Transition Probabilities for the $2p^5 3p \rightarrow 2p^5 3s$ Transitions in Neon

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2012

بسم الله الرحمن الرحيم

This work is submitted as a dissertation

in partial fulfillment of

the requirement for the award of the degree of

MASTER OF PHILOSOPHY

IN

PHYSICS

DEPARTMENT OF PHYSICS
QUAID-i-AZAM UNIVERSITY
ISLAMABAD, PAKISTAN

Certificate

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Dedicated

To

My Loving Parents

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Acknowledgement

*All praise to the Almighty **Allah** who enabled me to complete this research work successfully, without His will and consent we can't precede a single step.*

*I feel honour to express my deepest gratitude to my supervisor **Prof. Dr. M. Aslam Baig**, for his scholarly guidance, generous encouragement, thought provoking discussions, pleasant attitude, ever helping and kind behavior throughout my research work. I wish to extend my thanks to all of my teachers especially Dr. Raheel Ali, for his valuable suggestions and guidance throughout the period.*

I would extend my gratitude to Ashiq Fareed for his loving attitude and constant encouragement and guidance. Also I would like to thank to Mr. Ahmad Yar, Ijaz Bokhari, Muhammad Asif, Mudassar Nazar, Mirza Oun-ul-Haq, Awais Mohsin and Mr. Khalid for their help during the research work. I can never forget the continuously encouraging and friendly behavior of my roommate Izhar Sagheer.

I offer my regards and blessings to all of those who supported me in any respect during the completion of the M.Phil degree.

Last but not the least, I wish to express my deep gratitude towards my loving parents. I believe, I did nothing more than their prayers did for me.

Haroon Asghar

ABSTRACT

We present line strengths and transition probabilities for the spectral lines of neon originating due to transitions between the $2p^5 3p$ upper and $2p^5 3s$ lower configurations based levels. The emission spectra generated by the laser produced neon plasma by focusing a 1064 nm Nd:YAG laser was registered using the LIBS 2000 detection system comprising of five spectrometers covering the region between 200 – 720 nm. Absolute transition probabilities are calculated by using the intensities of the spectral lines covering the region from 540 nm – 808 nm. The relative line strengths of all the dipole allowed transitions are calculated by using the intensity ratios within the multiplets. The experimental results have been compared with the calculated results obtained by the J-File Sum Rule within the framework of the four coupling schemes; LS, LK, j_cK and jj. The experimental results reveal that LK coupling is the more appropriate scheme to represent these levels in neon.

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CHAPTER 1

Laser Induced breakdown Spectroscopy (LIBS):

Elemental analysis based on the emission from plasma, generated by focusing a powerful laser beam on a solid sample is known as laser induced breakdown spectroscopy (LIBS). Laser induced breakdown spectroscopy is an emission spectroscopy technique where atoms and ions are initially produced in the excited states due to interaction of focused laser and target material. The interaction between matter and high density photons generates a plasma plume, which evolves with time and may eventually acquire thermodynamic equilibrium. One of the important features of this technique is that it does not require any sample preparation, unlike conventional spectroscopic analytical techniques. With the help of LIBS technique analysis of any material regardless of its physical state, be it solid, liquid or gas can be analyzed at almost equal ease, because all elements emit light of characteristic frequencies when excited to a sufficiently high temperatures. (Singh 2007).LIBS have the capability of detecting all chemical elements in a sample, of real- time response, and stand-off analysis of targets. Nd: YAG pulse Laser is used as an excitation source for ablation process. The laser-ablation process can be divided roughly in three phases.

(i) Primary laser-matter interaction, that is heating and evaporation,

(ii) Plasma generation and, in the case of ns pulses, laser plasma interaction (laser-induced breakdown),

(iii) Adiabatic expansion of the plasma.

1.1 Advantages and Disadvantages of LIBS Method:

The specific advantages and disadvantages of the LIBS for direct elemental analysis over the conventional analytical spectroscopic technique are mentioned below (Sneddon& Lee 1998)

Advantages:

1. Requires, little sample preparation for elemental analysis.

2. Can be applied to both conducting and non-conducting samples.

3. Possibility of simultaneous multi element analysis.

4. Is non-destructive; only a small mass (sub micrograms) of material is ablated.

5. Remote, in-situ analysis in hazardous environments can be done with fiber optics.

6. Highly refractory materials can be analyzed due to the very high temperatures achieved in laser induced plasmas.

Disadvantages:

1. Current systems are complex and costly.

2. Obtaining suitable standards is difficult.

3. Large interference effects.

4. Poor precision generally 5 to 10% as compared to conventional techniques.

5. Possibility of optical damage due to the high-energy laser pulses.

1.1.2 Real life Applications of LIBS:

Some important uses and examples of real life applications of LIBS are (Doria, Kavanagh 2006)

1. Soils and minerals analysis which are helpful in geology, mining and construction.

2. Exploration of planets to understand the elemental composition of Mars and Venusetc.

3. Environmental monitoring to check the quality of air and water and industrial sewage control.

4. Biological sampling such as bacteria type detection, poisoning deduction by using human hair or teeth, cancer tissue diagnosis, infect ional diseases and DNA types of analysis.

5. Defense system by detection of explosives and biochemical weapons for homeland security.

6. Metal industry to control the quality of metals such as steel sheet or Al alloys etc.

7. Nuclear industry for detection of cerium and radioactive elements.

1.2 Neon:

Neon was first discovered in *1898* by British chemists *Sir William Ramsay* and *Morris W. Travers* in London. *British chemist Sir William Ramsay* discovered the five noble gases between *1894 -1898* and got noble prize in *1904*. The noble gases could be made to produce light discharge when electrical charges were passed through it, this was best desired method which the scientist were looking to produce the light without heat. Neon is very common element in the universe, it is rare on Earth. Neon is the second lightest element in inert gases. Neon has three stable elements. Neon is the second lightest noble gas after helium. It glows reddish-orange in a vacuum discharge tube when we apply voltage across it. Neon plasma has a very intense light discharge at a very normal voltage. The normal color of this gas for the human eye is red-orange. During the last decades, Neon has seen to use in signs and also used in high voltage indicator and vacuum tubes. Neon gas and liquid neon both are relatively very expensive.

1.3 Coupling Schemes:

There are four types of homogenous coupling schemes to designate the energy levels. These coupling schemes reflect the relative contributions of the dominant interactions; electrostatic interaction and spin-orbit interaction. Below we describe these coupling of four angular momenta in these four coupling schemes.

1.3.1 *LS*-Coupling

Levels in this coupling scheme are represented as:

$$[(\lambda_1,\lambda_2)L,(s_1,s_2)S]_J$$

The orbital angular momenta λ_i of electrons are coupled to form the total angular momenta L

$$L \equiv \sum_{i=1}^{n} \lambda_i$$

The spin angular momenta s_i of each electron are coupled to form the total spin angular momentum S.

$$S \equiv \sum_{i=1}^{n} s_i$$

Finally L and S combine to form the total angular momentum J:

$$J = |L \pm S|$$

A level in the LS-coupling scheme is designated as $^{2S+1}L_J$, where $2S+1$ is known as the multiplicity of the level. Selection rule for the allowed transitions are $\Delta L = 0, \pm 1, \Delta J = 0, \pm 1, \Delta l = \pm 1, \Delta S = 0$

1.3.2 *jj* Coupling

In heavy atoms, the spin-orbit interaction is dominant over the electrostatic interaction. As a result each electron's spin couples to its orbital angular momenta. This coupling scheme isrepresented as

$$[(\lambda_1, s_1) j_1, (\lambda_2, s_2) j_2]_J$$

Where, $j_i = |\lambda_i \pm s_i|$

All j_i's are then coupled to form J, the total angular momentum as

$$J = | j_1 \pm j_2 |$$

This coupling is called the *jj*-coupling scheme. A level with given values of j_1, j_2 and J is denoted by $(j_1, j_2)_J$. Selection rules for the *jj*-coupling scheme are

1.3.3 Intermediate Coupling:

LK and j_cK-coupling schemes are called intermediate coupling. Intermediate coupling scheme was introduced by Racah [35] and Cowan [14].

1.3.3.1 *LK*-Coupling:

This coupling scheme is represented as:

$$[\{(l_1, l_2)L, s_1\}K, s_2]_J$$

In this coupling scheme the orbital angular momenta of both the electrons are coupled to form total L. Then L couples with the spin of the first electron to form the K quantum number. Finally, K couples with the spin quantum number of the second electron s_2 to give total J. The levels are designated as $L[K]_J$. The selection rules for this coupling scheme are:

$\Delta L = 0,\pm 1, \Delta K = 0,\pm 1, \Delta J = 0,\pm 1$

1.3.3.2 J_ck-Coupling:

This coupling scheme is represented as:

$$[\{(l_1, s_1)j_c, l_2\}K, s_2]_J$$

In this coupling scheme the orbital angular momentum ℓ_1 of the first electron couples with the spin quantum number of the first electron s_1 to form the resultant angular momentum of the core electrons j_c. Then j_c is coupled with the orbital angular momentum of the second electron ℓ_2 to form K. Finally, K coupled with spin quantum number of the second electron s_2 to yield the the total angular momentum J.

The levels in this coupling scheme are designated as: $j_c[K]_J$. The selection rules for the dipole transitions are:

$\Delta j_c = 0,\pm 1, \Delta K = 0,\pm 1, \Delta J = 0,\pm 1$

In this thesis we are studying the transitions between the levels based on the *$2p^5 3p$ and $2p^5 3s$* configurations on neon. The dipole allowed transitions have been drawn using the above mentioned four coupling schemes and determined their transition probabilities. The ground-state level of neon, like all other inert gases, is $^1S_0$. In the first excited state one of $2p^6$ electrons is excited to the $3s$ orbital and this configuration $1s^2 2s^2 2p^5 3s$ gives rise to four energy levels. Another group of excited states arises from the electron configuration $1s^2 2s^2 2p^5 3p$ and gives rise to ten energy levels. Below, we present the designations of all the levels in the four coupling schemes, *LS, LK, J_ck* and *jj* in addition to the representations in the Paschen notations; being used in the Moor's Table.

Table 1.1: Various coupling schemes from 1s and 2p levels in Ne

Paschen Notation	*LS*	*LK*	*J_cK*	*jj*
$1s_5$	$^3P_2$	$P[3/2]_2$	$3/2[3/2]_2$	$(3/2,1/2)_2$
$1s_4$	$^3P_1$	$P[3/2]_1$	$3/2[3/2]_1$	$(3/2,1/2)_1$
$1s_3$	$^3P_0$	$P[1/2]_0$	$1/2[1/2]_0$	$(1/2,1/2)_0$
$1s_2$	$^1P_1$	$P[1/2]_1$	$1/2[1/2]_1$	$(1/2,1/2)_1$
$2p_{10}$	$^3S_1$	$S[1/2]_1$	$3/2[1/2]_1$	$(3/2,1/2)_1$
$2p_9$	$^3D_3$	$D[5/2]_3$	$3/2[5/2]_3$	$(3/2,1/2)_3$
$2p_8$	$^3D_2$	$D[5/2]_2$	$3/2[5/2]_2$	$(3/2,1/2)_2$
$2p_7$	$^3D_1$	$D[3/2]_1$	$3/2[3/2]_1$	$(3/2,3/2)_1$
$2p_6$	$^1D_2$	$P[3/2]_2$	$3/2[3/2]_2$	$(3/2,3/2)_2$
$2p_5$	$^1P_1$	$P[3/2]_1$	$1/2[3/2]_1$	$(1/2,3/2)_1$
$2p_4$	$^3P_2$	$D[3/2]_2$	$1/2[3/2]_2$	$(1/2,3/2)_2$
$2p_3$	$^3P_0$	$P[1/2]_0$	$3/2[1/2]_0$	$(3/2,3/2)_0$
$2p_2$	$^3P_1$	$P[1/2]_1$	$1/2[1/2]_1$	$(1/2,1/2)_1$
$2p_1$	$^1S_0$	$S[1/2]_0$	$1/2[1/2]_0$	$(1/2,1/2)_0$

CHAPTER 2

Experimental Setup:

A schematic diagram of the experimental arrangement of the LIBS apparatus used in the present study is shown in Fig. 2.1. An Nd: YAG pulsed laser with pulse duration of 5 ns and repetition rate 10Hz is used as a plasma generating source. This laser is capable of delivering energy 400mJ at 1064nm and 200mJ at 532nm. The laser pulse energy was varied by varying the flash lamp Q-switch delay through the laser controller or by the LIBS software (OOLIBS2000), and the pulse was measured by an energy meter (Nova, Quantel). The experiment was performed to investigate the spectral emission of the neon plasma formed in a stainless-steel chamber with a four crossed windows filled with Neon gas by mean of a focused beam of a Q-switched Nd: YAG laser. The chamber was evacuated to a pressure ~10mbar and then purged before filling the chamber with a gas to perform the experiment. This purging process was repeated several times in order to obtain the highest percentage of gas purity. The primary of the laser beam was defined in such a way that the laser beam impinges exactly at the specific spots of the chamber`s window for plasma generation. The laser beam is deflected using a right-angle prism onto a focusing lens, which directs the beam into the gas chamber through the focusing lens. Breakdown then takes place in the neon gas, which is observed visually. The spectral emission of the plasma is collected through the window, which is perpendicular to the path of the laser beam. This emission is then focused and imaged onto the entrance slit of the spectrograph which enables us to collect a wide range of spectral wavelength that is required for the study of the emission features of the gas sample. The emission signal was corrected by subtracting the dark signal of the detector through the OOLIBS2000 software, which was equipped with five spectrometers each having slit width of 5μm, covering the range between 200 – 720nm. Each spectrometer has 2048 element linear CCD array and an optical resolution of ~.06 nm. The LIBS2000 detection system and the Q-switch of the Nd: YAG laser were synchronized. The LIBS2000 system triggered the Q-switch of the Nd: YAG laser and the flash lamp out of the Nd: YAG laser triggered the LIBS2000 detection system through a four-channel digital delay/Pulse generator (SRS DG 535). The output data were averaged for 10 laser shots to minimize the statistical errors. All the five spectrometers installed in the LIBS2000 are manufacturer calibrated in efficiency using the DH-2000-CAL standard light source. The data acquired simultaneously by all the five spectrometers were stored on a PC through the OOI LIBS software for subsequent analysis.

