^3D_1$	12.133		2.65E+04	1.76E−09	5.27E−06		M1
9	$2s^22p^6\ ^1S_0$	$2s^22p^53p\ ^3P_1$	12.072		6.84E+05	4.48E−08	1.34E−04		M1
10	$2s^22p^6\ ^1S_0$	$2s^22p^53p\ ^3P_2$	12.064		1.56E+09	1.71E−04	1.79E−03	0.97	E2
11	$2s^22p^6\ ^1S_0$	$2s^22p^53d\ ^3P_1$	11.76	11.736	1.56E+11	9.71E−03	3.76E−04	0.99	E1
12	$2s^22p^6\ ^1S_0$	$2s^22p^53d\ ^3P_2$	11.732		1.82E+07	1.88E−06	1.36E+00		M2
13	$2s^22p^6\ ^1S_0$	$2s^22p^53d\ ^1D_2$	11.701		4.49E+06	4.61E−07	3.30E−01		M2
14	$2s^22p^6\ ^1S_0$	$2s^22p^53d\ ^3D_1$	11.611	11.594	1.46E+13	8.84E−01	3.38E−02	0.99	E1
15	$2s^22p^6\ ^1S_0$	$2s^22p^53d^3\ ^3F_2$	11.501		9.90E+05	9.82E−08	6.68E−02		M2
16	$2s^22p^6\ ^1S_0$	$2s^22p^53d\ ^3D_2$	11.49		1.61E+06	1.60E−07	1.08E−01		M2
17	$2s^22p^6\ ^1S_0$	$2s^22p^53d\ ^1P_1$	11.391	11.383	4.03E+13	2.35E+00	8.82E−02	0.99	E1
18	$2s^22p^6\ ^1S_0$	$2s2p^63s\ ^3S_1$	11.023		7.92E+04	4.33E−09	1.18E−05		M1
19	$2s^22p^6\ ^1S_0$	$2s2p^63p\ ^3P_1$	10.647	10.653	1.07E+12	5.47E−02	1.92E−03	1	E1
20	$2s^22p^6\ ^1S_0$	$2s2p^63p\ ^3P_2$	10.61		2.75E+06	2.32E−07	1.24E−01		M2
21	$2s^22p^6\ ^1S_0$	$2s2p^63p\ ^1P_1$	10.59	10.597	6.04E+12	3.04E−01	1.06E−02	1	E1
22	$2s^22p^6\ ^1S_0$	$2s2p^63d\ ^3D_1$	10.179		9.46E+03	4.41E−10	1.11E−06		M1
23	$2s^22p^6\ ^1S_0$	$2s2p^63d\ ^3D_2$	10.177		1.07E+08	8.34E−06	5.23E−05	0.97	E2
24	$2s^22p^6\ ^1S_0$	$2s2p^63d\ ^1D_2$	10.124		2.42E+10	1.86E−03	1.15E−02	0.97	E2
25	$2s^22p^6\ ^1S_0$	$2s^22p^54s\ ^3P_2$	9.5392		3.78E+05	2.58E−08	1.00E−02		M2
26	$2s^22p^6\ ^1S_0$	$2s^22p^54s\ ^1P_1$	9.5337	9.521	6.43E+11	2.63E−02	8.25E−04	0.83	E1
27	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^3S_1$	9.4287		4.84E+05	1.93E−08	4.51E−05		M1
28	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^3D_2$	9.4225		5.15E+08	3.43E−05	1.71E−04	0.81	E2
29	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^1P_1$	9.4098		9.89E+03	3.94E−10	9.17E−07		M1
30	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^3P_2$	9.404		4.91E+08	3.26E−05	1.61E−04	0.82	E2
31	$2s^22p^6\ ^1S_0$	$2s^22p^54s\ ^3P_1$	9.3865	9.375	4.74E+11	1.88E−02	5.80E−04	0.84	E1
32	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^3P_1$	9.2826	9.274	8.50E+10	3.29E−03	1.01E−04	0.93	E1
33	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^3F_3$	9.2761		8.51E+06	5.49E−07	1.96E−01		M2
34	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^3D_1$	9.2782		1.82E+04	7.05E−10	1.62E−06		M1
35	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^1D_2$	9.2705		3.45E+06	2.22E−07	7.93E−02		M2
36	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^3P_1$	9.2644		2.62E+05	1.01E−08	2.32E−05		M1
37	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^1D_2$	9.2625		5.77E+08	3.71E−05	1.76E−04	0.82	E2
38	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^1P_1$	9.2443	9.237	1.12E+13	4.30E−01	1.31E−02	0.93	E1
39	$2s^22p^6\ ^1S_0$	$2s^22p^54f\ ^3D_1$	9.2126		1.16E+03	4.44E−11	1.01E−07		M1
40	$2s^22p^6\ ^1S_0$	$2s^22p^54f\ ^3G_5$	9.2112		2.04E+09	1.30E−04	6.03E−04	1	E2
41	$2s^22p^6\ ^1S_0$	$2s^22p^54f\ ^1D_2$	9.2077		5.42E+09	3.45E−04	1.60E−03	1	E2
42	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^3F_2$	9.1351		3.28E+05	2.05E−08	7.00E−03		M2
43	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^3D_2$	9.1323		1.66E+06	1.04E−07	3.55E−02		M2
44	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^3D_1$	9.1144	9.106	1.06E+13	3.97E−01	1.19E−02	0.93	E1
45	$2s^22p^6\ ^1S_0$	$2s^22p^54f\ ^3F_2$	9.0685		3.64E+09	2.25E−04	9.97E−04	1	E2
46	$2s^22p^6\ ^1S_0$	$2s^22p^55s\ ^3P_2$	8.5746		3.40E+05	1.87E−08	5.29E−03		M2
47	$2s^22p^6\ ^1S_0$	$2s^22p^55s\ ^1P_1$	8.5723		3.89E+11	1.29E−02	3.63E−04	0.72	E1
48	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3S_1$	8.5317		3.06E+05	1.00E−08	2.11E−05		M1

