Canadian Journal of Physics
Revue canadienne de physique

X-Ray Laser lines in Nickel-Like Erbium

Journal:	<i>Canadian Journal of Physics</i>
Manuscript ID	cjp-2015-0438.R1
Manuscript Type:	Article
Date Submitted by the Author:	13-Jan-2016
Complete List of Authors:	Abdelaziz, Wessameldin S.; Cairo Univ, laser metrology; Laser Institute 9NILES),
Keyword:	Energy levels, Nickel-like Erbium, X-Ray Laser lines, excited states, FAC code

SCHOLARONE™
Manuscripts

Only

X-Ray Laser lines in Nickel-Like Erbium

Wessameldin S. Abdelaziz*

National Institute of Laser Enhanced Sciences, Cairo University, Giza, Egypt

wessamlaser@yahoo.com

Abstract

Energy levels of 249 excited levels in Nickel-like Erbium are calculated using the $3s^23p^63d^{10}$ as a ground state and the single electron excited states from $n=3$ to $n=4,5$ orbitals, calculations have been performed using FAC code, Gu[1]. The populations are calculated over electron densities from 10^{20} to 10^{23}cm^{-3} and electron temperatures $1/2, 3/4$ of the ionization potential of Ni-like Er. The gain coefficients of the transitions are calculated.

Keywords: Energy levels, excited levels, Nickel-like Erbium, X-Ray Laser lines

PACs: 34

1-Introduction

X-ray lasers based on the laser-produced plasmas by electron de-excitation was first proposed by the Soviet scientists Gudzenko and Shelepin in 1965[2], they predicted that the short wavelength laser in the X-ray region of the electromagnetic spectrum needs a large energy gap which is sustained in the highly ionized ions. After ionization, in the equilibrium plasma, ions having specific number of electrons such as 2 (helium-like), 10 (neon-like), 28 (nickel-like) and 46 (palladium-like) are relatively stable and survive in a wide range of temperatures and densities [3,4].

X-ray lasers pumping methods are electron collisional excitation, photo-excitation, charge transfer, electron collisional recombination and di-electronic recombination pumping using a picosecond chirped pulse amplification (CPA) pulses [5]. However, the electron collisional excitation pumping of the inner shell and outer shell of highly ionization states have shown a more stable and a higher output [6,7]. Thus, the electron collisional pumping was proven to be the most efficient method in producing the X-ray lasers.

Experimentally, the first X-ray laser in a laser produced plasma with the electron collisional pumping was demonstrated in 1985 [8,9]. In addition, there were trials proposing the original mechanism for demonstrating X-ray lasing by resonant photopumping to produce high-efficiency X-ray laser with significant gain by Vinogradov et al. [10] and Norton et al. [11]. Several authors during the past four decades have studied this lasing mechanism both experimentally and theoretically, in the hope of developing high-efficiency X-ray laser[12]. Nickel-like ions are of considerable interest in laser-plasma interaction because of the large gain in the EUV and X-ray regions.

Rare earths are promising for the production of X-ray lasers, which needs a theoretical calculation to approve these observations [13,14]. Thus, a fully relativistic atomic data calculations are needed for solving steady state coupled rate equations in the collisional radiative model (CRM) using electron impact excitation (EIE) pumping mechanism.

In this paper, we calculated energy levels for 249 fine-structure states using a fully relativistic approach based on Dirac equation[1]. Collision strengths by electron impact using the factorization-interpolation method is calculated in the distorted wave approximation. Effective collision strengths are calculated by interpolating the data from the collision strengths and integrating over Maxwellian distribution at different temperatures. Rate coefficients were calculated from effective collision strengths using a formula that will be described later in this paper. Then, we predicted the gain coefficient for Ni-like Er by a steady state equation in the collisional radiative model after achieving a population inversion between the allowed transition states.

2- Energy levels

In this paper, we calculated the atomic structure and energy levels for Er XLI. We reported 249 energy levels having the configurations $(1s^2 2s^2 2p^6) 3s^2 3p^6 3d^{10}, 3s^2 3p^6 3d^9 nl, 3s^2 3p^5 3d^{10} nl, 3s 3p^6 3d^{10} nl$ where $(n= 4,5; l= s, p, d, f, \dots)$. Dirac Coulomb Hamiltonian with a fully relativistic effects are taken into account. This data are calculated using the Atomic Structure Program FAC [1]. The energy levels of Er XLI are given in table 1. The levels are ordered ascending according to of their energy. The ground state energy was -328130.717 eV that is in good agreement with ref [15].

3-Oscillator strength and Radiative transition rates

In this part, we are concerned about the calculation of oscillator strengths and spontaneous radiative decay rates for the configurations $(1s^2 2s^2 2p^6) 3s^2 3p^6 3d^{10}$, $3s^2 3p^6 3d^9 nl$, $3s^2 3p^5 3d^{10} nl$, $3s3p^6 3d^{10} nl$ where $(n= 4,5; l= s, p, d, f, g)$ The weighted oscillator strengths (gf_{ul}) are given by Gu[1]:

$$gf_{ul} = L^{-1} \omega (\alpha \omega)^{2L-2} S_{ul} \quad (1)$$

Where ω is the transition energy and S_{ul} is the line strength which is given as:

$$S_{ul} = |\langle \psi_u || O^L || \psi_l \rangle| \quad (2)$$

where O^L denotes the Spherical multipole operator of rank L representing the interactions of electrons with the electromagnetic field, ψ_l and ψ_u are the final and initial states of the transition respectively. Thus the weighted radiative decay rates (gA_{ul}) can be written in terms of the Oscillator strengths as:

$$gA_{ul} = 2 \alpha^3 \omega^2 gf_{ul} \quad (3)$$

The radiative decay rates are calculated in the single multipole approximation with arbitrary ranks. These data have been also calculated using the atomic structure program FAC [1].