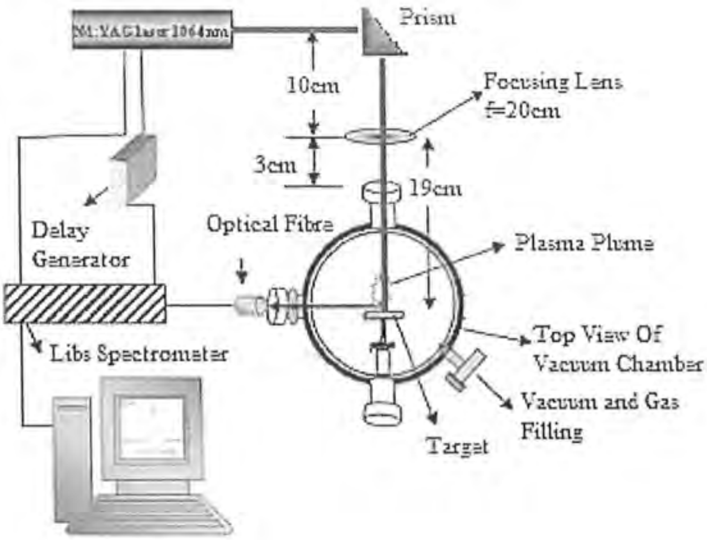


Figure 2-1: Laser-induced break down spectroscopy schematic diagram

The detail of various instruments used in this apparatus is briefly described in following sections".

The specifications of the equipment are given below:

1. Q-Switch Nd: YAG Laser
2. Focusing lens
3. Stainless steel chamber
4. Triggering device
5. LIBS 2000 + Spectrometers
6. Fiber optics cable
7. Computer
8. Vacuum system

2.1 Nd: YAG Laser:

The Nd: YAG laser is one of the most commonly used solid-state lasers in such experiments. In the Nd: YAG lasers the host is yttrium aluminum garnet (Nd: Y_3 Al_5 O_{12}), a hard brittle crystal that can be manufactured with high quality. "The active medium is the triply ionized neodymium (Nd^{+3}), present with low concentration 1% or less, which is optically pumped by flash lamps. The neodymium YAG laser is a four level laser system, shown in Fig. 2,2.

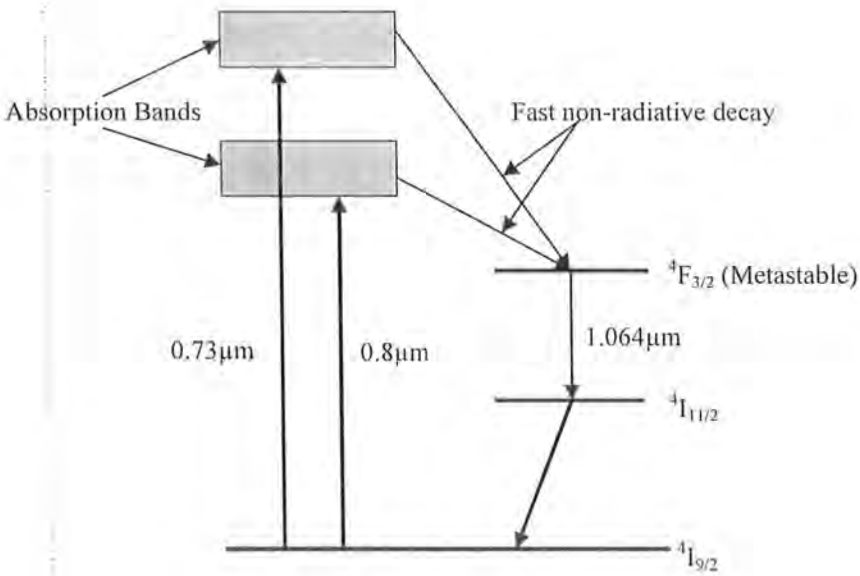


Fig 2.2: Energy levels in the Nd: YAG laser.

The flash lamps emit broad spectrum of light, but the neodymium ions absorb most strongly around 0.7 to 0.8 μm and the neodymium ions are raised from the ground state to the higher energy state, from which they decay to the $^4F_{3/2}$ metastable state and releasing their excess energy to the crystalline lattice. This metastable state has comparatively long lifetime (about 230 μs), so this state will be heavily populated. In this state these ions are stimulated to emit 1064 nm laser transition dropping to the $^4I_{11/2}$ level. The $^4I_{11/2}$ state is an unstable state, consequently the ions will rapidly return to the $^4I_{9/2}$, producing a population inversion between the $^4F_{3/2}$ and $^4I_{11/2}$ states. The strongest emission of neodymium is at 1064 nm, although the energy level splitting allows weaker emission on other lines as well. The neodymium laser can be arranged in series, in an oscillator-amplifier configuration to achieve more pulse power than is available from a single laser oscillator. A Q-switch is used to reduce the pulse duration and to raise its peak power".

2.2 LIBS 2000+Spectrometer:

The LIBS 2000 spectrometer, sensing system consist of five high resolution HR 2000 type spectrometers which cover different wavelength ranges. "The LIBS 2000 spectrometer is connected to a PC via USB port and opened through OOI LIBS software. Data is programmed into chip of each HR 2000 spectrometer includes wavelength calibration co-efficient. When the laser beam strikes the sample, excitation is produced and plasma is generated. The light in the plume is emitted due to the de-excitation process which is transmitted through an optical fiber to the LIBS 2000 spectrometer. The spectrometers measure the amount of light and transform the data collected by the spectrometer into digital information that is passed to the spectrometer operating software on a PC. The OOI LIBS software is used to measure absorption, reflection and emission. It has digital library which controls all the parameters, collect and display the resulting spectra as intensities against wavelengths". The specifications of each spectrometer is given in Table 2.1

Table 2.1: Specifications of different HR2000 used in the LIBS 2000 spectrometer

Model	Grating (lines/mm)	Region	Band width
LIBS HR 1	2400	Ultra violet	200-301nm
LIBS HR 2	2400	Ultra violet	296-391nm
LIBS HR 3	1800	Visible	386-513nm
LIBS HR 4	1800	Visible	509-623nm
LIBS HR 5	1800	Visible	619-720nm

2.3 HR2000 High Resolution Spectrometer:

The HR2000 high resolution Miniature Fiber Optic Spectrometer provides optical resolution up to 0.06 nm (FWHM). The range and resolution of HR 2000 depends on the grating and the entrance slit width selections. An external power supply is not required for HR2000 when interfaced to a computer via the USB port.

The spectrometer measures the amount of light and transforms the data collected by the spectrometer into digital information that is passed to the spectrometer operating software on a PC. To collect and display the data from the five HR spectrometers via LIBS Base software is used.

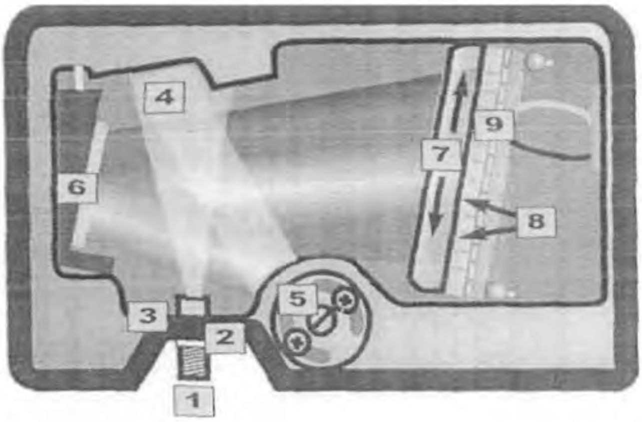


Fig 2.3: Optical bench of HR2000 Spectrometer.

In the next two chapters we present the theoretical approach to calculate the line strength and transition probabilities of the spectral lines observed in the laser produced neon plasma.

CHAPTER 3

Theoretical Approach:

The intensity I_{ij} of a transition from a level i to level j is normally expressed as:

$$I_{ik} \alpha \; N_i g_i A_{ik} \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where N_i is the number density, g_i is the statistical weight, and A_{ik} is the transition probability. The relation between the life time and the transition probabilities can be written as [19]:

$$A_{ik} = \{\tau_i (1 + \sum_{j \neq k} \frac{I_{ij}}{I_{ik}})\}^{-1}$$

Where, $\sum_{j \neq k} \frac{I_{ij}}{I_{ik}}$ is the branching ratio of the intensities from the upper level i to the lower level j

and k and τ_i is the life time of the upper level.

The more convenient relationship between A (transition Probability) and S (Line Strength) is given in the NIST data base [3]:

$$A_{ij} = \frac{2.026 \times 10^{18}}{\lambda_{ij}^3 g_i} S_{ij} \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Here A is in s^{-1} *and* λ_{ij} is inA^0 and S is in arbitrary units. Similarly for the second combination

$$A_{ik} = \frac{2.026 \times 10^{18}}{\lambda_{ik}^3 g_i} S_{ik} \ldots\ldots\ldots\ldots(3)$$

By combining *equation (2) and (3)*

$$\frac{A_{ij}}{A_{ik}} = \frac{\lambda_{ik}^3 S_{ij}}{\lambda_{ij}^3 S_{ik}}$$

$$\frac{S_{ij}}{S_{ik}} = \frac{\lambda_{ij}^3 A_{ij}}{\lambda_{ik}^3 A_{ik}}$$

From equation (1)

$$\frac{S_{ij}}{S_{ik}} = \frac{\lambda_{ij}^3 I_{ij}}{\lambda_{ik}^3 I_{ik}} \ldots\ldots\ldots\; \ldots\ldots(4)$$

$$S_{ij} = \frac{\lambda_{ij}^3 I_{ij}}{\lambda_{ik}^3 I_{ik}} S_{ik} \ldots\ldots\ldots\ldots (5)$$

Thus the relative line strengths can be determined directly by measuring the intensities of the spectral lines in a multiplet. The individual line strength can then be obtained by applying the *J-File* Sum Rule [3]

$$\sum_j S_{ij} = \frac{2l_i + 1}{2j_i + 1} = S_i \ldots\ldots\ldots\ldots\ldots (6)$$

Where l_i is the orbital angular momentum and j_i is the total angular momentum of the excited state. Combine Eqs. *(5)*and *(6)* we get a relation to determine the line strengths of the individual spectral line.

$$S_{ik} = S_i [1 + \sum_{j \neq k} \frac{\lambda^3{}_{ij} I_{ij}}{\lambda^3{}_{ik} I_{ik}}]^{-1} \ldots\ldots (7)$$

In this relation we have to measure the experimental line strength, by measuring the intensities of the spectral lines from the spectrum $\sum_{j \neq k} \frac{I_{ij}}{I_{ik}}$ and then convert them into the relative line strength by using the above relation. In above relation we keep above relation we open the summation is such a way that I_{ik} remains fix and summation applies only on the upper level I_{ij}.

All the experimental values of the relative line strength need to be normalized. Normalization can be done so that the sum of the entries for the given multiplets is $S = (2L+1)(2S+1)(2L'+1)$ [13]. Where L is the total orbital angular momentum of the lower level, S is the total spin quantum number of the lower level and L' is total orbital angular momentum of the upper level.

3.1 Relative Line strength:

The line strength S, defined as the sum of the square of the matrix elements of the electric dipole moments joining the sets of upper and lower levels that are included in the transitions [20].

$$I = |\langle \psi_2 | er | \psi_1 \rangle|^2$$

For the Einstein spontaneous transition probability A_{ij}

$$g_i A_{ij} = \frac{128\pi^5 \nu^3}{3hc^2} S$$

Where *i* refer to the upper level and *j* to the lower level

The quantity S is commonly divided into three factors

$$S = S(M)S(L)\sigma^2$$

Where $S(M)$ and $S\ (L)$, derived from integration over the angular part of the wave functions, represents the relative line strengths in a multiplets and the line within the multiplet respectively. Here σ^2 depends on the radial part of the wave function through a quantum number n and l.