Table 5. *Continued.*

S. No.	I	J	λ (Å) MCDF	λ (Å) NIST	A_{ji} (s^{-1}) (MCDF)	f_{ij} (MCDF)	S_{ij} (a.u.) (MCDF)	Velocity/length	Type
49	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3D_2$	8.5271		4.69E+08	2.56E−05	9.44E−05	0.55	E2
50	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^1P_1$	8.5222		1.88E+03	6.16E−11	1.30E−07		M1
51	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3P_2$	8.5196		4.29E+08	2.33E−05	8.59E−05	0.55	E2
52	$2s^22p^6\ ^1S_0$	$2s2p^64s\ ^3S_1$	8.4808		6.14E+03	1.98E−10	4.16E−07		M1
53	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3P_1$	8.4708		7.86E+10	2.54E−03	7.08E−05	0.88	E1
54	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3F_0$	8.468		4.83E+06	2.60E−07	7.05E−02		M2
55	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^1D_2$	8.4658		2.23E+06	1.20E−07	3.25E−02		M2
56	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^1P_1$	8.4562	8.447	6.14E+12	1.97E−01	5.50E−03	0.88	E1
57	$2s^22p^6\ ^1S_0$	$2s^22p^55s\ ^3P_1$	8.4507		1.23E+12	3.96E−02	1.10E−03	0.97	E1
58	$2s^22p^6\ ^1S_0$	$2s^22p^55f\ ^3D_1$	8.4424		1.76E+03	5.63E−11	1.18E−07		M1
59	$2s^22p^6\ ^1S_0$	$2s^22p^55f\ ^3D_2$	8.4416		1.14E+09	6.08E−05	2.18E−04	1.1	E2
60	$2s^22p^6\ ^1S_0$	$2s^22p^55f\ ^1D_2$	8.4395		4.35E+09	2.32E−04	8.31E−04	1.1	E2
61	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3D_1$	8.4077		8.22E+03	2.61E−10	5.43E−07		M1
62	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3P_1$	8.4014		4.84E+08	2.56E−05	9.05E−05	0.55	E2
63	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^1D_2$	8.4013		1.48E+05	4.69E−09	9.75E−06		M1
64	$2s^22p^6\ ^1S_0$	$2s2p^64p\ ^3P_1$	8.3899	8.400	1.12E+12	3.55E−02	9.80E−04	0.94	E1
65	$2s^22p^6\ ^1S_0$	$2s2p^64p\ ^3P_2$	8.3808		2.35E+06	1.24E−07	3.26E−02		M2
66	$2s^22p^6\ ^1S_0$	$2s2p^64p\ ^1P_1$	8.3763	8.385	3.14E+12	9.91E−02	2.73E−03	0.95	E1
67	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3F_2$	8.3499		2.16E+05	1.13E−08	2.95E−03		M2
68	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3D_2$	8.3484		7.83E+05	4.09E−08	1.06E−02		M2
69	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3D_1$	8.3419	8.333	3.98E+12	1.24E−01	3.42E−03	0.89	E1
70	$2s^22p^6\ ^1S_0$	$2s^22p^55f\ ^3F_2$	8.3224		2.90E+09	1.51E−04	5.17E−04	1.1	E2
71	$2s^22p^6\ ^1S_0$	$2s2p^64d\ ^3D_1$	8.2765		4.70E+03	1.45E−10	2.97E−07		M1
72	$2s^22p^6\ ^1S_0$	$2s2p^64d\ ^3D_2$	8.2757		1.65E+07	8.48E−07	2.86E−06	0.65	E2
73	$2s^22p^6\ ^1S_0$	$2s2p^64d\ ^1D_2$	8.2632		6.22E+09	3.18E−04	1.07E−03	0.91	E2
74	$2s^22p^6\ ^1S_0$	$2s2p^64f\ ^3F_2$	8.2251		1.98E−01	1.01E−14	2.50E−09		M2

J, M and parity P are approximated by a linear combination of n_c electronic configuration state functions (CSF)

$$|\psi_\alpha(PJM)\rangle = \sum_{i=1}^{n_c} C_i(\alpha)|\gamma_i(PJM)\rangle, \quad (5)$$

where n_c is the number of CSFs included in the expansion, $C_i(\alpha)$ are the expansion mixing coefficients and α represents all information such as orbital occupation numbers, coupling etc. For expectation of Dirac–Hamiltonian we get the energy of the N-electron system as

$$E_\alpha^{PJM} = \left\langle \Psi_\alpha(PJM)\left|\mathrm{H}^{\mathrm{DC}}\right|\Psi_\alpha(PJM)\right\rangle$$
$$= \sum_{ij} C_i^*(\alpha)\, C_j(\alpha)\langle\gamma_i^{PJM}|H^{\mathrm{DC}}|\gamma_j^{PJM}\rangle \quad (6)$$
$$= (C_\alpha^{\mathrm{DC}})^+ H^{\mathrm{DC}} C_\alpha^{\mathrm{DC}}. \quad (7)$$

The Hamiltonian matrix H^{DC} has elements

$$H_{rs}^{\mathrm{DC}} = \langle\gamma_r^{PJM}|H^{\mathrm{DC}}|\gamma_s^{PJM}\rangle. \quad (8)$$

Requiring eq. (8) to be stationary with respect to the mixing coefficients leads to the eigenvalue problem to the mixing coefficients

$$(H^{\mathrm{DC}} - E_\alpha^{\mathrm{DC}}\, I)\, C_\alpha^{\mathrm{DC}} = 0, \quad (9)$$

where I is the $n_c \times n_c$ unit matrix. Thus, the predicted atomic energy level E_α^{PJM} can be taken to be the eigenvalues of H^{DC}. There is inclusion of the relativistic two-body Breit interaction and the QED corrections due to vacuum polarization and self-energy. Vacuum polarization and self-energy make up the Lamb shift to the energy and mainly affect the orbitals which penetrate the nucleus. We have used this method to calculate various atomic data parameters in the past [28–38] as it can provide reliable energies and radiative rates among multiplet states of atoms for a wide range of ionizations.

Due to the shortage of data for comparison and to check the accuracy of our reported energy levels, we have used the FAC for the other calculation. This is a fully relativistic method based on distorted wave

Table 6. Transition data for E1, E2, M1 and M2 transitions from ground levels and $2J$ for lower level I, upper level k, wavelength λ (Å), line strength S (length form), oscillator strength f (length form), transition rate A_{ji} (length form) calculated using MCDF for Ne-like Zn.