4-Effective collision strength and rate coefficients

This part deals with the calculation of electron impact excitation (EIE) in the distorted wave (DW) approximation using the factorization interpolation method [16]. Accurate collision strengths are important for the calculation of level populations and line emissivities that are used in the calculation of the gain coefficient of laser-induced plasmas. We use the FAC to calculate the collision strengths (Ω) between lower and upper states in terms of the electron energy. We perform the calculation for a grid of 15 scattered electron energies ranging from 10 eV to 20000 eV. Using the results of the FAC, collision strengths are averaged over a Maxwellian velocity distribution to obtain the effective collision strength as a function of electron temperature [17]:

$$\gamma_{lu}(T_e) = \int_0^\infty \Omega(E) \exp\left(\frac{-E_u}{kT_e}\right) d\left(\frac{-E_u}{kT_e}\right) \quad (4)$$

where γ_{lu} is the effective collision strength, E_u is the electron energy after the collision and T_e is the temperature in Kelvin. The excitation rate coefficients ($\text{cm}^3 \cdot \text{sec}^{-1}$) for a transition from l to u is related to the effective collision strengths by [18, 19]:

$$C_{lu}^e = \frac{8.6287 \cdot 10^{-6}}{g_l T_e^{1/2}} \gamma_{lu} \exp\left(\frac{E_{lu}}{kT_e}\right) \quad (5)$$

The de-excitation rate coefficients can be obtained from the formula [18, 19]:

$$C_{ul}^d = \frac{8.6287 \cdot 10^{-6}}{g_u T_e^{1/2}} \gamma_{lu} \quad (6)$$

where g_l and g_u are the statistical weights of the levels l and u respectively, E_{lu} is the energy difference between lower and upper levels.

5-Levels population and gain coefficients

The steady state Collisional-Radiative rate equation for calculating the level populations can be written as[20]:

$$N_u \left[\sum_{l < u} A_{ul} + N_e \left(\sum_{l < u} C_{ul}^d + \sum_{l > u} C_{ul}^e \right) \right] = N_e \left(\sum_{l < u} N_l C_{lu}^e + \sum_{l > u} N_l C_{lu}^d \right) + \sum_{l > u} N_l A_{lu} \quad (7)$$

where N_u and N_l are the fractional populations of level u and l respectively, N_e is the electron density, A_{ul} is the Einstein coefficient for radiative decay from u to l ; and C_{lu}^e and C_{ul}^d represent the rate coefficients for collisional excitation and de-excitation respectively. The actual population density N_U of the u^{th} level can be calculated from the equation of identity [21].

$$N_U = N_u * N_I \quad (8)$$

where N_I is the quantity of ions which reached the ionization stage I [22],

$$N_I = f_I \frac{N_e}{Z_{avg}} \quad (9)$$

where N_e is the electron density, Z_{avg} is the average degree of ionization and f_I is the fractional abundance of the ionization states which can be calculated from the relation [14]:

$$f_I = N_i / N_{total} \quad (10)$$

This leads to the normalization condition,

$$\sum_{J=1}^{249} \frac{N_U}{N_I} = 1 \quad (11)$$

Once a population inversion has been ensured a positive gain, where $F > 0$, is obtained, according the equation [23]:

$$F = \frac{g_u}{N_u} \left[\frac{N_u}{g_u} - \frac{N_l}{g_l} \right] \quad (12)$$

where $\frac{N_u}{g_u}$ and $\frac{N_l}{g_l}$ are the reduced populations of the upper and lower levels respectively. Thus, the calculation of the gain coefficient α of the various transitions can be obtained from the equation [13,14]:

$$\alpha_{ul} = \frac{\lambda_{lu}^3}{8\pi} \left[\frac{M}{2\pi K T_i} \right]^{1/2} A_{ul} N_u F \quad (13)$$

where M is the ion mass, λ_{lu} is transition wavelength in cm, T_i is the ion temperature in Kelvin and u, l are the upper and lower transition levels respectively.

6-Results and Discussions

By solving the coupled rate equations eqn. (7) together and assuming that the fractional abundance of the ionization state under consideration is about 0.35 with calculating the gain coefficients using MATLAB 2013Bb of the transitions we found that the most powerful transition is between the levels 93 and 73 which is listed in table 2. We plot the gain coefficient versus the electron density as shown in figures 1-a and 1-b at two different electron temperatures 1.6 KeV and 2.4KeV. The gain values that greater than 1cm^{-1} are listed in table 2.

Figures 1-a and 1-b can be generally explained by saying that at low electron density while trying to produce a population inversion the spontaneous decay from upper levels is still dominant and by increasing the electron density and making excitation to the upper levels the collisional excitation is more dominant and greater than the spontaneous decay so the population inversion condition is satisfied and we get a gain till it reaches the maximum values of gain and then by continuing the electron collisional pumping the electron deexcitation mechanism increases and then the net gain decreases again as shown in figures 1-a and 1-b.