The radial transition integral σ^2 is given by

$$\sigma^2 = [\frac{1}{(4l_g^2 - 1)}][\int rR(n,l)R(n',l')dr]^2$$

The r is the radial distance, l is the orbital angular momentum and n is the principal quantum number for the initial state, n' and l' are the same quantities for the final state, $R(n,l)$ and $R(n',l')$ are the radial wave functions of the optical electrons in its initial and final state. These two quantities in the LS coupling are determined theoretically. So it is very difficult to calculate accurate individual line strengths. *Mehlhorn* [21]calculated these values using configuration interaction technique which are in good agreement with the experimental data. The *j-File* sum rule was first derived by *Shortley* [24] which states that the line strength sum of various J files within a transition array are in the ratios of their respective statistical weights $2J+1$. Thus we have the relation:

$$\sum_i S(i,k)\alpha 2J_K + 1$$

3.2 Line Strength Formula S (ab: a′b′):

The levels participating in a transition can be represented in different coupling schemes, *(LS, LK, jK and jj)* to calculate the line strengths of the transitions. The first case is when the lower level as well as the upper level is represented in the LS-coupling scheme:

i. $$S(LS:L'S') = \delta_{SS'}[L,L',J,J']\begin{Bmatrix} L & J & S \\ J' & L' & I \end{Bmatrix}^2 \begin{Bmatrix} l_2 & L & l_1 \\ L' & l'_2 & I \end{Bmatrix}^2$$

The second case is when the lower level is designated as LS and the upper level is designated in the LK coupling.

ii. $$S(LS:L'K') = [L,L',K',S,J,J']\begin{Bmatrix} L & J & S \\ J' & L' & I \end{Bmatrix}^2 \begin{Bmatrix} l_2 & L & l_1 \\ L' & l'_2 & I \end{Bmatrix}^2 \begin{Bmatrix} K' & s_2 & J' \\ S & L' & s_1 \end{Bmatrix}^2$$

The third case is that when the lower level as well as the upper level is represented in *LK* coupling.

iii. $$S(LK:L'K')=[L,L',K,K',J,J']\begin{Bmatrix} K & J & s_2 \\ J' & K' & I \end{Bmatrix}^2 \begin{Bmatrix} L & K & S \\ K' & L' & I \end{Bmatrix}^2 \begin{Bmatrix} l_2 & L & l_1 \\ L' & l'_2 & I \end{Bmatrix}^2$$

In this case the lower level as well as the upper level is represented in the LK-coupling scheme.

iv. $$S(j_1k:j_1'k')=\delta_{j_1j_1'}[K,K',J,J']\begin{Bmatrix} K & J & s_2 \\ J' & K & I \end{Bmatrix}^2 \begin{Bmatrix} l_2 & K & j_1 \\ K' & l_2' & I \end{Bmatrix}^2$$

In this case the lower level as well as the upper levels is designated in *jk* coupling.

v. $$S(j_1k:j_1'j_2')=\delta_{j_1j_1'}[K,j_2',J,J']\begin{Bmatrix} K & s_2 & J \\ j_1 & j_2' & J' \\ l_2 & l_2' & I \end{Bmatrix}^2$$

Now the last case in that in which the both lower and upper level are represented in *jj* coupling.

vi. $$S(j_1j_2:j_1'j_2')=\delta_{j_1j_1'}[j_2,j_2',J,J']\begin{Bmatrix} j_2 & J & j_1 \\ J' & j_2' & I \end{Bmatrix}^2 \begin{Bmatrix} l_2 & j_2 & s_2 \\ j_2' & l_2' & I \end{Bmatrix}^2$$

3.3 Absolute Transition Probabilities:

Three methods are used generally for calculation of absolute transition probabilities. These methods are briefly described below.

i. Transition probabilities of *30* spectral lines of *Ne* originating from the common upper levels have been determined from branching ratio measurements and taken into consideration of the known life time of the upper level.

$$A_{ik}=(\tau_i\sum_{j=1}^{n}\frac{I_{ij}}{I_{ik}})^{-1}..........(8)$$

In this technique, we measure the intensities of all the lines originating from a common level from the observed spectrum. A point of confusion in this relation is how to open the summation. The branching ratio intensities are associated with dummy indices; *i* represent the upper level and *j, k, l, m*are associated with the lower level transitions. We apply the summation is such a way that level in the denominator remains fix *i.e. ik* remain fix and the summation apply on the upper level *i.e. ij, ik, il and im*. Then, we multiply these branching ratios with the life time of the upper level. Finally, inverse of product of both branching ratio and life time of the upper level gives us the transition probabilities of all the possible spectral lines. The lifetimes of all the upper levels have been taken from the literature; Fujimoto [7]

ii. For the measurement of the absolute transition probabilities without knowing the life time of the upper level, we can also determine the values of the transition probabilities using the relation [3]

$$A_{ij} = 2.026 \times 10^{18} \frac{S_{ij} R_{ij}}{\lambda_{ij}^{3}(2J_i + 1)}$$

Here λ_{ij} is the wavelength of the transition, S_{ij} is the line strength measured from the observed spectrum (in arbitrary units), $2J_i+1$ is the statistical weight for excited level and R_{ij} is the radial integral documented in the literature [28]. The Radial integrals were measured by Bates and Damgard [28] in 1949 for different elements. By measuring transition probabilities we can measure the life time of upper levels. The relation we used to measure the life time of an upper level from the known transition probabilities is:

$$\tau_{ij} = \frac{1}{\sum_j A_{ij}}$$

The above relation shows that the mean radiative life time of the upper level τ_{ij} is simply the inverse of summation of all the transition probabilities for that level, $\sum_j A_{ij}$. That means, if from any one level there are allowed transitions to four lower levels then the transition probabilities of all these four transitions adds up, and its inverse will yield the radiative life time for upper level.

iii. Transition probabilities can be also determined from the relative intensity measurements or branching ratio methods. The branching ratio method in generally used when we study the transition probabilities within multiplets. In this method, all transitions from same upper levels are considered. Using the known upper state lifetimes τ_i and the branching ratios R_{ij} for the transitions, the transition probabilities can then be calculated from the relation:

$$A_{ij} = \frac{R_{ij}}{\tau_i} \qquad \text{Where, } R_{ij} = \frac{I_{ij}}{\sum I_{ij}}$$

We have recorded the intensities of *30* spectral lines of *Ne* covering the wavelength range *540-808nm*and determined the transition probabilities of all these transitions.

CHAPTER 4

Results and Discussions

Introduction

In *1917* Einstein published his classic papers in which he introduced the concept of transition probabilities. Since that time many efforts have been devoted theoretically and experimentally to determine the transition probabilities or the associated oscillator strength because of their importance in many fields of basic scientific research. For example, transition probabilities are the essential in plasma physics. In plasma spectroscopy these quantities are essential for the quantitative analysis of the plasma radiation. Furthermore, the advent of laser has increased the demand for more accurate values for transition probabilities in order to ascertain which transition is most suitable for laser action. In astrophysics, transition probabilities are essential for the determination of such quantities is elemental abundance, degree of ionization, electron number density and temperature from an analysis of spectral line intensities. Theoretical values of transition probabilities may be calculated once the eigenfunctions for the atomic states have been determined. For hydrogen, the simplest atomic system, the exact analytical calculations of the wave function allows good theoretical estimates to be made.

Most assessable quantities to be measured are the relative transition probabilities for the spectral lines with either a common upper or a common lower level. For transitions with a common upper level the relative intensities of these lines in emission yield the relative transition probabilities directly. This thesis reports on an experiment designed to measure the absolute transition probabilities for the $2p^5 3p \rightarrow 2p^5 3s$ transitions of natural neon. This gas was chosen for several reasons. Neon appears in the hotter stars and in some cases is as abundant as oxygen, making it an interesting subject for an astrophysical research, as the knowledge of neon transition probabilities in very important. From an experimental point of view, neon spectrum is rich in spectral lines in the visible part of the electromagnetic spectrum.

The theory developed in this chapter indicates how the absolute transition probabilities of the individual levels of neon for configuration $\boldsymbol{2p^5 3p\text{-}2p^5 3s}$ can be determined by using life time of the upper levels.

4.1 Spectrum of Neon

The energy levels of neon obey the intermediate coupling scheme. All these levels have been represented by the J_cK-coupling scheme (*Racah 1942, Cowan 1981*). In this scheme, the angular momenta of the core electron are coupled with the orbital angular momentum of the excited electron revealing K-quantum number. The K-quantum number is then coupled with the spin quantum number of the excited electron, which gives the resultant J-quantum number. All the levels have been designated using J_cK-coupling scheme as $J_c[K]_J$.

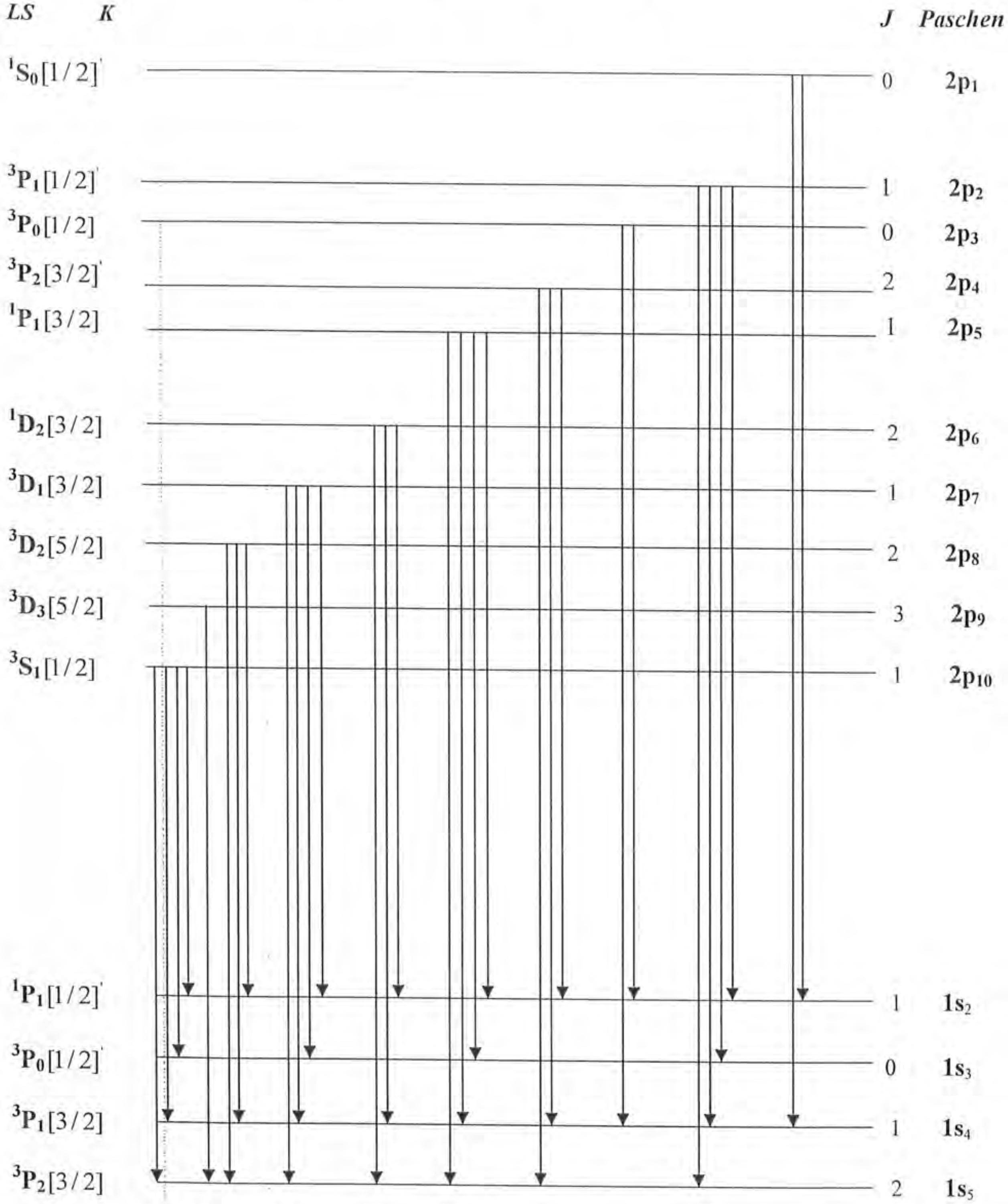
The selection rules, which are used to find out the allowed one-photon dipole transitions in this coupling scheme, are

$$\Delta l = \pm 1, \Delta J = 0, \pm 1, \Delta K = 0, \pm 1$$

Where $J = 0 \nleftrightarrow 0$ is forbidden.