I	j	λ (Å) MCDF	A_{ji} (s^{-1}) (MCDF)	f_{ij} (MCDF)	S_{ij} (a.u.) (MCDF)	Velocity/length	Type
$2s^22p^6\,^1S_0$	$2s^22p^53s\,^3P_2$	11.822	9.50E+05	9.96E−08	7.36E−02		M2
$2s^22p^6\,^1S_0$	$2s^22p^53s\,^1P_1$	11.794	2.16E+12	1.35E−01	5.25E−03	0.95	E1
$2s^22p^6\,^1S_0$	$2s^22p^53s\,^3P_1$	11.54	1.60E+12	9.58E−02	3.64E−03	0.95	E1
$2s^22p^6\,^1S_0$	$2s^22p^53p\,^3S_1$	11.402	1.23E+06	7.22E−08	2.03E−04		M1
$2s^22p^6\,^1S_0$	$2s^22p^53p\,^3D_2$	11.365	1.68E+09	1.63E−04	1.42E−03	0.97	E2
$2s^22p^6\,^1S_0$	$2s^22p^53p\,^1P_1$	11.313	3.04E+01	1.75E−12	4.89E−09		M1
$2s^22p^6\,^1S_0$	$2s^22p^53p\,^3P_2$	11.284	1.73E+09	1.65E−04	1.41E−03	0.97	E2
$2s^22p^6\,^1S_0$	$2s^22p^53p\,^3D_1$	11.127	4.22E+04	2.35E−09	6.46E−06		M1
$2s^22p^6\,^1S_0$	$2s^22p^53p\,^3P_1$	11.068	9.89E+05	5.45E−08	1.49E−04		M1
$2s^22p^6\,^1S_0$	$2s^22p^53p\,^1D_2$	11.06	2.02E+09	1.85E−04	1.49E−03	0.97	E2
$2s^22p^6\,^1S_0$	$2s^22p^53d\,^3P_1$	10.814	1.81E+11	9.52E−03	3.39E−04	0.99	E1
$2s^22p^6\,^1S_0$	$2s^22p^53d\,^3P_2$	10.789	2.49E+07	2.17E−06	1.22E+00		M2
$2s^22p^6\,^1S_0$	$2s^22p^53d\,^1D_2$	10.761	6.95E+06	6.04E−07	3.36E−01		M2
$2s^22p^6\,^1S_0$	$2s^22p^53d\,^3D_1$	10.677	1.92E+13	9.87E−01	3.47E−02	0.99	E1
$2s^22p^6\,^1S_0$	$2s^22p^53d\,^3F_2$	10.563	1.28E+06	1.07E−07	5.65E−02		M2
$2s^22p^6\,^1S_0$	$2s^22p^53d\,^3D_2$	10.552	2.58E+06	2.15E−07	1.13E−01		M2
$2s^22p^6\,^1S_0$	$2s^22p^53d\,^1P_1$	10.467	4.65E+13	2.29E+00	7.89E−02	0.99	E1
$2s^22p^6\,^1S_0$	$2s^22p^63s\,^3S_1$	10.151	1.20E+05	5.58E−09	1.40E−05		M1
$2s^22p^6\,^1S_0$	$2s^22p^63p\,^3P_1$	9.8156	1.40E+12	6.07E−02	1.96E−03	1	E1
$2s^22p^6\,^1S_0$	$2s^22p^63p\,^3P_2$	9.7774	3.88E+06	2.78E−07	1.16E−01		M2
$2s^22p^6\,^1S_0$	$2s^22p^63p\,^1P_1$	9.7599	7.13E+12	3.05E−01	9.81E−03	1	E1
$2s^22p^6\,^1S_0$	$2s^22p^63d\,^3D_1$	9.3936	1.44E+04	5.72E−10	1.33E−06		M1
$2s^22p^6\,^1S_0$	$2s^22p^63d\,^3D_2$	9.3914	1.77E+08	1.17E−05	5.79E−05	0.97	E2
$2s^22p^6\,^1S_0$	$2s^22p^63d\,^1D_2$	9.343	3.09E+10	2.02E−03	9.81E−03	0.97	E2
$2s^22p^6\,^1S_0$	$2s^22p^54s\,^3P_2$	8.7431	5.35E+05	3.06E−08	9.16E−03		M2
$2s^22p^6\,^1S_0$	$2s^22p^54s\,^1P_1$	8.7382	7.63E+11	2.62E−02	7.54E−04	0.84	E1
$2s^22p^6\,^1S_0$	$2s^22p^54p\,^3S_1$	8.645	7.31E+05	2.46E−08	5.25E−05		M1
$2s^22p^6\,^1S_0$	$2s^22p^54p\,^3D_2$	8.6398	6.78E+08	3.80E−05	1.46E−04	0.82	E2
$2s^22p^6\,^1S_0$	$2s^22p^54p\,^1P_1$	8.6273	2.44E+04	8.16E−10	1.74E−06		M1
$2s^22p^6\,^1S_0$	$2s^22p^54p\,^3P_2$	8.6219	6.50E+08	3.62E−05	1.38E−04	0.83	E2
$2s^22p^6\,^1S_0$	$2s^22p^54p\,^3P_0$	8.5939	5.85E+11	1.94E−02	5.50E−04	0.85	E1
$2s^22p^6\,^1S_0$	$2s^22p^54d\,^3P_1$	8.5146	9.23E+10	3.01E−03	8.44E−05	0.93	E1
$2s^22p^6\,^1S_0$	$2s^22p^54d\,^3P_2$	8.5086	1.15E+07	6.22E−07	1.71E−01		M2
$2s^22p^6\,^1S_0$	$2s^22p^54d\,^1D_2$	8.5038	5.40E+06	2.93E−07	8.05E−02		M2
$2s^22p^6\,^1S_0$	$2s^22p^54d\,^1D_1$	8.4982	2.75E+04	8.94E−10	1.88E−06		M1
$2s^22p^6\,^1S_0$	$2s^22p^54d\,^1P_1$	8.4846	3.87E+05	1.25E−08	2.63E−05		M1
$2s^22p^6\,^1S_0$	$2s^22p^54p\,^3P_1$	8.4829	7.65E+08	4.13E−05	1.50E−04	0.83	E2
$2s^22p^6\,^1S_0$	$2s^22p^54p\,^1D_2$	8.4802	1.36E+13	4.41E−01	1.23E−02	0.93	E1
$2s^22p^6\,^1S_0$	$2s^22p^54f\,^3D_1$	8.4518	1.82E+03	5.86E−11	1.22E−07		M1
$2s^22p^6\,^1S_0$	$2s^22p^54f\,^3D_2$	8.4504	2.53E+09	1.36E−04	4.87E−04	1	E2
$2s^22p^6\,^1S_0$	$2s^22p^54f\,^1D_2$	8.4473	7.53E+09	4.03E−04	1.45E−03	1	E2
$2s^22p^6\,^1S_0$	$2s^22p^54d\,^3F_2$	8.3706	4.43E+05	2.33E−08	6.10E−03		M2
$2s^22p^6\,^1S_0$	$2s^22p^54d\,^3D_2$	8.3678	2.45E+06	1.28E−07	3.36E−02		M2
$2s^22p^6\,^1S_0$	$2s^22p^54d\,^3D_1$	8.3525	1.22E+13	3.84E−01	1.06E−02	0.93	E1
$2s^22p^6\,^1S_0$	$2s^22p^54f\,^3F_2$	8.3108	4.93E+09	2.55E−04	8.72E−04	1	E2
$2s^22p^6\,^1S_0$	$2s^22p^55s\,^3P_2$	7.8556	4.96E+05	2.29E−08	4.97E−03		M2