Fig 1-a

Fig 1-b

7- Figures Captures :

Fig 1-a: Gain coefficient against electron density (N_e) at electron temperature= 1.6 KeV

Fig 1-b: Gain coefficient against electron density (N_e) at electron temperature= 2.4 KeV

7-Conclusion

Laser transitions in Ni-like Er in the spectral bands of the soft X-ray and the extreme UV are listed in table 2. The maximum gain occurs at transition (93 to 73) with gain coefficient 177.181 cm^{-1} at electron density $4 \times 10^{22} \text{ cm}^{-3}$, see fig.1-b. The shortest wavelength transition occurs at the transition 63 to 12 with the wavelength 3.06 nm where the gain is 1.594 cm^{-1} and occurs at electron densities of $3 \times 10^{21} \text{ cm}^{-3}$.

8-References

- [1] F. Gu M 2003 *Astrophys. J.* 582 1241.
 - [2] I. Gudzenko L and A , Shelepin L 1965 *Sov. Phys. Doki.* 160 10147.
 - [3] S. Maxon, P Hagelstein, K Reed and J Scofield 1985 *J. Appl. Phys.* 57 971.
 - [4] V. Vinogradov A, I Sobelman and E Yukov 1977 *Sov. J. Quantum Electron.* 7 32.
 - [5] G. J. Pert, S.P. McCabe, P.A. Simms, A.G. MacPhee, R.M.N. O'Rourke, G.J. Tallents, R. Allott, R.E. King, C.L., S. Lewis, R., J. Keenan, S., P. F. Strati and D. Neely, Saturated X-ray lasers at 196 Å and 73 Å pumped by picosecond travelling wave excitation, *Phys. Rev. A* 64(2001)53810.
 - [6] S.P. Healy, K A Janulewicz and [G J Pert](#) , Short wavelength lasing on collisionally pumped, highly excited 2s hole states of neon like ions in performed plasmas irradiated with picosecond pulses , *Opt. Commun.* 144(1997)24-30.
 - [7] P. A Simms, S. [McCabe](#), G. J. Pert, Comparison of neon like germanium inner shell and nickel like gadolinium at 62 Å and 66 Å by picosecond heating of a performed plasma, 153(1998)164-171.
 - [8] L. Matthews D, L Hagelstein P, D Rosen M, J Eckart M, M Ceglio N, U. Hazi A, H Medeck, J MacGowan B, E Trebes J, L Whitten B, M Campbell E, W Hatcher C, M Hawryluk A, L Kauffman R, D Pleasance L, S Rambach G, H, Stone G and A Weave T, 1985 *Phys. Rev. Lett.* 54 110.
 - [9] D Rosen M, L Hagelstein P, L Matthews D , M Campbell E, U Hazi A, L Whittan B, J MacGowan B, E Turner R, W Lee R, G Charatis, E Busch Gar, L Shepard C and D Rockett P 1985 *Phys. Rev. Lett.* 54 106.
- <https://mc06.manuscriptcentral.com/cjp-pubs>
- [10] V Vinogradov A, I Sobelman and E Yukov 1977 *Sov. J. Quantum Electron.* 7 32.

- [11] A. Norton, B. and J. Peacock N., 1975 J. Phys. B 8, 989.
- [12] G. Chapline and L. Wood 1975 "X-Ray Lasers," Physics To-day, Vol. 28, pp. 40-48.
- [13] W. S. Abdelaziz and Th.M. El Sherbini 2010 Optics & Laser Technology 42 699–702.
- [14] D. Guo-Xuan and, Z. Jiao-Long 2004 Chin. Phys. Lett. Vol. 21, No. 9 1780.
- [15] G.C. Rodrigues et al, Systematic calculation of total atomic energies of ground state configurations, Atomic Data and Nuclear Data Tables 86 (2004) 117–233.
- [16] <https://github.com/fnevgeny/fac/tree/master/doc/papers> .
- [17] A Wessameldin S. and I Hamed Mahmoud , Optics and Photonics Journal 1(2011)110-115.
- [18] G Chapline, L. Wood Phys Today (1975) 28:40.
- [19] V Vinogradov A, S. Shlyaptsev VN. , J Quantum Electron (1980) 10:754.
- [20] U. Feldman, A. K. Bhatia and S. Suckewer 1983 Journal of Applied Physics, Vol. 54, No. 5, pp. 2188-2197.
- [21] H Goldstein W, J Oreg, A Zigler, A Bar-Shalom, M. Klapisch , Phys Rev A (1988) 38:1797.
- [22] W. H. Goldstein, J. Oreg, A. Zigler, A. Bar-Shalom and M. Klapisch 1988 Physical Reviews A , Vol. 38, No. 4, pp. 1797-1804
- [23] I. I. Sobel'man, "Introduction to the Theory of Atomic Spectra," *International Series of Monographs in Natural Philosophy*, Pergamon Press, Oxford, Vol. 40, 1979.