It has been observed that the lines for which $\Delta l = \Delta J = \Delta K$, are intense in comparison with the other lines. The de-excitation of these levels $2p^5 3p$ *to* $2p^5 3s$ configuration based levels generates a spectrum of neon as shown in figure 4.1. The ground state electronic configuration of neon is $1s^2 2s^2 2p^{6}\,{}^1S_0$. The first excited state for neon $2p^5 3s$ gives rise to four states, which are designated as "$2p^5 3s\ [3/2]_2$, $2p^5 3s\ [3/2]_1$, $2p^5 3s\ [1/2]_0$ and $2p^5 3s\ [1/2]'_1$". Two of these levels $3s[3/2]_2$ and $3s'[1/2]_0$ are metastable; with radiative life times on the order of seconds while the other two levels $2p^5 3s[3/2]_1$ and $2p^5 3s[1/2]_1$ have very short radiative life times of *16* and *1.2 ns* respectively. The second group of the excited levels arises from the electronic configuration $2p^5 3p$. There are ten energy levels designated by "$3p[5/2]_3$, $3p[5/2]_2$, $3p[3/2]_1$, $3p[3/2]_2$, $3p[3/2]_1$, $3p[1/2]_0$, $3p[1/2]_1$, $3p[3/2]'_2$, $3p[1/2]'_1$ and $3p[1/2]'_0$" respectively. In the figure, all the levels have been designated in *LS*, J_ck and Paschen notations. The dipole allowed transitions are drawn such that the lines appear due to transitions from the same upper level to different lower levels as members of a multiplet. The energy levels diagram for all the ten excited levels and four lower levels are given below.

Figure 4.1: Transitions between $2p^5 3p$ and $2p^5 3s$ configurations based levels in neon



In the below figure we show the emission spectrum of neon recorded using the laser produced neon plasma. The spectrum shows nearly all the transitions which lie in the spectral region between 500 – 720 nm.

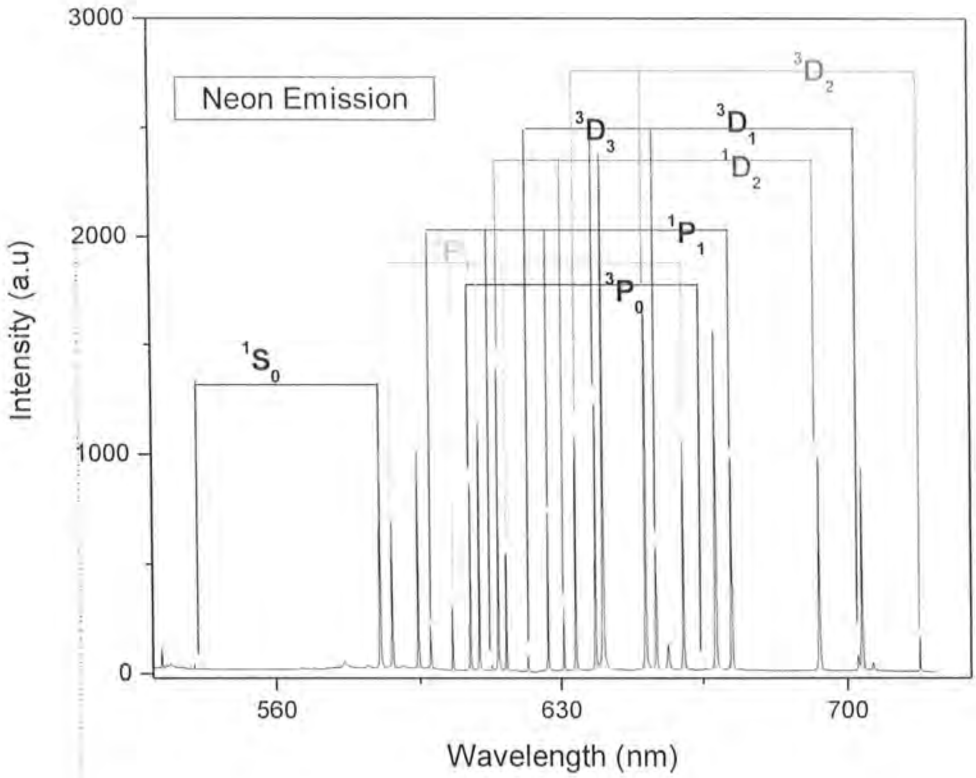
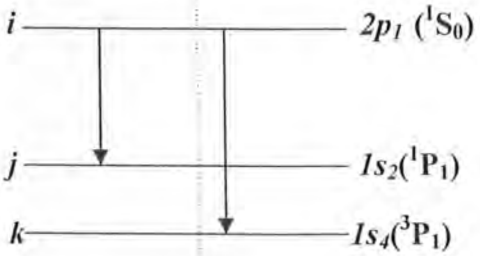


Figure 4.2: Spectrum of Neon

4.2 Calculations of relative line strength of 30 spectral lines of Neon

We have calculated the relative line strengths for all the observed lines of neon using the relations mentioned above. The calculations for all the ten upper levels of neon are given below. The first group consists of two lines due to transitions between $2p^5 3p\ ^1S_0 \rightarrow 2p^5 3s\ ^1P_1$ and $^3P_1$ at 585.4 nm and 540.2 nm. The observed intensities and calculated line strengths are listed.

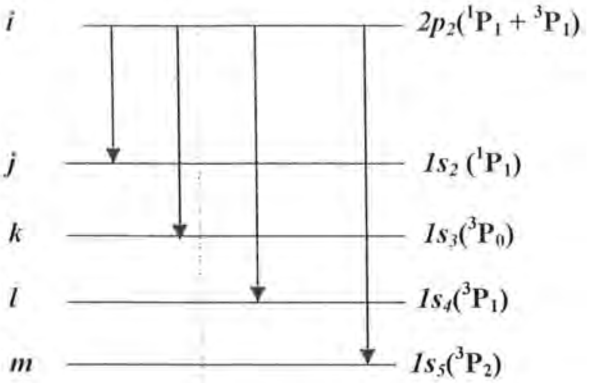


Transitions	*Wavelengths*	*Intensity*	S_{ij}
$2p_1.1s_2$	585.3	998.77	**11.58**
$1s_4$	540.2	46.1	**0.42**

$S_{ij}=S_i[1+ 1.998\times10^{11}/6.9\times10^{9}]^{-1}$

S_{ij}=*11.58* S_{ik}=*0.42*

The second group shows transitions from $2p_2$ upper level to all the four levels based on the $2p^5 3s$ configuration. The table on the right has shown the observed intensities as well as the calculated line strengths.

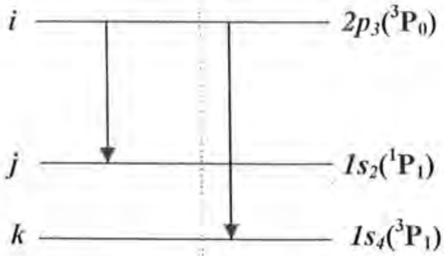


Transitions	*Wavelength*	*Intensity*	S_{ij}
$2p_2 \rightarrow 1s2$	*659.9*	*1054.31*	***17.08***
$\rightarrow 1s_3$	*616.4*	*544.11*	***7.18***
$\rightarrow 1s_4$	*603.0*	*298.94*	***3.69***
$\rightarrow 1s_5$	*588.2*	*701.36*	***8.05***

$S_{ij}=[1+1.275\times10^{11}/3.03\times10^{11}+6.56\times10^{10}/3.03\times10^{11}+1.428\times10^{11}/3.03]^{-1}$

S_{ij}=17.08 S_{ik}=7.18 S_{il}=3.69 S_{im}=8.05

The third group shows the transitions between the $2p_3$ upper level to the $1s_2$ and $1s_4$ lower levels. The corresponding line intensities and strengths are also listed.

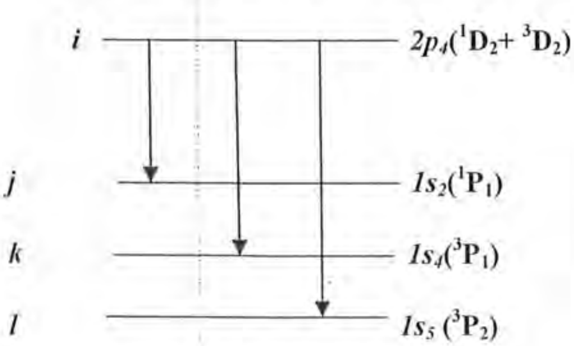


Transitions	*Wavelength*	*Intensity*	S_{ij}
$2P_3 \rightarrow 1s_2$	*665.2*	*23.86*	***0.42***
$\rightarrow 1s_4$	*607.5*	*865.66*	***11.58***

$S_{ij}=1/3[1+1.94\times10^{11}/6.48\times10^{9}]^{-1}$

S_{ij} =11.58 S_{ik}=**0.**42

The fourth group contains three transitions between $2p_4$upper level and $1s_2$, $1s_4$ and $1s_5$ lower levels.

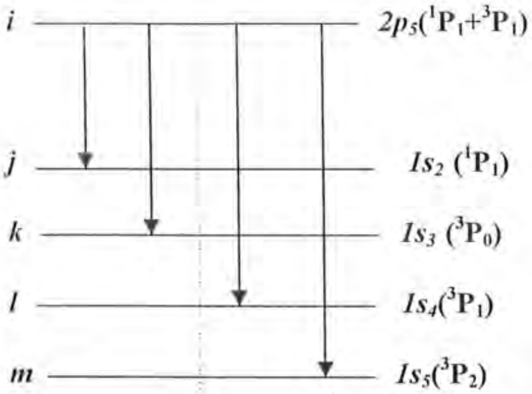


Transitions	*Wavelength*	*Intensity*	S_{ij}
$2p_4 \rightarrow 1s_2$	*667.8*	*1567.39*	***29.85***
$\rightarrow 1s_4$	*609.6*	*1143.6*	***16.57***
$\rightarrow 1s_5$	*594.5*	*1010.94*	***13.58***

S_{ik}=5/3[1+4.67×10^{11}/2.59×10^{11}+2.13×10^{11}/2.59×10^{11}]$^{-1}$

S_{ij}=29.85 S_{ik}=16.57 S_{il}=13.58

The fifth group shows four transitions, involving $2p_5$ upper level and all the four levels based on the $2p^5 3s$ configuration. The observed intensities and the calculated line strengths are listed in the table.

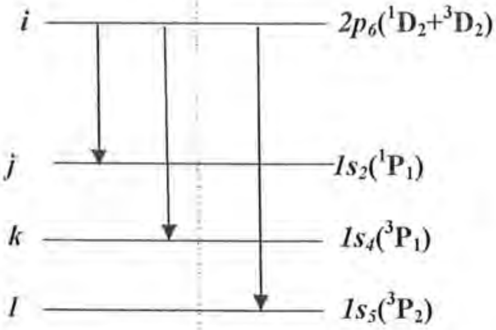


Transitions	*Wavelength*	*Intensity*	S_{ij}
$2p_5 \rightarrow 1s2$	671.7	986.78	20.11
$\rightarrow 1s_3$	626.6	729.51	12.07
$\rightarrow 1s_4$	612.8	43.23	0.67
$\rightarrow 1s_5$	597.6	220.39	3.16

S_{ij}=[1+1.79×10^{11}/2.993×10^{11}+9.958×10^{9}/2.993×10^{11}+4.71×10^{11} /2.993×10^{11}]$^{-1}$

S_{ik}=20.11 S_{ij}=12.07 S_{il}=**0.67** S_{im}=3.1

The sixth group contains three transitions involving $2p_6$ upper level and $1s_2, 1s_4$ and $1s_5$ lower levels.

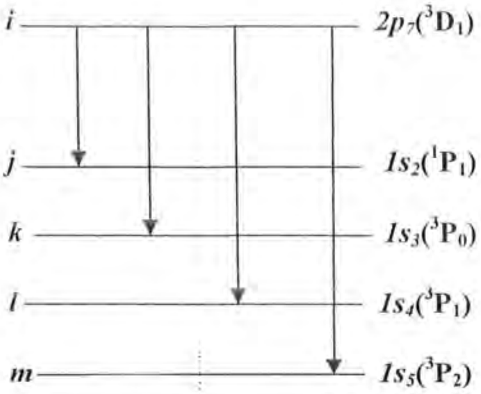


Transitions	*Wavelength*	*Intensity*	S_{ij}
$2p_6 \rightarrow 1s_2$	692.9	988.35	27.08
$\rightarrow 1s_4$	630.5	305.37	6.31
$\rightarrow 1s_5$	614.3	1393.09	26.61

S_{ik}= [1+3.29×10^{11}/7.66×10^{10}+3.23×10^{11}/7.66×10^{10}]$^{-1}$

S_{ij}=27.08 S_{ik}=6.31 S_{il}=26.61

The seventh group contains transitions between $2p_7$ upper levels to all the four levels of the lower configuration.

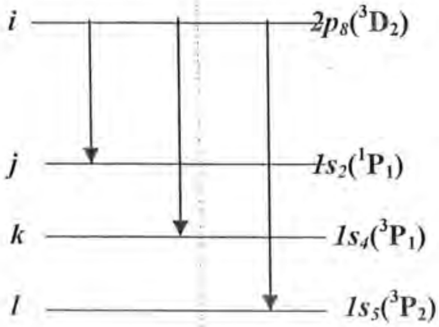


Transitions	*Wavelength*	*Intensity*	S_{ij}
$2p_7 \rightarrow 1s_2$	703.3	84.79	2
$\rightarrow 1s_3$	653.3	577.52	10.93
$\rightarrow 1s_4$	638.3	1232.55	21.75
$\rightarrow 1s_5$	621.7	80.83	1.32

S_{ij}=3/5[1+1.62×10^{11}/2.94×10^{10}+3.21×10^{11}/2.94×10^{10}+1.95×10^{10}/2.94×10^{10}]$^{-1}$

S_{ik}=10.93 S_{ij}=2 S_{il}=21.75 S_{im}=1.32

Eight group contain transitions between $2p_8$ upper level and three $1s_2$, $1s_4$, $1s_5$ lower levels.