Table 6. *Continued.*

I	j	λ (Å) MCDF	A_{ji} (s^{-1}) (MCDF)	f_{ij} (MCDF)	S_{ij} (a.u.) (MCDF)	Velocity/length	Type
$2s^22p^6\ ^1S_0$	$2s^22p^55s\ ^1P_1$	7.8536	4.71E+11	1.31E−02	3.38E−04	0.73	E1
$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3S_1$	7.8201	4.86E+05	1.34E−08	2.59E−05		M1
$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3D_2$	7.8135	6.04E+08	2.76E−05	7.85E−05	0.56	E2
$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^1P_1$	7.8092	9.03E+01	2.48E−12	4.78E−09		M1
$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3P_2$	7.8062	5.57E+08	2.54E−05	7.21E−05	0.57	E2
$2s^22p^6\ ^1S_0$	$2s2p^64s\ ^3S_1$	7.7948	1.33E+03	3.63E−11	6.99E−08		M1
$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3P_1$	7.7632	7.43E+10	2.01E−03	5.14E−05	0.88	E1
$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3P_2$	7.7606	6.61E+06	2.99E−07	6.24E−02		M2
$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3P_2$	7.7587	3.48E+06	1.57E−07	3.28E−02		M2
$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^1P_1$	7.7492	9.01E+12	2.43E−01	6.21E−03	0.9	E1
$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^1P_1$	7.7378	2.88E+03	7.75E−11	1.48E−07		M1
$2s^22p^6\ ^1S_0$	$2s^22p^55f\ ^3D_2$	7.737	1.42E+09	6.36E−05	1.76E−04	1.1	E2
$2s^22p^6\ ^1S_0$	$2s^22p^55f\ ^3F_2$	7.735	5.99E+09	2.68E−04	7.40E−04	1.1	E2
$2s^22p^6\ ^1S_0$	$2s^22p^55s\ ^3P_1$	7.7365	6.62E+09	1.78E−04	4.54E−06	2.4	E1
$2s^22p^6\ ^1S_0$	$2s2p^64p\ ^3P_1$	7.7165	1.41E+12	3.78E−02	9.60E−04	0.94	E1
$2s^22p^6\ ^1S_0$	$2s2p^64p\ ^3P_2$	7.7078	2.95E+06	1.31E−07	2.69E−02		M2
$2s^22p^6\ ^1S_0$	$2s2p^64p\ ^1P_1$	7.7036	3.07E+12	8.21E−02	2.08E−03	0.96	E1
$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3D_1$	7.6966	1.30E+04	3.46E−10	6.58E−07		M1
$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3P_1$	7.6905	2.13E+05	5.67E−09	1.08E−05		M1
$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^1D_2$	7.6905	6.59E+08	2.92E−05	7.91E−05	0.57	E2
$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3F_2$	7.645	2.51E+05	1.10E−08	2.20E−03		M2
$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3D_2$	7.6437	1.41E+06	6.17E−08	1.23E−02		M2
$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3D_1$	7.6381	4.98E+12	1.31E−01	3.29E−03	0.9	E1
$2s^22p^6\ ^1S_0$	$2s^22p^55f\ ^3F_2$	7.6219	4.30E+09	1.87E−04	4.93E−04	1.1	E2
$2s^22p^6\ ^1S_0$	$2s^22p^64d\ ^3D_1$	7.6151	7.03E+03	1.83E−10	3.45E−07		M1
$2s^22p^6\ ^1S_0$	$2s^22p^64d\ ^3D_2$	7.6128	1.53E+08	6.64E−06	1.74E−05	1.3	E2
$2s^22p^6\ ^1S_0$	$2s^22p^64d\ ^1D_2$	7.6031	7.10E+09	3.08E−04	8.06E−04	0.91	E2
$2s^22p^6\ ^1S_0$	$2s^22p^64f\ ^3F_2$	7.5687	3.79E−02	1.63E−15	3.16E−10		M2

approximation and developed by Gu [39]. It offers consistent and user-friendly platform for users to perform calculations in a systematic way.

3. Results and discussions

3.1 *Energy levels*

We have included enlarged configuration interaction (CI) to attain accuracy in our results since it is a necessary tool for an accurate determination of energy levels, transition probabilities, oscillator strength etc. for highly ionized ions. We have reported 127 fine structural levels belonging to $2s^22p^6$, $2s^22p^53s$, $2s^22p^53p$, $2s^22p^53d$, $2s2p^63s$, $2s2p^63p$, $2s2p^63d$, $2s^22p^54s$, $2s^22p^54p$, $2s^22p^5$ 4d, $2s^22p^54f$, $2s^22p^55s$, $2s^22p^55p$, $2s^22p^55d$, $2s^22p^55f$, $2s2p^64p$, $2s2p^64s$, $2s2p^64d$ and $2s2p^64f$ for Ne-like ions ($Z = 29$–31).

In our MCDF calculations, we have included 51 configurations, $2s^22p^6$, $2s^22p^53l$ (l = 0–2), $2s2p^63l$ (l = 0–2), $2s2p^64l$ (l = 0–3), $2s^22p^54l$ (l = 0–3), $2s^22p^55l$ (l = 0–3), $2s2p^65l$ (l = 0–3), $2s^22p^56l$ (l = 0–3), $2s2p^66l$ (l = 0–3), $2s^22p^57l$ (l = 0–3), $2s2p^67l$ (l = 0–3), $2s^22p^43s^2$, $2s^22p^43p^2$, $2s^22p^43d^2$, $2s2p^53s^2$, $2s2p^53p^2$, $2s2p^53d^2$, $2s^22p^43s3p$, $2s^22p^43$ p3d, $2s^22p^43s$ 3d, $2s2p^53s3p$, $2s2p^53p3d$ and $2s2p^53s3d$ which give rise to 1016 fine structural levels, out of which 127 levels are reported. We mainly focus on one-electron excitation by taking 39 configurations of single excitation due to negligible contributions of two or more electron excitations on energy levels and radiative rates.

In tables 1–3, we have listed 127 fine structure levels obtained with MCDF method along with the mixing coefficients for Ne-like Cu, Zn and Ga. Lifetimes of all the excited levels have also been reported in tables 1–3. In the column mixing coefficients, the first number of each level denotes the leading percentage of that level. The next percentage, which is in the form $P(Q)$ says that the next leading percentage is $P\%$ with level number Q. We observe that some of the levels can be

Table 7. Transition data for E1, E2, M1 and M2 transitions from ground levels and $2J$ for lower level I, upper level k, wavelength λ (Å), line strength S (length form), oscillator strength f (length form), transition rate A_{ji} (length form) calculated using MCDF for Ne-like Ga. Results are compared with NIST values.