Table 1:

index	state configuration	J ^π	Energy(eV)	index	state configuration	J ^π	Energy(eV)
1	3d	0 ^e	0.00	47	3d _{5/2} 4f _{7/2}	5 ^o	1667.74
2	3d _{5/2} 4s _{1/2}	3 ^o	1232.03	48	3d _{5/2} 4f _{7/2}	3 ^o	1668.39
3	3d _{5/2} 4s _{1/2}	2 ^e	1233.75	49	3d _{5/2} 4f _{7/2}	1 ^o	1677.65
4	3d _{3/2} 4s _{1/2}	1 ^e	1275.98	50	3p _{3/2} 4p _{1/2}	1 ^e	1701.13
5	3d _{3/2} 4s _{1/2}	2 ^e	1277.13	51	3p _{3/2} 4p _{1/2}	2 ^e	1702.22
6	3d _{5/2} 4p _{1/2}	2 ^o	1314.57	52	3d _{3/2} 4f _{5/2}	4 ^o	1703.30
7	3d _{5/2} 4p _{1/2}	3 ^o	1315.74	53	3d _{3/2} 4f _{7/2}	2 ^o	1703.81
8	3d _{3/2} 4p _{1/2}	2 ^o	1358.63	54	3d _{3/2} 4f _{5/2}	2 ^o	1706.54
9	3d _{3/2} 4p _{1/2}	1 ^o	1361.61	55	3d _{3/2} 4f _{7/2}	5 ^o	1707.64
10	3d _{5/2} 4p _{3/2}	4 ^o	1380.33	56	3d _{3/2} 4f _{5/2}	3 ^o	1709.36
11	3d _{5/2} 4p _{3/2}	2 ^o	1382.20	57	3d _{3/2} 4f _{7/2}	3 ^o	1710.49
12	3d _{5/2} 4p _{3/2}	1 ^o	1383.28	58	3d _{3/2} 4f _{7/2}	4 ^o	1711.56
13	3d _{5/2} 4p _{3/2}	3 ^o	1384.99	59	3d _{3/2} 4f _{5/2}	1 ^o	1728.40
14	3d _{3/2} 4p _{3/2}	0 ^o	1421.20	60	3p _{3/2} 4p _{3/2}	3 ^e	1766.65
15	3d _{3/2} 4p _{3/2}	1 ^o	1425.49	61	3p _{3/2} 4p _{3/2}	1 ^e	1766.74
16	3d _{3/2} 4p _{3/2}	3 ^o	1425.65	62	3p _{3/2} 4p _{3/2}	2 ^e	1771.36
17	3d _{3/2} 4p _{3/2}	2 ^o	1428.08	63	3p _{3/2} 4p _{3/2}	0 ^e	1788.46
18	3d _{5/2} 4d _{3/2}	1 ^e	1504.89	64	3p _{1/2} 4s _{1/2}	0 ^o	1820.59
19	3d _{5/2} 4d _{3/2}	4 ^e	1509.60	65	3p _{1/2} 4s _{1/2}	1 ^o	1822.48
20	3d _{5/2} 4d _{3/2}	2 ^e	1510.76	66	3p _{3/2} 4d _{3/2}	0 ^o	1892.11
21	3d _{5/2} 4d _{3/2}	3 ^e	1512.85	67	3p _{3/2} 4d _{3/2}	1 ^o	1895.36
22	3d _{5/2} 4d _{5/2}	1 ^e	1520.99	68	3p _{3/2} 4d _{3/2}	3 ^o	1896.46
23	3d _{5/2} 4d _{5/2}	5 ^e	1522.35	69	3p _{3/2} 4d _{3/2}	2 ^o	1899.14
24	3d _{5/2} 4d _{5/2}	3 ^e	1525.82	70	3p _{1/2} 4p _{1/2}	1 ^e	1903.77
25	3d _{5/2} 4d _{5/2}	2 ^e	1526.94	71	3p _{3/2} 4d _{5/2}	4 ^o	1909.41
26	3d _{5/2} 4d _{5/2}	4 ^e	1527.54	72	3p _{3/2} 4d _{5/2}	2 ^o	1911.17
27	3d _{5/2} 4d _{5/2}	0 ^e	1537.28	73	3p _{3/2} 4d _{5/2}	1 ^o	1911.79
28	3d _{3/2} 4d _{3/2}	1 ^e	1552.63	74	3p _{3/2} 4d _{5/2}	3 ^o	1914.07
29	3d _{3/2} 4d _{3/2}	3 ^e	1553.03	75	3p _{1/2} 4p _{1/2}	0 ^e	1917.92
30	3d _{3/2} 4d _{3/2}	2 ^e	1558.20	76	3p _{1/2} 4p _{3/2}	1 ^e	1969.24
31	3d _{3/2} 4d _{5/2}	1 ^e	1564.98	77	3p _{1/2} 4p _{3/2}	2 ^e	1971.41
32	3d _{3/2} 4d _{5/2}	4 ^e	1567.78	78	3d _{5/2} 5s _{1/2}	3 ^e	2005.67
33	3d _{3/2} 4d _{5/2}	2 ^e	1569.32	79	3d _{5/2} 5s _{1/2}	2 ^e	2006.26
34	3d _{3/2} 4d _{5/2}	3 ^e	1571.03	80	3s _{1/2} 4s _{1/2}	1 ^e	2031.54
35	3d _{3/2} 4d _{3/2}	0 ^e	1596.48	81	3s _{1/2} 4s _{1/2}	0 ^e	2039.92
36	3p _{3/2} 4s _{1/2}	2 ^o	1618.24	82	3p _{3/2} 4f _{5/2}	1 ^e	2040.60
37	3p _{3/2} 4s _{1/2}	1 ^o	1621.18	83	3p _{3/2} 4f _{5/2}	2 ^e	2044.41
38	3d _{5/2} 4f _{5/2}	0 ^o	1653.33	84	3d _{5/2} 5p _{1/2}	2 ^o	2045.63
39	3d _{5/2} 4f _{5/2}	1 ^o	1655.71	85	3p _{3/2} 4f _{5/2}	4 ^e	2045.98
40	3d _{5/2} 4f _{5/2}	5 ^o	1659.55	86	3d _{5/2} 5p _{1/2}	3 ^o	2046.02
41	3d _{5/2} 4f _{5/2}	2 ^o	1659.74	87	3p _{3/2} 4f _{7/2}	5 ^e	2047.19
42	3d _{5/2} 4f _{7/2}	6 ^o	1661.57	88	3p _{3/2} 4f _{5/2}	3 ^e	2048.97