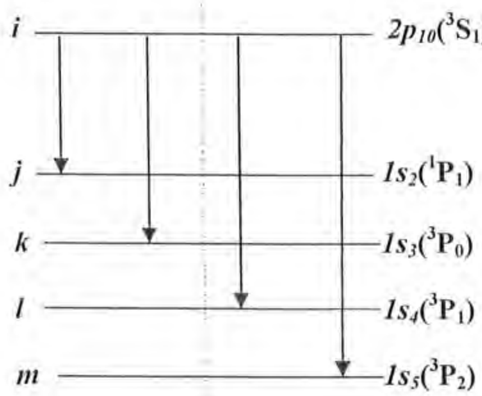


Transitions	*Wavelength*	*Intensity*	S_{ij}
$2p_8 \rightarrow 1s_2$	717.4	163.6	4.51
$\rightarrow 1s_4$	650.6	1701.42	34.95
$\rightarrow 1s_5$	633.5	1083.14	20.54

S_{ik}= [1+4.69×10^{11}/6.04×10^{10}+2.76×10^{11}/6.04×10^{10}]$^{-1}$

S_{ij}=4.51 S_{ik}=34.95 S_{il}=20.54

The tenth group contains transitions between $2p_{10}$ upper level to all the four levels of the lower configuration.



Transitions	*Wavelength*	*Intensity*	S_{ij}
$2p_{10} \rightarrow 1s2$	808.3	23.49	0.39
$\rightarrow 1s_3$	743.9	379.53	4.98
$\rightarrow 1s_4$	724.5	982.58	11.94
$\rightarrow 1s_5$	703.3	1683.57	18.69

$S_{ij}= [1+1.37\times10^{11}/1.69\times10^{11}+4.11\times10^{11}/1.69\times10^{11}+6.63\times10^{11}/1.69\times10^{11}]^{-1}$

$S_{ik}=4.98$ $S_{ij}=0.39$ $S_{il}=11.94$ $S_{im}=18.69$

The calculated line strengths of all the observed lines are listed in Table-2 along with the data from *Ellis* [3], *Krebs* [9] and *Garbury*[10] for comparison, showing good agreement with the previously quoted values.

Table 4.1: Relative Line Strength

Transitions	*Wavelength*	*Present Experiment*	*Ellis*[3]	*Krebs*[9]	*Garbuny*[10]
Paschen Notation	**A⁰**	S_{ij}	S_{ij}	S_{ij}	S_{ij}
$2p_1$-$1s_2$	585.25	**11.58**	11.88	14.16	11.88
$1s_4$	540.056	**0.42**	0.12	....	0.12
$2p_2$-$1s_2$	659.89	**17.08**	18.14	16.2	20.76
$1s_3$	616.36	**7.18**	9.41	10.92	8.16
$1s_4$	602.99	**3.69**	2.63	3.96	2.64
$1s_5$	588.19	**8.05**	5.82	6.6	4.44
$2P_3$-$1s_2$	665.21	**0.42**	0.18	...	0.24
$1s_4$	607.44	**11.58**	11.82	12.84	11.76
$2p_4$-$1s_2$	667.83	**29.85**	33.09	28.8	37.68
$1s_4$	609.62	**16.57**	16.88	18.96	14.64
$1s_5$	594.48	**13.58**	10.03	12.6	7.68
$2p_5$-$1s_2$	671.71	**20.11**	17.76	16.65	20.04
$1s_3$	626.65	**12.07**	15.89	14.64	13.92
$1s_4$	612.85	**0.67**	0.35	...	0.36
$1s_5$	597.55	**3.16**	1.99	2.52	1.68
$2p_6$-$1s_2$	692.95	**27.08**	26.4	25.08	33.84
$1s_4$	630.48	**6.31**	4.43	5.4	4.32
$1s_5$	614.31	**26.61**	29.17	31.44	21.84
$2p_7$-$1s_2$	703.24	**2**	1.76	...	2.88
$1s_3$	653.29	**10.93**	7.47	8.04	8.04
$1s_4$	638.3	**21.75**	21.7	23.04	21.6
$1s_5$	621.73	**1.32**	5.07	4.8	3.84
$2p_8$-$1s_2$	717.39	**4.51**	5.29	4.8	8.76
$1s_4$	650.65	**34.95**	36.23	34.8	32.52
$1s_5$	633.44	**20.54**	18.48	20.04	18.72
$2p_{10}$-$1s_2$	808.25	**0.39**	0.54	...	3.24
$1s_3$	743.89	**4.98**	3.39	2.4	2.76
$1s_4$	724.52	**11.94**	8.54	8.88	9
$1s_5$	703.24	**18.69**	23.52	2.4	2.76

Relative line strength for all *30* optically allowed transitions of neon have been calculated by using the *eq. (5)* and we have compared these calculated values with the literature line strengths. To calculate the line strengths, first we calculate S_{ik} and then put this value of S_{ik} in *eq. (5)* and finally we get S_{ij}. Here all the measured relative line strengths are normalized line strength. Each level has its own normalization factor, which can be calculated by using the relation $S = (2L+1)(2S+1)(2L^{'}+1)$. This normalization factor is then multiplied with calculated S_{ij}. The relative line strengths for each multiplets are different and the total sum of all the transitions line strengths gives us the total line strength for that level. These calculated line strengths are also compared with the *J*-File sum rule. The *J*-File sum is calculated taking in to consideration the statistical weight of the upper level multiplied by the sum of the statistical weight of all the lower levels. We explain the calculations to get the *J*-file sum for these transitions. The *J*-sums listed at the end of each column is the equal to the product of the statistical weight of the upper level and the sum of the statistical weights of all the lower levels based on the $2p^5 3s$ configuration; which is = 12. Whereas the *J*-sums listed at the end of each row is equal to the product of the statistical weight of the lower level and the sum of the statistical weights of all the upper levels that of $2p^5 3p$ configuration; which is equal to =36.

The relative line strength also gives us the idea about the absolute transition probabilities. If the intensity of a spectral line is high then its transition probability is also large. Following expression describes the relation between transition probabilities and line strengths [3]

$$A_{ij} = 2.026 \times 10^{18} \frac{S_{ij} R_{ij}}{\lambda_{ij}^{3} (2J_i + 1)}$$

In this relation λ_{ij} is the wavelength, S_{ij} is the relative line strength and R_{ij} is the coulomb approximation [28]. Above relation show that transition probability is proportional to line strength. Transition with intense line strength will have maximum transition probability. Transition probability is actually the probability of transferring atoms from one level to another level and it depends upon the spatial overlap of the wave functions of the upper and lower level. In the above table, we measure the experimental relative line strengths for all spectral lines of neon and compare with the previously reported values by other researchers.

Table 4.2: Comparison of experimental line strength with *J-file* Sum rule

	$2p_1$	$2p_2$	$2p_3$	$2p_4$	$2p_5$	$2p_6$	$2p_7$	$2p_8$	$2p_9$	$2p_{10}$	Experiment	Ellis	*J*-File
$1s_2$	11.58	17.08	0.42	29.85	20.11	27.08	2	4.51	....	0.39	113.02	115.04	108
$1s_3$	....	7.18	....	....	12.07	....	10.93	....	....	4.98	35.16	36.16	36
$1s_4$	0.42	3.69	11.6	16.57	0.67	6.31	21.75	34.95	....	11.94	107.88	102.69	108
$1s_5$	....	8.05	....	13.58	3.16	26.61	1.32	20.54	84	18.69	175.95	178.12	180
Total	12	36	12	60	36	60	36	60	84	36	432.01	432.01	432

The resulting line strength sum for the ten *3p* levels and four *3s* levels are given in the above table. In this table we compare the experimental line strength with *J-file* Sum rule. The statistical weight of all the four lower levels $^1P_1$, $^3P_2$, $^3P_1$, $^3P_0$ is *3,5,3,1* respectively gives the sum = 12. The upper levels sum of the statistical weights is equal to 36. The values listed at the end of each row is calculated by multiplying the statistical weight of the lower with the sum of the statistical weights if the upper levels, which turns out to be; *(3×36=108), (1×36= 36), (3×36=108), (5x36=180),* and the total sum is equal to 432. 80 then these values become 108,180,108 and 36 respectively. Similarly the values listed at the end of each row are calculated by multiplying the statistical of upper level with the sum of the statistical weights of the upper levels, that yields the values; *(1×12), (3×12), (1×12), (5×12), (3×12), (5×12), (3×12), (5×12), (7×12), (3×12)* and the total sum is equal to 432. In is interesting to note that the experimentally observed and the calculated *J*-sums are in excellent agreement, which is mainly due to the normalization procedure.

4.3 Comparison of Line Strength with NIST:

Since the complete set of spectral lines belonging to the *3s-3p*transition array has been studied in this work, it is therefore possible to test the *J*-File sum rulefor this transition array. For this purpose the obtained absolute transition probabilities have been converted into line strength according to the formula given by the *National Bureau of Standards (NBS, 2012)*.

$$S_{ki} = 4.9356 \times 10^{-19} \lambda_{ki}^3 g_k A_{ki}$$

Where g_k the statistical weight of the upper level is, λ_{ik} is the wavelength in angstrom units and A_{ki} is the transition probability in sec^{-1}. The line strengths are then obtained in the atomic units. In the table below, we compare the line strengths obtained in the present work with that reported in the *NIST* Data base which shows an excellent agreement. However, we believe our values are more consistent as no other researcher has given the spectral lines and their intensities as we have presented in this work.

Table 4.3: Comparison of Line Strength with NIST:

Transitions	Wavelength	Present Experiment	*NIST*
Paschen Notation	**Nm**	S_{ii}	S_{ii}
$2p_1$-$1s_2$	585.25	5.13	6.75
$1s_4$	540.06	0.23	0.07
$2p_2$-$1s_2$	659.89	9.33	9.88
$1s_3$	616.36	3.92	5.07
$1s_4$	602.99	2.02	1.82
$1s_5$	588.19	4.39	3.47
$2P_3$-$1s_2$	665.21	0.23	0.04
$1s_4$	607.44	6.16	6.68
$2p_4$-$1s_2$	667.83	15.96	17.1
$1s_4$	609.62	8.86	10.1
$1s_5$	594.48	7.25	5.86
$2p_5$-$1s_2$	671.71	11.29	9.75
$1s_3$	626.65	6.78	9.08
$1s_4$	612.85	0.38	0.37
$1s_5$	597.55	1.77	1.11
$2p_6$-$1s_2$	692.95	15.42	14.3
$1s_4$	630.48	3.58	2.57
$1s_5$	614.31	15.13	16.1
$2p_7$-$1s_2$	703.24	1.13	0.97
$1s_3$	653.29	6.16	4.46
$1s_4$	638.3	12.27	12.4
$1s_5$	621.73	0.74	2.27
$2p_8$-$1s_2$	717.39	2.45	2.62
$1s_4$	650.65	19.05	20.4
$1s_5$	633.44	11.19	10.1
$2p_{10}$-$1s_2$	808.25	0.23	0.09
$1s_3$	743.89	2.91	1.41
$1s_4$	724.52	6.96	5.27
$1s_5$	703.24	10.91	13

4.4 Theoretical Line Strength:

Theoretical lines strengths get measured with *Brain Warner* formulas [11]. Calculations for all coupling schemes *(LS, LK, J_ck, jj)*. First we consider these transitions in *LS*-coupling in which the $\Delta S=0$ selection rule restricts the number of allowed transitions as singlet to triplet transitions are forbidden.

LS-L′S′

$$S(LS:L'S') = \delta_{SS'}[L,L',J,J']\begin{Bmatrix} L & J & S \\ J' & L' & 1 \end{Bmatrix}^2 \begin{Bmatrix} l_2 & L & l_1 \\ L' & l'_2 & 1 \end{Bmatrix}^2$$

First group contain transition from $2p_1$as upper level and $1s_2$, $1s_4$as the lower levels. Only one transition is possible here.

$2p_1 \rightarrow 1s_2$ ($^1S_0 \rightarrow {}^1P_1$)

$$= (1)(3)(3)(1)\begin{Bmatrix} 0 & 0 & 0 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 12$$

$2p_1 \rightarrow 1s_4$($^1S_0 \rightarrow {}^3P_1$)

Forbidden Transition

Second group contain transitions $2p_2$ upper level and $1s_3$, $1s_4$, $1s_5$ lower levels.

$2p_2 \rightarrow 1s_2$ ($^3P_1 \rightarrow {}^1P_1$)

Forbidden Transition

$2p_2 \rightarrow 1s_3$ ($^3P_1 \rightarrow {}^3P_0$)

$$= (3)(3)(3)\begin{Bmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 12$$

$2p_2 \rightarrow 1s_4$ ($^3P_1 \rightarrow {}^3P_1$)

$$= (3)(3)(3)(3)\begin{Bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 9$$

$2p_2 \rightarrow 1s_5$ ($^3P_1 \rightarrow {}^3P_2$)

$$= (3)(3)(5)(3)\begin{Bmatrix} 1 & 1 & 1 \\ 2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 15$$

Third group contain transitions $2p_3$ upper level and $1s_2$ and $1s_4$ lower levels.