S. No.	I	J	λ (Å) MCDF	λ (Å) NIST	A_{ji} (s^{-1}) (MCDF)	f_{ij} (MCDF)	S_{ij} (a.u.) (MCDF)	Velocity/length	Type
1	$2s^22p^6\ ^1S_0$	$2s^22p^53s\ ^3P_2$	10.882		1.31E+06	1.16E−07	6.70E−02		M2
2	$2s^22p^6\ ^1S_0$	$2s^22p^53s\ ^1P_1$	10.857	10.833	2.56E+12	1.36E−01	4.86E−03	0.96	E1
3	$2s^22p^6\ ^1S_0$	$2s^22p^53s\ ^3P_1$	10.607	10.583	1.85E+12	9.35E−02	3.27E−03	0.95	E1
4	$2s^22p^6\ ^1S_0$	$2s^22p^53p\ ^3S_1$	10.506		1.86E+06	9.25E−08	2.40E−04		M1
5	$2s^22p^6\ ^1S_0$	$2s^22p^53p\ ^3D_2$	10.475		2.17E+09	1.79E−04	1.22E−03	0.97	E2
6	$2s^22p^6\ ^1S_0$	$2s^22p^53p\ ^3P_1$	10.424		2.71E+03	1.33E−10	3.42E−07		M1
7	$2s^22p^6\ ^1S_0$	$2s^22p^53p\ ^3P_2$	10.397		2.23E+09	1.80E−04	1.21E−03	0.97	E2
8	$2s^22p^6\ ^1S_0$	$2s^22p^53p\ ^3D_1$	10.241		6.48E+04	3.05E−09	7.73E−06		M1
9	$2s^22p^6\ ^1S_0$	$2s^22p^53p\ ^3P_1$	10.182		1.41E+06	6.58E−08	1.66E−04		M1
10	$2s^22p^6\ ^1S_0$	$2s^22p^53p\ ^1D_2$	10.175		2.58E+09	2.00E−04	1.26E−03	0.97	E2
11	$2s^22p^6\ ^1S_0$	$2s^22p^53d\ ^3P_1$	9.9787	9.961	2.05E+11	9.20E−03	3.02E−04	0.99	E1
12	$2s^22p^6\ ^1S_0$	$2s^22p^53d\ ^3P_2$	9.9548		3.35E+07	2.49E−06	1.10E+00		M2
13	$2s^22p^6\ ^1S_0$	$2s^22p^53d\ ^1D_2$	9.9313		1.07E+07	7.88E−07	3.45E−01		M2
14	$2s^22p^6\ ^1S_0$	$2s^22p^53d\ ^3D_1$	9.8533	9.842	2.49E+13	1.09E+00	3.53E−02	0.99	E1
15	$2s^22p^6\ ^1S_0$	$2s^22p^53d\ ^3F_2$	9.7343		1.65E+06	1.17E−07	4.83E−02		M2
16	$2s^22p^6\ ^1S_0$	$2s^22p^53d\ ^3D_2$	9.7235		3.99E+06	2.82E−07	1.16E−01		M2
17	$2s^22p^6\ ^1S_0$	$2s^22p^53d\ ^1P_1$	9.6506	9.643	5.31E+13	2.22E+00	7.07E−02	0.99	E1
18	$2s^22p^6\ ^1S_0$	$2s^12p^63s\ ^3S_1$	9.3776		1.80E+05	7.14E−09	1.66E−05		M1
19	$2s^22p^6\ ^1S_0$	$2s^12p^63p\ ^3P_1$	9.077	9.081	1.79E+12	6.65E−02	1.99E−03	1	E1
20	$2s^22p^6\ ^1S_0$	$2s^12p^63p\ ^3P_2$	9.0382		5.41E+06	3.31E−07	1.09E−01		M2
21	$2s^22p^6\ ^1S_0$	$2s^12p^63p\ ^1P_1$	9.0228	9.027	8.37E+12	3.06E−01	9.10E−03	1	E1
22	$2s^22p^6\ ^1S_0$	$2s^12p^63d\ ^3D_1$	8.6945		2.16E+04	7.33E−10	1.58E−06		M1
23	$2s^22p^6\ ^1S_0$	$2s^12p^63d\ ^3D_2$	8.6922		2.87E+08	1.62E−05	6.35E−05	0.97	E2
24	$2s^22p^6\ ^1S_0$	$2s^12p^63d\ ^1D_2$	8.648		3.90E+10	2.19E−03	8.42E−03	0.97	E2
25	$2s^22p^6\ ^1S_0$	$2s^22p^54s\ ^3P_2$	8.0431		7.45E+05	3.61E−08	8.41E−03		M2
26	$2s^22p^6\ ^1S_0$	$2s^22p^54s\ ^1P_1$	8.0388	8.028	8.98E+11	2.61E−02	6.91E−04	0.85	E1
27	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^3S_1$	7.9555		1.08E+06	3.08E−08	6.06E−05		M1
28	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^3D_2$	7.9512		8.80E+08	4.17E−05	1.25E−04	0.83	E2
29	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^1P_1$	7.9388		5.27E+04	1.49E−09	2.93E−06		M1
30	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^3P_2$	7.9338		8.46E+08	3.99E−05	1.19E−04	0.83	E2
31	$2s^22p^6\ ^1S_0$	$2s^22p^54s\ ^3P_1$	7.8971	7.887	7.28E+11	2.04E−02	5.31E−04	0.86	E1
32	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^3P_1$	7.8385		9.70E+10	2.68E−03	6.92E−05	0.93	E1
33	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^3P_2$	7.833		1.51E+07	6.92E−07	1.49E−01		M2
34	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^1D_2$	7.8288		8.37E+06	3.84E−07	8.25E−02		M2
35	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^3D_1$	7.8121		4.07E+04	1.12E−09	2.16E−06		M1
36	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^1P_1$	7.8074	7.794	1.64E+13	4.50E−01	1.16E−02	0.93	E1
37	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^3P_1$	7.7987		5.63E+05	1.54E−08	2.97E−05		M1
38	$2s^22p^6\ ^1S_0$	$2s^22p^54p\ ^1D_2$	7.7971		1.02E+09	4.64E−05	1.31E−04	0.84	E2
39	$2s^22p^6\ ^1S_0$	$2s^22p^54f\ ^3D_1$	7.782		2.53E+03	6.89E−11	1.33E−07		M1
40	$2s^22p^6\ ^1S_0$	$2s^22p^54f\ ^3D_2$	7.7806		3.05E+09	1.38E−04	3.88E−04	1	E2
41	$2s^22p^6\ ^1S_0$	$2s^22p^54f\ ^1D_2$	7.7777		1.03E+10	4.67E−04	1.31E−03	1	E2
42	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^3F_2$	7.6976		5.93E+05	2.63E−08	5.37E−03		M2
43	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^3D_2$	7.6948		3.52E+06	1.56E−07	3.19E−02		M2
44	$2s^22p^6\ ^1S_0$	$2s^22p^54d\ ^3D_1$	7.6817	7.673	1.40E+13	3.72E−01	9.42E−03	0.93	E1
45	$2s^22p^6\ ^1S_0$	$2s^22p^54f\ ^3F_2$	7.6436		6.56E+09	2.87E−04	7.65E−04	1	E2