index	state configuration	J ^π	Energy(eV)	index	state configuration	J ^π	Energy(eV)
43	3d _{5/2} 4f _{5/2}	3 ^o	1662.80	89	3d _{3/2} 5s _{1/2}	1 ^e	2049.76
44	3d _{5/2} 4f _{7/2}	2 ^o	1663.23	90	3d _{3/2} 5s _{1/2}	2 ^e	2050.11
45	3d _{5/2} 4f _{5/2}	4 ^o	1663.91	91	3p _{3/2} 4f _{7/2}	3 ^e	2050.83
46	3d _{5/2} 4f _{7/2}	4 ^o	1666.47	92	3p _{3/2} 4f _{7/2}	4 ^e	2053.97
93	3p _{3/2} 4f _{7/2}	2 ^e	2057.32	139	3d _{5/2} 5f _{7/2}	5 ^o	2208.97
94	3d _{5/2} 5p _{3/2}	4 ^o	2076.47	140	3d _{5/2} 5f _{7/2}	3 ^o	2209.20
95	3d _{5/2} 5p _{3/2}	2 ^o	2077.13	141	3d _{5/2} 5f _{7/2}	1 ^o	2215.34
96	3d _{5/2} 5p _{3/2}	1 ^o	2077.28	142	3d _{5/2} 5g _{7/2}	1 ^e	2237.06
97	3d _{5/2} 5p _{3/2}	3 ^o	2078.30	143	3d _{5/2} 5g _{7/2}	6 ^e	2237.51
98	3d _{3/2} 5p _{1/2}	2 ^o	2088.66	144	3d _{5/2} 5g _{7/2}	2 ^e	2237.64
99	3d _{3/2} 5p _{1/2}	1 ^o	2090.65	145	3d _{5/2} 5g _{9/2}	7 ^e	2238.19
100	3p _{1/2} 4d _{3/2}	1 ^o	2097.57	146	3d _{5/2} 5g _{7/2}	3 ^e	2238.51
101	3p _{1/2} 4d _{3/2}	2 ^o	2100.52	147	3d _{5/2} 5g _{9/2}	2 ^e	2239.02
102	3p _{1/2} 4d _{5/2}	2 ^o	2112.35	148	3d _{5/2} 5g _{7/2}	5 ^e	2239.04
103	3s _{1/2} 4p _{1/2}	0 ^o	2112.67	149	3d _{5/2} 5g _{9/2}	3 ^e	2239.05
104	3p _{1/2} 4d _{5/2}	3 ^o	2113.04	150	3d _{5/2} 5g _{7/2}	4 ^e	2239.06
105	3s _{1/2} 4p _{1/2}	1 ^o	2118.12	151	3d _{5/2} 5g _{9/2}	4 ^e	2239.80
106	3d _{3/2} 5p _{3/2}	0 ^o	2119.97	152	3d _{5/2} 5g _{9/2}	6 ^e	2239.82
107	3d _{3/2} 5p _{3/2}	1 ^o	2121.14	153	3d _{5/2} 5g _{9/2}	5 ^e	2239.89
108	3d _{3/2} 5p _{3/2}	3 ^o	2122.26	154	3p _{1/2} 4f _{5/2}	3 ^e	2248.72
109	3d _{3/2} 5p _{3/2}	2 ^o	2122.36	155	3d _{3/2} 5f _{5/2}	4 ^o	2248.92
110	3d _{5/2} 5d _{3/2}	1 ^e	2136.37	156	3d _{3/2} 5f _{5/2}	2 ^o	2249.42
111	3d _{5/2} 5d _{3/2}	4 ^e	2137.84	157	3p _{1/2} 4f _{7/2}	3 ^e	2250.35
112	3d _{5/2} 5d _{3/2}	2 ^e	2138.39	158	3d _{3/2} 5f _{7/2}	2 ^o	2250.60
113	3d _{5/2} 5d _{3/2}	3 ^e	2139.19	159	3d _{3/2} 5f _{7/2}	5 ^o	2251.34
114	3d _{5/2} 5d _{5/2}	1 ^e	2143.69	160	3d _{3/2} 5f _{5/2}	3 ^o	2251.43
115	3d _{5/2} 5d _{5/2}	5 ^e	2144.15	161	3d _{3/2} 5f _{7/2}	3 ^o	2252.43
116	3d _{5/2} 5d _{5/2}	3 ^e	2145.59	162	3p _{1/2} 4f _{5/2}	2 ^e	2252.55
117	3d _{5/2} 5d _{5/2}	2 ^e	2145.90	163	3d _{3/2} 5f _{7/2}	4 ^o	2252.92
118	3d _{5/2} 5d _{5/2}	4 ^e	2146.21	164	3p _{1/2} 4f _{7/2}	4 ^e	2253.43
119	3d _{5/2} 5d _{5/2}	0 ^e	2155.17	165	3d _{3/2} 5f _{5/2}	1 ^o	2257.24
120	3s _{1/2} 4p _{3/2}	2 ^o	2180.35	166	3d _{3/2} 5g _{7/2}	5 ^e	2281.80
121	3d _{3/2} 5d _{3/2}	3 ^e	2181.47	167	3d _{3/2} 5g _{9/2}	6 ^e	2282.66
122	3d _{3/2} 5d _{3/2}	1 ^e	2181.55	168	3d _{3/2} 5g _{7/2}	4 ^e	2283.34
123	3s _{1/2} 4p _{3/2}	1 ^o	2181.85	169	3d _{3/2} 5g _{7/2}	2 ^e	2283.50
124	3d _{3/2} 5d _{3/2}	2 ^e	2183.63	170	3d _{3/2} 5g _{7/2}	3 ^e	2283.59
125	3d _{3/2} 5d _{5/2}	1 ^e	2187.64	171	3d _{3/2} 5g _{9/2}	5 ^e	2284.04
126	3d _{3/2} 5d _{5/2}	4 ^e	2188.56	172	3d _{3/2} 5g _{9/2}	3 ^e	2284.29
127	3d _{3/2} 5d _{5/2}	2 ^e	2189.32	173	3d _{3/2} 5g _{9/2}	4 ^e	2284.45
128	3d _{3/2} 5d _{5/2}	3 ^e	2190.01	174	3s _{1/2} 4d _{3/2}	1 ^e	2308.26
129	3d _{3/2} 5d _{3/2}	0 ^e	2194.94	175	3s _{1/2} 4d _{3/2}	2 ^e	2309.28
130	3d _{5/2} 5f _{5/2}	0 ^o	2202.70	176	3s _{1/2} 4d _{5/2}	3 ^e	2322.60
131	3d _{5/2} 5f _{5/2}	1 ^o	2203.73	177	3s _{1/2} 4d _{5/2}	2 ^e	2323.44
132	3d _{5/2} 5f _{5/2}	5 ^o	2205.05	178	3p _{3/2} 5s _{1/2}	2 ^o	2390.69