$2p_3 \rightarrow 1s_2$ ($^3P_0 \rightarrow {}^1P_1$)

Forbidden Transition

$2p_3 \rightarrow 1s_4\ (^3P_0 \rightarrow {}^3P_1)$

$$= (3)(3)(3)\begin{Bmatrix} 1 & 0 & 1 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 12$$

The **fourth group** contains transitions between $2p_4$ upper levels to $1s_2$, $1s_4$, $1s_5$ levels of the lower configuration.

$2p_4 \rightarrow 1s_2(^3P_2 \rightarrow {}^1P_1)$

Forbidden Transition

$2p_4 \rightarrow 1s_5\ (^3P_2 \rightarrow {}^3P_2)$

$$= (3)(5)(3)(3)\begin{Bmatrix} 1 & 2 & 1 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 15$$

$2p_4 \rightarrow 1s_4\ (^3P_2 \rightarrow {}^3P_1)$

$$= (3)(5)(5)(3)\begin{Bmatrix} 1 & 2 & 1 \\ 2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 45$$

Fifth group contain the transition $2p_5$upper level and all four $1s_2$, $1s_3$, $1s_4$, $1s_5$as lower levels. Only one transition is possible here. There is only one possible transition from triplet to triplet.

$2p_5 \rightarrow 1s_2\ (^1P_1 \rightarrow {}^1P_1)$

$$= (3)(3)(3)(3)\begin{Bmatrix} 1 & 1 & 0 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 36$$

$2p_5 \rightarrow 1s_3\ (^1P_1 \rightarrow {}^3P_0)$

Forbidden Transition

$2p_5 \rightarrow 1s_4\ (^1P_1 \rightarrow {}^3P_1)$

Forbidden Transition

$2p_5 \rightarrow 1s_5(^1P_1 \rightarrow {}^3P_2)$

Forbidden Transition

Sixth group contain only $2p_6$ upper level and $1s_2$, $1s_4$, $1s_5$ as lower levels.

$2p_6 \rightarrow 1s_2\ (^1D_2 \rightarrow {}^1P_1)$

$$= (5)(5)(3)(3)\begin{Bmatrix} 2 & 2 & 0 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 60$$

$2p_6 \rightarrow 1s_4(^1D_2 \rightarrow {}^3P_1) 2p_6 \rightarrow 1s_5(^1D_2 \rightarrow {}^3P_2)$

Forbidden Transition Forbidden Transition

Seventh group contain $2p_7$ upper level and $1s_2$, $1s_3$, $1s_4$, $1s_5$ as the lower levels.

$2p_7 \rightarrow 1s_2\ (^3D_1 \rightarrow {}^1P_1)$

Forbidden transition

$2p_7 \rightarrow 1s_3$ ($^3D_1 \rightarrow {}^3P_0$)

$$= (5)(3)(3)\begin{Bmatrix} 2 & 2 & 1 \\ 0 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 20$$

$2p_7 \rightarrow 1s_4$ ($^3D_1 \rightarrow {}^3P_1$)

$$= (5)(3)(3)(3)\begin{Bmatrix} 2 & 1 & 1 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 15$$

$2p_7 \rightarrow 1s_5$ ($^3D_1 \rightarrow {}^3P_2$)

$$= (5)(3)(3)(5)\begin{Bmatrix} 2 & 1 & 1 \\ 2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 1$$

Eight group contain transitions*$2p_8$* as upper level and *$1s_2$, $1s_4$, $1s_5$* as lower levels.

$2p_8 \rightarrow 1s_2$($^3D_2 \rightarrow {}^1P_1$)

Forbidden Transition

$2p_8 \rightarrow 1s_4$ ($^3D_2 \rightarrow {}^3P_1$)

$$= (5)(5)(3)(3)\begin{Bmatrix} 2 & 2 & 1 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 45$$

$2p_8 \rightarrow 1s_5$ ($^3D_2 \rightarrow {}^3P_2$)

$$= (5)(5)(5)(3)\begin{Bmatrix} 2 & 2 & 1 \\ 2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 15$$

Tenth group contain transition*$2p_{10}$* as upper levels and *$1s_2$, $1s_3$, $1s_4$, $1s_5$* as the lower transitions.

$2p_{10} \rightarrow 1s_2$($^3S_1 \rightarrow {}^1P_1$)

Forbidden Transition

$2p_{10} \rightarrow 1s_3$ ($^3S_1 \rightarrow {}^3P_0$)

$$= (3)(3)\begin{Bmatrix} 0 & 1 & 1 \\ 0 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 4$$

$2p_{10} \rightarrow 1s_4$ ($^3S_1 \rightarrow {}^3P_1$)

$$= (3)(3)(3)\begin{Bmatrix} 0 & 1 & 1 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 12$$

$2p_{10} \rightarrow 1s_5$ ($^3S_1 \rightarrow {}^3P_2$)

$$= (3)(5)(3)\begin{Bmatrix} 0 & 1 & 1 \\ 2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 20$$

LS-L'K'

$$S(LS:L'K') = [L, L', K', S, J, J']\begin{Bmatrix} L & J & S \\ J' & L' & 1 \end{Bmatrix}^2 \begin{Bmatrix} l_2 & L & l_1 \\ L' & l'_2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} K' & s_2 & J' \\ S & L' & s_1 \end{Bmatrix}^2$$

For measurement of theoretical line strength we represent the upper levels in *LS*-Coupling and lower level in *LK*-Coupling scheme.

First group contain transition from $2p_1$ as upper level and $1s_2$, $1s_4$ as the lower levels.

$2p_1 \rightarrow 1s_2$ ($^1S_0 \rightarrow P\ [1/2]_1$)

$$=(1)(3)(2)(1)(1)(3)\begin{Bmatrix} 0 & 0 & 0 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1/2 & 1/2 & 1 \\ 0 & 1 & 1/2 \end{Bmatrix}^2 = 4$$

$2p_1 \rightarrow 1s_4$ ($^1S_0 \rightarrow P\ [3/2]_1$)

$$=(1)(3)(4)(1)(1)(3)\begin{Bmatrix} 0 & 0 & 0 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 3/2 & 1/2 & 1 \\ 0 & 1 & 1/2 \end{Bmatrix}^2 = 8$$

Second group contain transitions $2p_2$ upper level and $1s_2$, $1s_3$, $1s_4$, and $1s_5$ lower levels.

$2p_2 \rightarrow 1s_2$ ($^3P_1 \rightarrow P\ [1/2]_1$)

$$=(3)(3)(3)(3)(2)(3)\begin{Bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1/2 & 1/2 & 1 \\ 1 & 1 & 1/2 \end{Bmatrix}^2 = 6$$

$2p_2 \rightarrow 1s_3$ ($^3P_1 \rightarrow P\ [1/2]_0$)

$$=(3)(3)(3)(2)(3)\begin{Bmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1/2 & 1/2 & 0 \\ 1 & 1 & 1/2 \end{Bmatrix}^2 = 12$$

$2p_2 \rightarrow 1s_4$ ($^3P_1 \rightarrow P\ [3/2]_1$)

$$=(3)(3)(3)(3)(4)(3)\begin{Bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 3/2 & 1/2 & 1 \\ 1 & 1 & 1/2 \end{Bmatrix}^2 = 3$$

$2p_2 \rightarrow 1s_5$ ($^3P_1 \rightarrow P\ [3/2]_2$)

$$=(3)(3)(3)(5)(4)(3)\begin{Bmatrix} 1 & 1 & 1 \\ 2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 3/2 & 1/2 & 2 \\ 1 & 1 & 1/2 \end{Bmatrix}^2 = 15$$

Third group contain transitions $2p_3$ upper level and $1s_2$ and $1s_4$ lower levels.

$2p_3 \rightarrow 1s_2$ ($^3P_0 \rightarrow P\ [1/2]_1$)

$$=(3)(3)(3)(3)(2)\begin{Bmatrix} 1 & 0 & 1 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1/2 & 1/2 & 1 \\ 1 & 1 & 1/2 \end{Bmatrix}^2 = 8$$

$2p_3 \rightarrow 1s_4$ ($^3P_0 \rightarrow P\ [3/2]_1$)

$$=(3)(3)(3)(4)(3)\begin{Bmatrix} 1 & 0 & 1 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 3/2 & 1/2 & 1 \\ 1 & 1 & 1/2 \end{Bmatrix}^2 = 4$$

The **fourth group** contains transitions between $2p_4$ upper levels to $1s_2$, $1s_4$ and $1s_5$ levels of the lower configuration.

$2p_4 \rightarrow 1s_2$ ($^3P_2 \rightarrow P\ [1/2]_1$)

$$=(3)(5)(3)(3)(2)(3)\begin{Bmatrix} 1 & 2 & 1 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1/2 & 1/2 & 1 \\ 1 & 1 & 1/2 \end{Bmatrix}^2 = 10$$

$2p_4 \rightarrow 1s_4$ ($^3P_2 \rightarrow P\ [3/2]_1$)

$$=(3)(5)(3)(3)(4)(3)\begin{Bmatrix} 1 & 2 & 1 \\ 1 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 3/2 & 1/2 & 1 \\ 1 & 1 & 1/2 \end{Bmatrix}^2 = 5$$

$2p_4 \rightarrow 1s_5$ ($^3P_2 \rightarrow P\ [3/2]_2$)

$$=(3)(5)(5)(3)(4)(3)\begin{Bmatrix} 1 & 2 & 1 \\ 2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 3/2 & 1/2 & 2 \\ 1 & 1 & 1/2 \end{Bmatrix}^2 = 45$$

Fifth group contain the transition $2p_5$upper level and all four $1s_2$, $1s_3$, $1s_4$,and $1s_5$ as lower levels. But only two transitions are possible according to formula.

$2p_5 \rightarrow 1s_2$ ($^1P_1 \rightarrow P\ [1/2]_1$)

$$=(3)(3)(3)(3)(2)\begin{Bmatrix}1 & 1 & 0\\ 1 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}1/2 & 1/2 & 2\\ 0 & 1 & 1/2\end{Bmatrix}^2=12$$

$2p_5 \rightarrow 1s_4$ ($^1P_1 \rightarrow P\ [3/2]_1$)

$$=(3)(3)(3)(3)(4)\begin{Bmatrix}1 & 1 & 0\\ 1 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}3/2 & 1/2 & 1\\ 0 & 1 & 1/2\end{Bmatrix}^2=24$$

$2p_5 \rightarrow 1s_3$($^1P_1 \rightarrow P\ [1/2]_0$)

Forbidden Transition

$2p_5 \rightarrow 1s_5$ ($^1P_1 \rightarrow P\ [3/2]_2$)

Forbidden Transition

Sixth group contain only $2p_6$ upper level and $1s_2$, $1s_4$, $1s_5$as the lower levels. Only two transitions are allowed.

$2p_6 \rightarrow 1s_2$ ($^1D_2 \rightarrow P\ [1/2]_1$)

$$=(5)(5)(3)(3)(2)\begin{Bmatrix}2 & 2 & 0\\ 1 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 2 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}1/2 & 1/2 & 1\\ 0 & 1 & 1/2\end{Bmatrix}^2=20$$

$2p_6 \rightarrow 1s_4$ ($^1D_2 \rightarrow P\ [3/2]_1$)

$$=(5)(5)(3)(3)(4)\begin{Bmatrix}2 & 2 & 0\\ 1 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 2 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}3/2 & 1/2 & 1\\ 0 & 1 & 1/2\end{Bmatrix}^2=40$$

$2p_6 \rightarrow 1s_5$ ($^1D_2 \rightarrow P\ [3/2]_2$)

Forbidden Transition

Seventh group contain $2p_7$ upper level and $1s_2$, $1s_3$, $1s_4$, and $1s_5$ as the lower levels

$2p_7 \rightarrow 1s_2$ ($^3D_1 \rightarrow P\ [1/2]_1$)

$$=(5)(3)(3)(3)(2)(3)\begin{Bmatrix}2 & 1 & 1\\ 1 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 2 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}1/2 & 1/2 & 1\\ 0 & 1 & 1/2\end{Bmatrix}^2=10$$

$2p_7 \rightarrow 1s_3$ ($^3D_1 \rightarrow P\ [1/2]_0$)

$$=(5)(3)(3)(2)(3)\begin{Bmatrix}2 & 1 & 1\\ 0 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 2 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}1/2 & 1/2 & 0\\ 1 & 1 & 1/2\end{Bmatrix}^2=20$$

$2p_7 \rightarrow 1s_4$ ($^3D_1 \rightarrow P\ [3/2]_1$)

$$=(5)(3)(3)(3)(4)(3)\begin{Bmatrix}2 & 1 & 1\\ 1 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 2 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}3/2 & 1/2 & 1\\ 1 & 1 & 1/2\end{Bmatrix}^2=5$$

$2p_7 \rightarrow 1s_5$ ($^3D_1 \rightarrow P\ [3/2]_2$)

$$=(5)(5)(3)(3)(4)(3)\begin{Bmatrix}2 & 1 & 1\\ 2 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 2 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}3/2 & 1/2 & 1\\ 1 & 1 & 1/2\end{Bmatrix}^2=1$$

Eight group contain transitions$2p_8$ as upper level and $1s_2$, $1s_4$, $1s_5$ as lower levels.