Table 7. *Continued.*

S. No.	I	J	λ (Å) MCDF	λ (Å) NIST	A_{ji} (s^{-1}) (MCDF)	f_{ij} (MCDF)	S_{ij} (a.u.) (MCDF)	Velocity/length	Type
46	$2s^22p^6\ ^1S_0$	$2s^22p^55s\ ^3P_2$	7.2237		7.20E+05	2.82E−08	4.75E−03		M2
47	$2s^22p^6\ ^1S_0$	$2s^22p^55s\ ^1P_1$	7.2219		5.70E+11	1.34E−02	3.18E−04	0.74	E1
48	$2s^22p^6\ ^1S_0$	$2s^12p^64s\ ^3S_1$	7.202		5.22E+05	1.22E−08	2.17E−05		M1
49	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3D_2$	7.1862		7.70E+08	2.98E−05	6.59E−05	0.58	E2
50	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3P_1$	7.1841		1.15E+05	2.66E−09	4.72E−06		M1
51	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3P_2$	7.1791		7.17E+08	2.77E−05	6.11E−05	0.59	E2
52	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^1P_1$	7.179		1.02E+05	2.36E−09	4.19E−06		M1
53	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3P_1$	7.1412		6.10E+10	1.40E−03	3.29E−05	0.87	E1
54	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3P_2$	7.1386		9.12E+06	3.48E−07	5.67E−02		M2
55	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^1D_2$	7.1369		5.32E+06	2.03E−07	3.31E−02		M2
56	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^1P_1$	7.1284	7.119	1.12E+13	2.56E−01	6.01E−03	0.91	E1
57	$2s^22p^6\ ^1S_0$	$2s^12p^64p\ ^3P_1$	7.1226	7.119	1.08E+12	2.46E−02	5.76E−04	0.98	E1
58	$2s^22p^6\ ^1S_0$	$2s^22p^55f\ ^3D_1$	7.1182		4.66E+03	1.06E−10	1.87E−07		M1
59	$2s^22p^6\ ^1S_0$	$2s^22p^55f\ ^3D_2$	7.1174		1.74E+09	6.60E−05	1.42E−04	1.1	E2
60	$2s^22p^6\ ^1S_0$	$2s^22p^55f\ ^1D_2$	7.1155		8.13E+09	3.08E−04	6.62E−04	1.1	E2
61	$2s^22p^6\ ^1S_0$	$2s^12p^64p\ ^3P_2$	7.112		3.57E+06	1.35E−07	2.18E−02		M2
62	$2s^22p^6\ ^1S_0$	$2s^12p^64p\ ^1P_1$	7.1117	7.009	2.82E+12	6.42E−02	1.50E−03	0.92	E1
63	$2s^22p^6\ ^1S_0$	$2s^22p^55s\ ^3P_1$	7.102		7.58E+11	1.72E−02	4.02E−04	1.1	E1
64	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3D_1$	7.0717		1.79E+04	4.04E−10	7.06E−07		M1
65	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^3S_1$	7.0657		3.10E+05	6.96E−09	1.22E−05		M1
66	$2s^22p^6\ ^1S_0$	$2s^22p^55p\ ^1D_2$	7.0657		9.31E+08	3.48E−05	7.32E−05	0.6	E2
67	$2s^22p^6\ ^1S_0$	$2s^12p^64d\ ^3D_1$	7.0291		9.87E+03	2.19E−10	3.81E−07		M1
68	$2s^22p^6\ ^1S_0$	$2s^12p^64d\ ^3D_2$	7.0291		6.88E+08	2.55E−05	5.27E−05	0.95	E2
69	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3F_2$	7.0253		3.23E+05	1.20E−08	1.85E−03		M2
70	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3D_2$	7.024		2.11E+06	7.80E−08	1.21E−02		M2
71	$2s^22p^6\ ^1S_0$	$2s^22p^55d\ ^3D_1$	7.0186	7.009	1.05E+10	3.87E−04	7.97E−04	0.93	E2
72	$2s^22p^6\ ^1S_0$	$2s^12p^64d\ ^1D_2$	7.0192		5.88E+12	1.30E−01	3.01E−03	0.9	E1
73	$2s^22p^6\ ^1S_0$	$2s^22p^55f\ ^3F_2$	7.0023		3.25E+09	1.20E−04	2.44E−04	1.1	E2
74	$2s^22p^6\ ^1S_0$	$2s^12p^64f\ ^3F_2$	6.9873		1.84E+00	6.73E−14	1.03E−08		M2

Table 8. Comparison of transition wavelengths (Å) calculated using MCDF method with other values.

Level	Ne-like Ga		Ne-like Cu		N-like Zn	
	Calculated value	Ref. [43]	Calculated value	Ref. [43]	Calculated value	Other value
$2s^22p^53s\ ^3P_2$					11.82	11.76^B
$2s^22p^53s\ ^1P_1$	10.85	10.84	12.83	12.85	11.79	11.49^B
$2s^22p^53s\ ^3P_1$	10.60	10.59	12.57	12.60	11.54	11.73^B
$2s^22p^53p\ ^3D_2$					11.36	11.31^B
$2s^22p^53p\ ^3P_2$					11.28	11.24^B
$2s^22p^53p\ ^1D_2$					11.06	11.01^B
$2s^22p^53d\ ^3P_1$	9.97	9.96	11.73	11.76	10.81	10.80^A, 10.76^B
$2s^22p^53d\ ^3D_1$	9.85	9.84	11.59	11.61	10.67	10.66^A, 10.63^B
$2s^22p^53d\ ^1P_1$	9.65	9.64	11.37	11.39	10.46	10.45^A, 10.42^B
$2s^12p^63p\ ^3P_1$	9.07	9.27	10.85	10.64	9.81	10.01^A
$2s^12p^63p\ ^1P_1$	9.02	9.22	10.79	10.59	9.75	9.96^A

A: Ref. [43].
B: Ref. [44].

Table 9. Comparison of transition probabilities (s^{-1}) calculated using MCDF method with other values.

	Ne-like Ga		Ne-like Cu		Ne-like Zn	
Level	Calculated value	Ref. [43]	Calculated value	Ref. [43]	Calculated value	Ref. [43]
$2s^22p^53s\ ^3P_1$	1.85E+12	5.16E+12	1.38E+12	3.84E+12	1.60E+12	4.47E+12
$2s^22p^53s\ ^1P_1$	2.56E+12	7.26E+12	1.80E+12	5.12E+12	2.16E+12	6.12E+12
$2s^22p^53d\ ^3P_1$	2.05E+11	7.45E+11	1.56E+11	5.48E+11	1.81E+11	6.50E+11
$2s^22p^53d\ ^3D_1$	2.49E+13	7.60E+13	1.46E+13	4.46E+13	1.92E+13	5.88E+13
$2s^22p^53d\ ^1P_1$	5.31E+13	1.56E+14	4.03E+13	1.16E+14	4.65E+13	1.35E+14
$2s2p^63p\ ^3P_1$	1.79E+12	4.05E+12	1.07E+12	2.60E+12	1.40E+12	3.30E+12
$2s2p^63p\ ^1P_1$	8.37E+12	2.12E+13	6.04E+12	1.57E+13	7.13E+12	1.84E+13

Table 10. Comparison of lifetimes (s) calculated using MCDF method with other values.