index	state configuration	J ^π	Energy(eV)	index	state configuration	J ^π	Energy(eV)
133	3d _{5/2} 5f _{5/2}	2 ^o	2205.35	179	3p _{3/2} 5s _{1/2}	1 ^o	2391.68
134	3d _{5/2} 5f _{5/2}	3 ^o	2206.42	180	3p _{3/2} 5p _{1/2}	1 ^e	2430.67
135	3d _{5/2} 5f _{7/2}	6 ^o	2206.50	181	3p _{3/2} 5p _{1/2}	2 ^e	2431.14
136	3d _{5/2} 5f _{5/2}	4 ^o	2206.82	182	3s _{1/2} 4f _{5/2}	2 ^o	2456.64
137	3d _{5/2} 5f _{7/2}	2 ^o	2207.06	183	3s _{1/2} 4f _{5/2}	3 ^o	2457.56
138	3d _{5/2} 5f _{7/2}	4 ^o	2208.48	184	3s _{1/2} 4f _{7/2}	4 ^o	2459.95
185	3p _{3/2} 5p _{3/2}	3 ^e	2461.59	231	3p _{1/2} 5g _{7/2}	3 ^o	2826.79
186	3p _{3/2} 5p _{3/2}	1 ^e	2461.61	232	3p _{1/2} 5g _{9/2}	5 ^o	2827.32
187	3p _{3/2} 5p _{3/2}	2 ^e	2463.41	233	3p _{1/2} 5g _{9/2}	4 ^o	2827.34
188	3s _{1/2} 4f _{7/2}	3 ^o	2464.15	234	3s _{1/2} 5p _{1/2}	0 ^o	2842.03
189	3p _{3/2} 5p _{3/2}	0 ^e	2468.71	235	3s _{1/2} 5p _{1/2}	1 ^o	2842.45
190	3p _{3/2} 5d _{3/2}	0 ^o	2521.28	236	3s _{1/2} 5p _{3/2}	2 ^o	2873.20
191	3p _{3/2} 5d _{3/2}	1 ^o	2522.76	237	3s _{1/2} 5p _{3/2}	1 ^o	2874.04
192	3p _{3/2} 5d _{3/2}	3 ^o	2523.22	238	3s _{1/2} 5d _{3/2}	1 ^e	2934.40
193	3p _{3/2} 5d _{3/2}	2 ^o	2524.32	239	3s _{1/2} 5d _{3/2}	2 ^e	2934.68
194	3p _{3/2} 5d _{5/2}	4 ^o	2529.63	240	3s _{1/2} 5d _{5/2}	3 ^e	2941.22
195	3p _{3/2} 5d _{5/2}	2 ^o	2530.32	241	3s _{1/2} 5d _{5/2}	2 ^e	2941.73
196	3p _{3/2} 5d _{5/2}	1 ^o	2530.37	242	3s _{1/2} 5f _{5/2}	2 ^o	3001.44
197	3p _{3/2} 5d _{5/2}	3 ^o	2531.46	243	3s _{1/2} 5f _{5/2}	3 ^o	3001.87
198	3p _{3/2} 5f _{5/2}	1 ^e	2588.48	244	3s _{1/2} 5f _{7/2}	4 ^o	3003.39
199	3p _{3/2} 5f _{5/2}	2 ^e	2590.14	245	3s _{1/2} 5f _{7/2}	3 ^o	3004.87
200	3p _{3/2} 5f _{5/2}	4 ^e	2590.40	246	3s _{1/2} 5g _{7/2}	3 ^e	3033.68
201	3p _{3/2} 5f _{7/2}	5 ^e	2591.60	247	3s _{1/2} 5g _{7/2}	4 ^e	3033.75
202	3p _{3/2} 5f _{5/2}	3 ^e	2591.77	248	3s _{1/2} 5g _{9/2}	5 ^e	3034.42
203	3p _{3/2} 5f _{7/2}	3 ^e	2593.00	249	3s _{1/2} 5g _{9/2}	4 ^e	3034.68
204	3p _{3/2} 5f _{7/2}	4 ^e	2594.22				
205	3p _{1/2} 5s _{1/2}	0 ^o	2594.23				
206	3p _{1/2} 5s _{1/2}	1 ^o	2594.73				
207	3p _{3/2} 5f _{7/2}	2 ^e	2595.13				
208	3p _{3/2} 5g _{7/2}	2 ^o	2621.83				
209	3p _{3/2} 5g _{7/2}	5 ^o	2622.10				
210	3p _{3/2} 5g _{9/2}	6 ^o	2622.70				
211	3p _{3/2} 5g _{9/2}	3 ^o	2622.71				
212	3p _{3/2} 5g _{7/2}	6 ^o	2623.69				
213	3p _{3/2} 5g _{7/2}	3 ^o	2623.76				
214	3p _{3/2} 5g _{9/2}	4 ^o	2624.14				
215	3p _{3/2} 5g _{9/2}	5 ^o	2624.55				
216	3p _{1/2} 5p _{1/2}	1 ^e	2634.18				
217	3p _{1/2} 5p _{1/2}	0 ^e	2638.77				
218	3p _{1/2} 5p _{3/2}	1 ^e	2665.33				
219	3p _{1/2} 5p _{3/2}	2 ^e	2665.79				
220	3p _{1/2} 5d _{3/2}	2 ^o	2726.70				
221	3p _{1/2} 5d _{3/2}	1 ^o	2727.41				
222	3p _{1/2} 5d _{5/2}	2 ^o	2733.48				