$2p_8 \rightarrow 1s_2$ ($^3D_2 \rightarrow P\ [1/2]_1$)

$$=(5)(5)(3)(3)(3)(2)\begin{Bmatrix}2 & 2 & 1\\ 1 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 2 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}1/2 & 1/2 & 1\\ 1 & 1 & 1/2\end{Bmatrix}^2=30$$

$2p_8 \rightarrow 1s_2$ ($^3D_2 \rightarrow {}^1P_1$)

Forbidden Transition

$2p_8 \rightarrow 1s_4$ ($^3D_2 \rightarrow$ P $[3/2]_1$)

$$=(5)(5)(3)(3)(4)(3)\begin{Bmatrix}2 & 2 & 1\\ 1 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 2 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}3/2 & 1/2 & 1\\ 1 & 1 & 1/2\end{Bmatrix}^2=15$$

$2p_8 \rightarrow 1s_5$ ($^3D_2 \rightarrow$ P $[3/2]_2$)

$$=(5)(5)(5)(3)(4)(3)\begin{Bmatrix}2 & 2 & 1\\ 2 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 2 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}3/2 & 1/2 & 2\\ 1 & 1 & 1/2\end{Bmatrix}^2=15$$

Tenth group contain transition*$2p_{10}$* as upper levels and *$1s_2$, $1s_3$, $1s_4$*, and *$1s_5$* as the lower transitions.

$2p_{10} \rightarrow 1s_2$ ($^3S_1 \rightarrow$ P $[1/2]_1$)

$$=(3)(3)(3)(2)(3)\begin{Bmatrix}0 & 1 & 1\\ 1 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 0 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}1/2 & 1/2 & 1\\ 1 & 1 & 1/2\end{Bmatrix}^2=8$$

$2p_{10} \rightarrow 1s_3$ ($^3S_1 \rightarrow$ P $[1/2]_0$))

$$=(3)(3)(3)(2)(\begin{Bmatrix}0 & 1 & 1\\ 0 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 0 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}1/2 & 1/2 & 0\\ 1 & 1 & 1/2\end{Bmatrix}^2=4$$

$2p_{10} \rightarrow 1s_4$ ($^3S_1 \rightarrow$ P $[3/2]_1$)

$$=(3)(3)(3)(3)(4)(\begin{Bmatrix}0 & 1 & 1\\ 1 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 0 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}3/2 & 1/2 & 1\\ 1 & 1 & 1/2\end{Bmatrix}^2=4$$

$2p_{10} \rightarrow 1s_5$ ($^3S_1 \rightarrow$ P $[3/2]_2$)

$$=(3)(3)(5)(4)(3)(\begin{Bmatrix}0 & 1 & 1\\ 2 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 0 & 1\\ 1 & 0 & 1\end{Bmatrix}^2\begin{Bmatrix}3/2 & 1/2 & 2\\ 1 & 1 & 1/2\end{Bmatrix}^2=20$$

Jk-J'k'

In this case, we represent the upper as well as the lower levels in *JK* coupling. The relations are given in the *6j* symbols which can easily be calculated. The selection rule the $\Delta j_c = \pm 1$ transitions are forbidden and the strongest transitions are that in which $\Delta J=\Delta\lambda=\Delta K$ changes in the same direction.

$$S(j_1k : j_1'k') = \delta_{j_1 j_1'}[K,K',J,J']\begin{Bmatrix}K & J & s_2\\ J' & K & I\end{Bmatrix}^2\begin{Bmatrix}l_2 & K & j_1\\ K' & l_2' & I\end{Bmatrix}^2$$

First group contain transition from *$2p_1$*as upper level and $1s_2$, $1s_4$ as the lower levels. When we place all quantum numbers in above relation then just one transition is allowed and other is forbidden.

$2p_1 \rightarrow 1s_4$ ($1/2[1/2]_0 \rightarrow 3/2[3/2]_1$)

Forbidden Transition

$2p_1 \rightarrow 1s_2$ ($1/2[1/2]_0 \rightarrow 1/2[1/2]_1$)

$$=(2)(2)(1)(3)\begin{Bmatrix}1/2 & 0 & 1/2\\ 1 & 1/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1/2 & 1/2\\ 1/2 & 0 & 1\end{Bmatrix}^2=12$$

Second group contain transitions *$2p_2$* upper level and*$1s_2$, $1s_3$, $1s_4$*, and*$1s_5$* lower levels. Only two transitions are possible according to above formula.

$2p_2 \rightarrow 1s_2$ $(1/2[1/2]_1 \rightarrow 1/2[1/2]_1)$

$$=(2)(3)(3)(2)\begin{Bmatrix}1/2 & 1 & 1/2\\ 1 & 1/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1/2 & 1/2\\ 1/2 & 0 & 1\end{Bmatrix}^2=24$$

$2p_2 \rightarrow 1s_3$ $(1/2[1/2]_1 \rightarrow 1/2[1/2]_0)$

$$=(2)(3)(2)\begin{Bmatrix}1/2 & 1 & 1/2\\ 0 & 1/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1/2 & 1/2\\ 1/2 & 0 & 1\end{Bmatrix}^2=12$$

$2p_2 \rightarrow 1s_4$ $(1/2[1/2]_1 \rightarrow 3/2[3/2]_1)$

Forbidden Transitions

$2p_2 \rightarrow 1s_5$ $(1/2[1/2]_1 \rightarrow 3/2[3/2]_2)$

Forbidden Transitions

Third group contain transitions $2p_3$ upper level and $1s_2$ and $1s_4$ lower levels. Only one transition is allowed.

$2p_3 \rightarrow 1s_2$ $(3/2[1/2]_0 \rightarrow 1/2[1/2]_1)$

Forbidden Transition

$2p_3 \rightarrow 1s_4$ $(3/2[1/2]_0 \rightarrow 3/2[3/2]_1)$

$$=(2)(3)(4)\begin{Bmatrix}1/2 & 0 & 1/2\\ 1 & 3/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1/2 & 3/2\\ 3/2 & 0 & 1\end{Bmatrix}^2=12$$

The **fourth group** contains transitions between the $2p_4$ upper levels to $1s_2$, $1s_4$, $1s_5$ levels of the lower configuration. Only one transition is allowed.

$2p_4 \rightarrow 1s_2$ $(1/2[3/2]_2 \rightarrow 1/2[1/2]_1)$

$$=(4)(5)(3)(2)\begin{Bmatrix}3/2 & 2 & 1/2\\ 1 & 1/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 3/2 & 1/2\\ 1/2 & 0 & 1\end{Bmatrix}^2=60$$

$2p_4 \rightarrow 1s_4$ $(1/2[3/2]_2 \rightarrow 3/2[3/2]_1)$

Forbidden Transition

$2p_4 \rightarrow 1s_5$ $(1/2[3/2]_2 \rightarrow 3/2[3/2]_2)$

Forbidden Transition

Fifth group contain the transitions from the $2p_5$upper level and all the four $1s_2$, $1s_3$, $1s_4$, $1s_5$lower levels. But only two transitions are possible according to formula.

$2p_5 \rightarrow 1s_4$ $(1/2[3/2]_1 \rightarrow 3/2[3/2]_1)$

Forbidden Transitions

$2p_5 \rightarrow 1s_5$ $(1/2[3/2]_1 \rightarrow 3/2[3/2]_2)$

Forbidden Transitions

$2p_5 \rightarrow 1s_2$ $(1/2[3/2]_1 \rightarrow 1/2[1/2]_1)$

$$=(4)(3)(3)(2)\begin{Bmatrix}3/2 & 1 & 1/2\\ 1 & 1/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 3/2 & 1/2\\ 1/2 & 0 & 1\end{Bmatrix}^2=12$$

$2p_5 \rightarrow 1s_3$ $(1/2[3/2]_1 \rightarrow 1/2[1/2]_0)$

$$=(4)(1)(3)(2)\begin{Bmatrix}3/2 & 1 & 1/2\\ 0 & 1/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 3/2 & 1/2\\ 1/2 & 0 & 1\end{Bmatrix}^2=24$$

Sixth group contain transitions from the $2p_6$ upper level and $1s_3$, $1s_4$, $1s_5$as the lower levels. Only two transitions are possible.

$2p_6 \rightarrow 1s_2$ $(3/2[3/2]_2 \rightarrow 1/2[1/2]_1)$

Forbidden Transitions

$2p_6 \rightarrow 1s_4$ $(3/2[3/2]_2 \rightarrow 3/2[3/2]_1)$

$$=(4)(5)(3)(4)\begin{Bmatrix} 3/2 & 2 & 1/2 \\ 1 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 3/2 \\ 3/2 & 0 & 1 \end{Bmatrix}^2 = 6$$

$2p_6 \rightarrow 1s_5$ $(3/2[3/2]_2 \rightarrow 3/2[3/2]_2)$

$$=(4)(5)(5)(4)\begin{Bmatrix} 3/2 & 2 & 1/2 \\ 2 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 3/2 \\ 3/2 & 0 & 1 \end{Bmatrix}^2 = 54$$

Seventh group contain $2p_7$ upper level and $1s_2$, $1s_3$, $1s_4$, and $1s_5$ as the lower levels. Two transitions are possible here.

$2p_7 \rightarrow 1s_2$ $(3/2[3/2]_1 \rightarrow 1/2[1/2]_1)$

Forbidden Transitions

$2p_7 \rightarrow 1s_3$ $(3/2[3/2]_1 \rightarrow 1/2[1/2]_0)$

Forbidden Transitions

$2p_7 \rightarrow 1s_4$ $(3/2[3/2]_1 \rightarrow 3/2[3/2]_1)$

$$=(4)(3)(3)(4)\begin{Bmatrix} 3/2 & 1 & 1/2 \\ 1 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 3/2 \\ 3/2 & 0 & 1 \end{Bmatrix}^2 = 30$$

$2p_7 \rightarrow 1s_5$ $(3/2[3/2]_1 \rightarrow 3/2[3/2]_2)$

$$=(4)(3)(5)(4)\begin{Bmatrix} 3/2 & 1 & 1/2 \\ 2 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 3/2 \\ 3/2 & 0 & 1 \end{Bmatrix}^2 = 6$$

Eight group contain transitions$2p_8$ as upper level and $1s_2$, $1s_4$, $1s_5$ as lower levels. Only two transitions are allowed.

$2p_8 \rightarrow 1s_2$ $(3/2[5/2]_2 \rightarrow 1/2[1/2]_1)$

Forbidden Transition

$2p_8 \rightarrow 1s_4$ $(3/2[5/2]_2 \rightarrow 3/2[3/2]_1)$

$$=(6)(5)(3)(4)\begin{Bmatrix} 5/2 & 2 & 1/2 \\ 1 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 5/2 & 3/2 \\ 3/2 & 0 & 1 \end{Bmatrix}^2 = 54$$

$2p_8 \rightarrow 1s_5$ $(3/2[5/2]_2 \rightarrow 3/2[3/2]_2)$

$$=(6)(5)(5)(4)\begin{Bmatrix} 5/2 & 2 & 1/2 \\ 2 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 5/2 & 3/2 \\ 3/2 & 0 & 1 \end{Bmatrix}^2 = 6$$

Tenth group contain transition$2p_{10}$ as upper levels and $1s_2$, $1s_3$, $1s_4$ and$1s_5$ as the lower transitions. Only two transitions are allowed.

$2p_{10} \rightarrow 1s_2$ $(3/2[1/2]_1 \rightarrow 1/2[1/2]_1)$

Forbidden Transition

$2p_{10} \rightarrow 1s_3$ $(3/2[1/2]_1 \rightarrow 1/2[1/2]_0)$

Forbidden Transition

2p$_{10}$→1s$_4$ (3/2[1/2]$_1$→3/2[3/2]$_1$)

$$=(2)(3)(3)(4)\begin{Bmatrix}1/2 & 1 & 1/2\\ 1 & 3/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1/2 & 3/2\\ 3/2 & 0 & 1\end{Bmatrix}^2=6$$

2p$_{10}$→1s$_5$ (3/2[1/2]$_1$→3/2[3/2]$_2$)

$$=(2)(3)(5)(4)\begin{Bmatrix}1/2 & 1 & 1/2\\ 2 & 3/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1/2 & 3/2\\ 3/2 & 0 & 1\end{Bmatrix}^2=30$$

Jk-jj

$$S(j_1k:j_1'j_2')=\delta_{j_1'j_2}[K,j_2',J,J']\begin{Bmatrix}K & s_2 & J\\ j_1 & j_2' & J'\\ l_2 & l_2' & I\end{Bmatrix}^2$$

We use the upper levels in *JK*-Coupling and the lower levels in *jj*-Coupling scheme.

First group contain transition from *2p$_1$*as upper level and *1s$_2$, 1s$_4$* as the lower levels. But only one transition is possible according to above formula.