	Ne-like Ga		Ne-like Cu		Ne-like Zn	
Level	Calculated value (m)	Ref. [43] (nm)	Calculated value (m)	Other values (nm)	Calculated value (m)	Other values (nm)
$2s^22p^53p\ ^3S_1$	1.81E−10	1.83(−1)	2.15E−10	2.16(−1)^A, 2.11(−1)^B	1.97E−10	1.99(−1)^A, 1.94(−1)^B
$2s^22p^53p\ ^3D_1$	1.50E−10	1.47(−1)	1.69E−10	1.66(−1)^A, 1.34(−1)^B	1.59E−10	1.57(−1)^A, 1.21(−1)^B
$2s^22p^53p\ ^3S_2$	1.09E−10	1.41(−1)	1.34E−10	1.60(−1)^A, 1.68(−1)^B	1.21E−10	1.51(−1)^A, 1.58(−1)^B
$2s^22p^53p\ ^3D_3$	9.45E−11	9.44(−2)	1.16E−10	1.16(−1)^A, 1.21(−1)^B	1.05E−10	1.05(−1)^A, 1.09(−1)^B
$2s^22p^53p\ ^1P_1$	1.07E−10	1.07(−1)	1.29E−10	1.29(−1)^A, 1.75(−1)^B	1.17E−10	1.18(−1)^A, 1.65(−1)^B
$2s^22p^53p\ ^3P_2$	6.69E−11	7.87(−2)	8.51E−11	9.67(−2)^A, 9.80(−2)^B	7.55E−11	8.78(−2)^A, 8.85(−2)^B
$2s^22p^53p\ ^3P_1$	8.55E−11	8.53(−2)	1.04E−10	1.04(−1)^A, 1.07(−1)^B	9.42E−11	9.48(−2)^A, 9.71(−2)^B
$2s^22p^53p\ ^3P_0$	5.75E−11	5.56(−2)	7.58E−11	7.38(−2)^A, 7.64(−2)^B	6.61E−11	6.43(−2)^A, 6.68(−2)^B
$2s^22p^53p\ ^1D_2$	7.32E−11	8.99(−2)	9.43E−11	1.11(−1)^A, 1.14(−1)^B	8.31E−11	1.00(−1)^A, 1.03(−1)^B
$2s^22p^53p\ ^1S_0$	2.48E−11	2.83(−2)	2.76E−11	3.17(−2)^A, 3.24(−2)^B	2.61E−11	3.00(−2)^A, 3.05(−2)^B
$2s^22p^53s\ ^3P_1$	5.41E−13	5.81(−4)	7.25E−13	7.81(−4)^A, 5.63(−4)^B	6.25E−13	6.71(−4)^A, 4.70(−4)^B
$2s^22p^53s\ ^1P_1$	3.90E−13	4.13(−4)	5.54E−13	5.86(−4)^A, 7.52(−4)^B	4.63E−13	4.90(−4)^A, 6.49(−4)^B
$2s^22p^53d\ ^3P_0$	5.97E−11	6.11(−2)	6.92E−11	6.95(−2)^A, 7.22(−2)^B	6.43E−11	6.57(−2)^A, 6.65(−2)^B
$2s^22p^53d\ ^3P_1$	4.50E−12	3.77(−3)	5.86E−12	5.07(−3)^A, 5.88(−3)^B	5.09E−12	4.31(−3)^A, 5.15(−3)^B
$2s^22p^53d\ ^3P_2$	6.23E−11	6.34(−2)	7.17E−11	7.13(−2)^A, 7.34(−2)^B	6.69E−11	6.78(−2)^A, 6.84(−2)^B
$2s^22p^53d\ ^3F_2$	5.22E−11	5.27(−2)	6.06E−11	6.02(−2)^A, 6.17(−2)^B	5.62E−11	5.68(−2)^A, 5.78(−2)^B
$2s^22p^53d\ ^3F_3$	5.36E−11	5.33(−2)	6.23E−11	6.11(−2)^A, 6.49(−2)^B	5.77E−11	5.75(−2)^A, 6.0(−2)^B
$2s^22p^53d\ ^3F_4$	6.80E−11	6.79(−2)	7.57E−11	7.43(−2)^A, 7.94(−2)^B	7.17E−11	7.16(−2)^A, 7.52(−2)^B
$2s^22p^53d\ ^1D_2$	5.28E−11	5.25(−2)	6.04E−11	5.92(−2)^A, 6.33(−2)^B	5.64E−11	5.61(−2)^A, 5.85(−2)^B
$2s^22p^53d\ ^3D_3$	6.05E−11	5.99(−2)	6.76E−11	6.57(−2)^A, 6.94(−2)^B	6.39E−11	6.32(−2)^A, 6.54(−2)^B
$2s^22p^53d\ ^3D_2$	6.26E−11	6.30(−2)	6.96E−11	6.86(−2)^A, 7.19(−2)^B	6.60E−11	6.63(−2)^A, 6.80(−2)^B
$2s^22p^53d\ ^3D_1$	4.01E−14	3.94(−5)	6.85E−14	6.71(−5)^A, 6.44(−5)^B	5.19E−14	5.09(−5)^A, 4.97(−5)^B
$2s^22p^53d\ ^1F_3$	6.39E−11	6.41(−2)	7.12E−11	7.00(−2)^A, 7.41(−2)^B	6.74E−11	6.75(−2)^A, 6.99(−2)^B
$2s^22p^53d\ ^1P_1$	1.88E−14	1.92(−5)	2.48E−14	2.57(−5)^A, 2.72(−5)^B	2.15E−14	2.22(−5)^A, 2.35(−5)^B

A: Ref. [43].
B: Ref. [44].

easily identified because of the dominance of these levels, for example, levels 1, 2, 8, 11, 16 for all three ions (Cu XX, Zn XXI and Ga XXII), as can be seen from tables 1–3. But, for most of the levels we find strong mixing of eigenvectors with different levels. For example, in Ne-like Zn, $2s^22p^53d\ ^1F_3$ is strongly coupled with $2s^22p^53d\ ^3F_3$ and $2s^22p^53d\ ^3D_3$ with their mixing percentage being 36.24, 36.12 and 27.35% respectively. Also, in Ne-like Cu, 50.84% of $2s^22p^54f\ ^1G_4$ is strongly mixed with 48.58% of $2s^22p^54f\ ^3G_4$. Therefore, same levels can be interchanged and there is scope for re-designation because the identification for a few levels is not unique.