index	state configuration	J^{π}	Energy(eV)	index	state configuration	J^{π}	Energy(eV)
223	$3p_{1/2}5d_{5/2}$	3°	2733.81				
224	$3p_{1/2}5f_{5/2}$	3^e	2793.98				
225	$3p_{1/2}5f_{5/2}$	2^e	2795.84				
226	$3p_{1/2}5f_{7/2}$	3^e	2795.95				
227	$3p_{1/2}5f_{7/2}$	4^e	2796.52				
228	$3s_{1/2}5s_{1/2}$	1^e	2802.01				
229	$3s_{1/2}5s_{1/2}$	0^e	2805.48				
230	$3p_{1/2}5g_{7/2}$	4°	2826.44				

For Review Only

Table 2: Laser transitions, Wavelengths and Gain coefficients in the possible laser transitions.

Transition	Wavelength in (nm)	Maximum Gain(cm^{-1}) at Electron Temperature = 1632.50 (eV)	Electron Density (cm^{-3}) at Temperature = 1632.50(eV)	Maximum Gain(cm^{-1}) at Electron Temperature = 2448.00 (eV)	Electron Density (cm^{-3}) at Temperature = 2448.00(eV)
6<>3	15.340	1.780	2E+21	2.689	3E+21
7<>3	15.121	8.115	2E+21	13.130	3E+21
8<>4	15.001			1.789	1E+21
30<>9	6.307			1.011	1E+21
35<>9	5.279	28.765	2E+22	46.330	5E+22
20<>12	9.725	2.534	3E+21	3.271	5E+21
22<>12	9.003	7.077	1E+21	10.163	2E+21
25<>12	8.630	18.524	3E+21	24.607	5E+21
27<>12	8.051	1.027	8E+20	1.314	1E+21
35<>12	5.815	44.260	2E+22	63.475	4E+22
63<>12	3.060			1.594	3E+21
35<>15	7.251	11.278	3E+22	16.640	6E+22
41<>22	8.936			1.646	1E+22
44<>22	8.717	5.584	3E+21	12.624	6E+21
53<>28	8.202			1.327	6E+21
54<>28	8.056			2.040	7E+21
50<>37	15.508	3.025	7E+21	4.638	1E+22
51<>37	15.300	21.968	8E+21	31.183	1E+22
61<>37	8.518	2.929	3E+21	5.540	5E+21
62<>37	8.256	10.599	5E+21	17.438	9E+21
63<>37	7.412	40.006	2E+22	58.308	4E+22
82<>49	3.416			1.166	1E+22
83<>49	3.381			1.141	1E+22
93<>49	3.266	3.878	8E+22	6.980	2E+22
63<>59	20.645	3.210	6E+22	4.478	1E+23
75<>59	6.542			1.114	5E+22
93<>59	3.769	4.499	2E+22	8.678	4E+22
72<>61	8.585			2.402	5E+21
75<>65	12.991	25.362	3E+22	37.917	5E+22
81<>65	5.702	1.064	6E+21	1.952	2E+22
93<>67	7.655	1.168	4E+21	1.734	6E+21
93<>69	7.838	1.089	3E+21	1.524	4E+21
93<>72	8.483	1.682	3E+21	2.596	6E+21
83<>73	9.349	5.339	2E+22	7.249	3E+22
93<>73	8.519	123.824	2E+22	177.181	4E+22
105<>80	14.319	1.412	4E+21	2.334	8E+21
101<>89	24.429	7.836	5E+22	11.409	9E+22
102<>89	19.809	3.413	5E+22	4.897	9E+22
103<>89	19.710	5.558	5E+22	8.148	1E+23
105<>89	18.137	6.419	6E+22	9.240	1E+23
99<>90	30.582			1.239	3E+21
101<>90	24.596	13.228	5E+22	19.483	9E+22

Continued Table 2: Laser transitions, Wavelengths and Gain coefficients in the possible laser transitions.