We reported the excitation energy of 127 levels obtained with MCDF method and with FAC in tables 1–3. In MCDF method, the total excitation energy is obtained by adding Breit and QED corrections to Dirac–Coulomb energy. It can be seen from tables 1–3 that, Breit corrections are greater than QED corrections in magnitude and lower than Dirac–Coulomb energy by ∼0.2 Ryd. We have also compared our energy levels calculated using MCDF and FAC with the data compiled by National Institute of Standards and Technology (NIST) [40]. We found that our MCDF are lower than NIST maximum by 0.3%, while the maximum percentage difference between NIST and FAC is 0.7% for all three ions reported in the present work. Both MCDF and FAC methods give comparable energy values. The ordering of levels is found to be generally the same except at a few places between MCDF and FAC calculations. This is because of different ways in which the central potential for radial orbitals and recoupling schemes of angular parts are calculated. As our MCDF result are very close to NIST, which is considered as a standard reference for comparison, we can state with confidence that our calculated results are reliable for Ne-like ions ($Z = 29$–31). One point worth mentioning here is that we have predicted energy values for many levels, which are not listed in NIST tables.

In table 4, we have compared the energy values calculated with MCDF method with the experimental values [41,42]. For Ne-like Ga and Cu, comparison is present only for one level, i.e. $2s^22p^53s\,^1P_1$, for which our result matches well (within 0.24%). For Ne-like Zn, for which energy values are available for $2s^22p^53l$ ($l = 0$–2) levels, we have compared experimental results [42] with our calculated MCDF results. Our calculated values agree within 0.3–2.3% with the experimental results [42], which shows the accuracy of our results.

3.2 *Radiative rates*

For a transition i–j the transition probability A_{ji} (per second) and oscillator strength f_{ij} (dimensionless) are related by the following expression:

$$f_{ij} = \frac{mc}{8\pi^2 e^2}\lambda_{ji}^2 \frac{w_j}{w_i} A_{ji}.$$

In the above formula, m and e represent the mass and charge of electron respectively, λ_{ji} is the transition wavelength in Å, w_i and w_j are the statistical weights of the lower and upper (i and j) levels.

The line strength s_{ij} and oscillator strength f_{ij} can be related by the following relation:

For E1 transitions

$$A_{ji} = \frac{2.0261 \times 10^{18}}{w_j \lambda_{ji}^3} S_{ij}$$

and

$$f_{ij} = \frac{303.75}{\lambda_{ji} w_i} S_{ij}.$$

For M1 transitions

$$A_{ji} = \frac{2.6974 \times 10^{13}}{w_j \lambda_{ji}^3} S_{ij}$$

and

$$f_{ij} = \frac{4.044 \times 10^{-3}}{\lambda_{ji} w_i} S_{ij}.$$

For E2 transitions

$$A_{ji} = \frac{1.1199 \times 10^{18}}{w_j \lambda_{ji}^5} S_{ij}$$

and

$$f_{ij} = \frac{167.89}{\lambda_{ji}^3 w_i} S_{ij}.$$

For M2 transition

$$A_{ji} = \frac{1.491 \times 10^{13}}{w_j \lambda_{ji}^5} S_{ij}$$

and

$$f_{ij} = \frac{2.236 \times 10^{-3}}{\lambda_{ji}^3 w_i} S_{ij}.$$

In tables 5–7, we have reported the transition wavelengths (λ in Å), radiative rates (A_{ji} in s^{-1}), oscillator strengths (f_{ij}, dimensionless), line strengths (S_{ij} in a.u.) for 127 levels determined from the ground level using MCDF wave functions. We present results for electric and magnetic dipole (E1, M1) and quadrupole (E2, M2) transitions. We have presented results in length form only as length form for transition is more stable. We have also reported velocity/length. ratio of oscillator strength, which is an accuracy indicator for MCDF calculations. One can see from tables 5–7 that the velocity/length ratio is generally within 10% for most of the strong transitions ($f \geq 0.1$) for all the three ions. For some transitions $2s^22p\,^1S_0$, $2s2p^63p\,^1P_1$, $2s2p^63p\,^3P_1$, $2s^22p^54f\,^3D_2$ etc. the velocity/length ratio is exactly one. For some weaker transition, the ratio is sometimes higher. These transitions do not affect the overall accuracy of our calculated results because they are sensitive to the mixing coefficients and go through cancellation effects. In tables 5 and 7, we have compared transition wavelength calculated using MCDF method with the transition lines compiled by NIST. Our transition wavelengths calculated using MCDF are in excellent agreement with the data compiled by NIST. The maximum error between MCDF and NIST for Ne-like Cu and

Ne-like Ga are 0.24% and 0.22% respectively, except for transition $2s^22p^6\,{}^1S_0 - 2s2p^64p\ {}^1P_1$ in Ne-like Ga, for which the difference is 1.46%.

We have also compared the transition wavelength calculated using MCDF method with the other theoretical work [43,44] which is reported in table 8. Hibbert *et al* [43] reported results for $2s^22p^53l$ ($l = 0$–2) level, while the results of Bhatia *et al* [42] are available only for Ne-like Zn. We observed that our transition wavelengths are in reasonable agreement with those of refs [43,44]. For some transitions, results may be different because of different types of configurations included. Our results are expected to be more reliable due to the inclusion of more and reasonable number of configurations.

In table 9, we have presented the comparison for transition probability calculated using MCDF method with the other calculated result [43]. One can view that transition probabilities for all ions are in good agreement and hence the accuracy of our results is assessed.

4. Lifetimes

The lifetime (τ) of a particular level can be defined as

$$\tau_j = \frac{1}{\sum_i A_{ji}}.$$

Transition probability calculations have become advanced which require relativistic effects to be included. We have calculated lifetime using all possible E1 (electric dipole), E2 (electric quadrupole), M1 (magnetic dipole) and M2 (magnetic quadrupole) transitions. In tables 1–3, we have reported the lifetime for all the excited states calculated by MCDF method for Ne-like ions ($Z = 29$–31). In table 10, we have compared our calculated lifetime with the other theoretical results [43,44] presented in the literature. One can see that lifetimes for all the excited states are comparable to the previous results [43,44]. We hope that lifetime reported in the present work will be useful to experimentalists for their future work.

5. Conclusion

In this paper, energy levels, transition probabilities, oscillator strength and line strength have been calculated for E1, E2, M1, M2 transitions for Ne-like ions ($Z = 29$–31). We have also reported the lifetimes for 127 fine structural levels. We have used two independent methods, namely MCDF and FAC, for our calculations. Comparisons have also been provided for energy levels, transition probability, oscillator strength and lifetimes with those available in the NIST and other experimental or theoretical results and a good agreement has been achieved. We believe that data presented in this work will be important for various fields like plasma diagnostics and astrophysics.

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