Transition	Wavelength in (nm)	Maximum Gain(cm^{-1}) at Electron Temperature = 1632.50 (eV)	Electron Density (cm^{-3}) at Temperature = 1632.50(eV)	Maximum Gain(cm^{-1}) at Electron Temperature = 2448.00 (eV)	Electron Density (cm^{-3}) at Temperature = 2448.00(eV)
102<>90	19.918	3.582	5E+22	5.186	9E+22
104<>90	19.700	27.520	4E+22	43.217	8E+22
119<>96	15.918	5.709	6E+21	7.725	8E+21
129<>96	10.538	1.752	1E+22	2.728	2E+22
154<>98	7.747	2.204	2E+22	4.371	4E+22
175<>98	5.620			1.418	5E+22
129<>99	11.888	12.604	7E+21	18.428	1E+22
162<>99	7.658			1.373	5E+22
162<>100	8.000	53.812	2E+22	84.147	4E+22
174<>100	5.885	5.448	2E+22	10.295	4E+22
162<>101	8.155	1.401	7E+21	2.141	1E+22
162<>102	8.843	1.091	6E+21	1.680	1E+22
176<>104	5.917			2.089	2E+21
162<>105	9.223			1.079	5E+21
174<>106	6.585	1.433	2E+22	3.096	5E+22
129<>107	16.801	2.710	7E+21	3.844	1E+22
175<>107	6.590	2.408	3E+22	4.386	5E+22
154<>108	9.805			1.398	5E+22
164<>108	9.452	11.097	2E+22	21.882	5E+22
176<>108	6.189			2.045	5E+22
177<>108	6.163			2.068	5E+22
157<>109	9.687	2.683	3E+22	4.797	5E+22
158<>122	17.957			1.373	3E+22
174<>123	9.808			1.053	1E+22
177<>123	8.757	9.395	7E+21	17.079	1E+22
142<>130	36.085	3.587	2E+22	4.350	3E+22
142<>131	37.202	5.203	2E+22	5.107	3E+22
144<>131	36.560	5.178	2E+22	11.802	4E+22
143<>132	38.196	10.019	9E+21	12.547	1E+22
144<>133	38.396	5.853	2E+22	11.669	4E+22
146<>133	37.398	7.710	2E+22	14.193	3E+22
146<>134	38.647	7.171	6E+22	12.969	4E+22
150<>134	37.988	7.184	1E+22	9.876	2E+22
145<>135	39.123	12.977	9E+21	16.181	1E+22
148<>136	38.477	6.893	8E+21	8.472	1E+22
149<>137	38.753	16.230	2E+22	30.119	4E+22
153<>138	39.470	11.551	1E+22	15.871	2E+22
152<>139	40.190	10.596	9E+21	12.794	1E+22
151<>140	40.517	12.796	2E+22	17.826	3E+22
147<>141	52.368	47.532	7E+22	64.252	1E+23
166<>155	37.712	3.045	5E+21	3.673	6E+21
170<>156	36.284	1.705	9E+21	2.207	2E+22

Continued Table 2: Laser transitions, Wavelengths and Gain coefficients in the possible laser transitions.

Transition	Wavelength in (nm)	Maximum Gain(cm^{-1}) at Electron Temperature = 1632.50 (eV)	Electron Density (cm^{-3}) at Temperature = 1632.50(eV)	Maximum Gain(cm^{-1}) at Electron Temperature = 2448.00 (eV)	Electron Density (cm^{-3}) at Temperature = 2448.00(eV)
167<>159	39.590	4.258	5E+21	4.878	7E+21
168<>160	38.848	3.304	6E+21	3.631	9E+21
173<>161	38.727	3.447	7E+21	3.783	9E+21
171<>163	39.846	4.905	6E+21	6.233	9E+21
169<>165	47.219	38.053	7E+21	52.667	1E+23
183<>169	7.123			1.502	8E+22
184<>172	7.058			1.421	5E+22
188<>177	8.811			2.638	5E+21
189<>179	16.097	5.791	8E+21	8.880	1E+22
199<>196	20.745	2.418	4E+22	4.071	7E+22
207<>196	19.145	32.291	3E+22	62.130	5E+22
208<>198	37.185	5.049	2E+22	7.853	3E+22
211<>199	38.069	8.085	2E+22	12.457	4E+22
209<>200	39.117	3.910	1E+22	5.554	2E+22
210<>201	39.865	4.876	1E+22	6.460	2E+22
212<>202	38.845	2.362	1E+22	2.184	1E+22
214<>203	39.817	7.021	2E+22	7.528	2E+22
215<>204	40.874	4.393	1E+22	6.623	2E+22
217<>206	28.152	2.735	9E+21	4.068	1E+22
213<>207	43.305	17.350	3E+22	26.551	6E+22
225<>221	18.118	1.790	1E+22	7.627	2E+22
231<>225	40.054			1.862	3E+22
247<>243	38.892	1.209	1E+22	2.426	2E+22
248<>244	39.956	1.736	1E+22	3.571	2E+22
249<>245	41.589	1.698	1E+22	3.221	2E+22