2p$_1$→1s$_4$ (1/2[1/2]$_0$→ (3/2, 1/2)$_1$)

Forbidden Transition

2p$_1$→1s$_2$ (1/2[1/2]$_0$→ (1/2, 1/2)$_1$)

$$=(2)(2)(1)(3)\begin{Bmatrix}1/2 & 1/2 & 0\\ 1/2 & 1/2 & 1\\ 1 & 0 & 1\end{Bmatrix}^2=12$$

Second group contain transitions *2p$_2$* upper level and *1s$_2$, 1s$_3$, 1s$_4$,* and *1s$_5$* lower levels. Only two transitions are possible according to above formula.

2p$_2$→1s$_4$(1/2[1/2]$_1$→(3/2, 1/2)$_1$)

Forbidden Transition

2p$_2$→1s$_5$ (1/2[1/2]$_1$→(3/2, 1/2)$_2$)

Forbidden Transition

2p$_2$→1s$_2$ (1/2[1/2]$_1$→(1/2, 1/2)$_1$)

$$=(2)(2)(3)(3)\begin{Bmatrix}1/2 & 1/2 & 1\\ 1/2 & 1/2 & 1\\ 1 & 0 & 1\end{Bmatrix}^2=24$$

2p$_2$→1s$_3$ (1/2[1/2]$_1$→(1/2, 1/2)$_0$)

$$=(2)(2)(3)\begin{Bmatrix}1/2 & 1/2 & 1\\ 1/2 & 1/2 & 0\\ 1 & 0 & 1\end{Bmatrix}^2=12$$

Third group contain transitions *2p$_3$* upper level and *1s$_2$* and *1s$_4$* lower levels. Only one transition is allowed.

2p$_3$→1s$_2$ (3/2[1/2]$_0$→(1/2, 1/2)$_1$)

Forbidden Transition

$2p_3 \rightarrow 1s_4$ (3/2[1/2]$_0$→(3/2, 1/2)$_1$)

$$= (2)(2)(3)\begin{Bmatrix} 1/2 & 1/2 & 0 \\ 3/2 & 1/2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 12$$

The **fourth group** contains transitions between *$2p_4$* upper levels to *$1s_2$, $1s_4$, $1s_5$* levels of the lower levels. Only one transition is allowed.

$2p_4 \rightarrow 1s_4$ (1/2[3/2]$_2$→(3/2, 1/2)$_1$)

Forbidden Transition

$2p_4 \rightarrow 1s_5$(1/2[3/2]$_2$→(3/2, 1/2)$_2$)

Forbidden Transition

$2p_4 \rightarrow 1s_2$ (1/2[3/2]$_2$→(1/2, 1/2)$_1$)

$$= (4)(2)(3)(5)\begin{Bmatrix} 3/2 & 1/2 & 2 \\ 1/2 & 1/2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 60$$

Fifth group contains the transitionsfrom the *$2p_5$*upper level and all the four *$1s_2$, $1s_3$, $1s_4$, $1s_5$* lower levels. But only two transitions are possible according to formula.

$2p_5 \rightarrow 1s_2$ (1/2[3/2]$_1$→(1/2, 1/2)$_1$)

$$= (4)(2)(3)(3)\begin{Bmatrix} 3/2 & 1/2 & 1 \\ 1/2 & 1/2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 12$$

$2p_5 \rightarrow 1s_3$ (1/2[3/2]$_1$→(1/2, 1/2)$_0$)

$$= (4)(2)(3)(1)\begin{Bmatrix} 3/2 & 1/2 & 1 \\ 1/2 & 1/2 & 0 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 24$$

$2p_5 \rightarrow 1s_4$(1/2[3/2]$_1$→(3/2, 1/2)$_1$)

Forbidden Transition

$2p_5 \rightarrow 1s_5$(1/2[3/2]$_1$→(3/2, 1/2)$_2$)

Forbidden Transition

Sixth group contains transitions from the *$2p_6$* upper level to the *$1s_2$, $1s_4$, $1s_5$*lower levels. Only two transitions are possible.

$2p_6 \rightarrow 1s_2$ (3/2[3/2]$_2$→(1/2, 1/2)$_1$)

Forbidden Transition

$2p_6 \rightarrow 1s_4$ (3/2[3/2]$_2$→(3/2, 1/2)$_1$)

$$= (4)(2)(3)(5)\begin{Bmatrix} 3/2 & 1/2 & 2 \\ 3/2 & 1/2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 6$$

$2p_6 \rightarrow 1s_5$ (3/2[3/2]$_2$→(3/2, 1/2)$_2$)

$$= (4)(2)(5)(5)\begin{Bmatrix} 3/2 & 1/2 & 2 \\ 3/2 & 1/2 & 2 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 54$$

Seventh group contains transitions from the $2p_7$ upper level and the $1s_2$, $1s_3$, $1s_4$, $1s_5$ lower levels. Two transitions are possible here.

$2p_7 \rightarrow 1s_2$ $(3/2[3/2]_1 \rightarrow (1/2, 1/2)_1)$

Forbidden Transition

$2p_7 \rightarrow 1s_3$ $(3/2[3/2]_1 \rightarrow (1/2, 1/2)_0)$

Forbidden Transition

$2p_7 \rightarrow 1s_4$ $(3/2[3/2]_1 \rightarrow (3/2, 1/2)_1)$

$$= (4)(2)(3)(3)\begin{Bmatrix} 3/2 & 1/2 & 1 \\ 3/2 & 1/2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 30$$

$2p_7 \rightarrow 1s_5$ $(3/2[3/2]_1 \rightarrow (3/2, 1/2)_2)$

$$= (4)(2)(3)(5)\begin{Bmatrix} 3/2 & 1/2 & 1 \\ 3/2 & 1/2 & 2 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 6$$

Eight group contains transitions from $2p_8$ upper level and $1s_2$, $1s_4$, $1s_5$ lower levels. Only two transitions are allowed.

$2p_8 \rightarrow 1s_2$ $(3/2[5/2]_2 \rightarrow (1/2, 1/2)_1)$

Forbidden Transition

$2p_8 \rightarrow 1s_4$ $(3/2[5/2]_2 \rightarrow (3/2, 1/2)_1)$

$$= (6)(2)(5)(3)\begin{Bmatrix} 5/2 & 1/2 & 2 \\ 3/2 & 1/2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 54$$

$2p_8 \rightarrow 1s_5$ $(3/2[5/2]_2 \rightarrow (3/2, 1/2)_2)$

$$= (6)(2)(5)(5)\begin{Bmatrix} 5/2 & 1/2 & 2 \\ 3/2 & 1/2 & 2 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 6$$

Tenth group contains transitionfrom$2p_{10}$upper level and $1s_2$, $1s_3$, $1s_4$ and $1s_5$ lower levels. Only two transitions are allowed.

$2p_{10} \rightarrow 1s_2$ $(3/2[1/2]_2 \rightarrow (1/2, 1/2)_1)$

Forbidden Transition

$2p_{10} \rightarrow 1s_3$ $(3/2[1/2]_2 \rightarrow (1/2, 1/2)_0)$

Forbidden Transition

$2p_{10} \rightarrow 1s_4$ $(3/2[1/2]_2 \rightarrow (3/2, 1/2)_1)$

$2p_{10} \rightarrow 1s_5$ $(3/2[1/2]_2 \rightarrow (3/2, 1/2)_2)$

$$= (2)(2)(3)(3)\begin{Bmatrix} 1/2 & 1/2 & 1 \\ 3/2 & 1/2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 6 = (2)(2)(3)(5)\begin{Bmatrix} 1/2 & 1/2 & 1 \\ 3/2 & 1/2 & 2 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 30$$

jj-j'j'

$$S(j_1 j_2 : j_1' j_2') = \delta_{j_1 j_1'} [j_2, j_2', J, J'] \begin{Bmatrix} j_2 & J & j_1 \\ J' & j_2' & I \end{Bmatrix}^2 \begin{Bmatrix} l_2 & j_2 & s_2 \\ j_2' & l_2' & I \end{Bmatrix}^2$$

In this relation both the upper and the lower level are represented in *jj*-Coupling.

First group contains transitions from the *2p₁* upper level to the *1s₂, 1s₄* lower levels. But only one transition is possible according to above formula.

2p₁→1s₄ ((1/2, 1/2)₀→ (3/2, 1/2)₁)

Forbidden Transition

2p₁→1s₂ ((1/2,1/2)₀→(1/2,1/2)₁)

$$= (2)(2)(1)(3) \begin{Bmatrix} 1/2 & 0 & 1/2 \\ 1 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 12$$

Second group contains transitions from the *2p₂* upper level to the *1s₂, 1s₃, 1s₄,* and *1s₅* lower levels. Only two transitions are possible according to above formula.

2p₂→1s₄((1/2,1/2)₁→(3/2,1/2)₁)

Forbidden Transition

2p₂→1s₅((1/2,1/2)₁→(3/2,1/2)₂)

Forbidden Transition

2p₂→1s₂ ((1/2,1/2)₁→(1/2,1/2)₁)

$$= (2)(3)(3)(2) \begin{Bmatrix} 1/2 & 1 & 1/2 \\ 1 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 24$$

2p₂→1s₃ ((1/2,1/2)₁→(1/2,1/2)₀)

$$= (2)(3)(2) \begin{Bmatrix} 1/2 & 1 & 1/2 \\ 0 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 12$$

Third group contains transitions from the *2p₃* upper level to the *1s₂* and *1s₄* lower levels. Only one transition is allowed.

2p₃→1s₂ ((3/2, 3/2)₀→(1/2,1/2)₁)

Forbidden Transition

2p₃→1s₄ ((3/2, 3/2)₀→(3/2,1/2)₁)

$$= (4)(3)(2) \begin{Bmatrix} 3/2 & 0 & 3/2 \\ 1 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 12$$

The **fourth group** contains transitions between $2p_4$ upper levels to $1s_2$, $1s_4$, $1s_5$ levels of the lower configuration. Only one transition is allowed.

$2p_4 \rightarrow 1s_2$ $((1/2, 3/2)_2 \rightarrow (1/2,1/2)_1)$

$$= (4)(5)(3)(2)\begin{Bmatrix} 3/2 & 2 & 1/2 \\ 1 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 60$$

$2p_4 \rightarrow 1s_4$ $((1/2, 3/2)_2 \rightarrow (3/2,1/2)_1)$

Forbidden Transition

$2p_4 \rightarrow 1s_5$ $((1/2, 3/2)_2 \rightarrow (3/2,1/2)_2)$

Forbidden Transition

Fifth group contains the transitions from $2p_5$upper level to all four $1s_2$, $1s_3$, $1s_4$, $1s_5$ as lower levels. But only two transitions are possible according to formula.

$2p_5 \rightarrow 1s_2$ $((1/2, 3/2)_1 \rightarrow (1/2,1/2)_1)$

$$= (4)(3)(3)(2)\begin{Bmatrix} 3/2 & 1 & 1/2 \\ 1 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 12$$

$2p_5 \rightarrow 1s_3$ $((1/2, 3/2)_1 \rightarrow (1/2,1/2)_0)$

$$= (4)(3)(1)(2)\begin{Bmatrix} 3/2 & 1 & 1/2 \\ 0 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 24$$

$2p_5 \rightarrow 1s_4$ $((1/2, 3/2)_1 \rightarrow (3/2,1/2)_1)$

Forbidden Transition

$2p_5 \rightarrow 1s_5$ $((1/2, 3/2)_1 \rightarrow (3/2,1/2)_2)$

Forbidden Transition

Sixth group contains transitions from the $2p_6$ upper level to the $1s_2$, $1s_4$, $1s_5$lower levels. Only two transitions are possible.

$2p_6 \rightarrow 1s_2$ $((3/2, 3/2)_2 \rightarrow (1/2,1/2)_1)$

Forbidden Transition

$2p_6 \rightarrow 1s_4$ $((3/2, 3/2)_2 \rightarrow (3/2,1/2)_1)$

$$= (4)(5)(3)(2)\begin{Bmatrix} 3/2 & 2 & 3/2 \\ 1 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 30$$

$2p_6 \rightarrow 1s_5$ $((3/2, 3/2)_2 \rightarrow (3/2,1/2)_2)$

$$= (4)(5)(5)(2)\begin{Bmatrix} 3/2 & 2 & 3/2 \\ 2 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 30$$

Seventh group contains transitions from the $2p_7$ upper level to the $1s_2$, $1s_3$, $1s_4$, and$1s_5$ lower levels. Two transitions are possible here.

$2p_7 \rightarrow 1s_2$ $((3/2, 3/2)_1 \rightarrow (1/2,1/2)_1)$

Forbidden Transition

$2p_7 \rightarrow 1s_3$ $((3/2, 3/2)_1 \rightarrow (1/2,1/2)_0)$

Forbidden Transition

$2p_7 \rightarrow 1s_4$ $((3/2, 3/2)_1 \rightarrow (3/2, 1/2)_1)$

$$= (4)(3)(3)(2)\begin{Bmatrix} 3/2 & 1 & 3/2 \\ 1 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 30$$

$2p_7 \rightarrow 1s_5$ $((3/2, 3/2)_1 \rightarrow (3/2,1/2)_2)$

$$= (4)(3)(5)(2)\begin{Bmatrix} 3/2 & 1 & 3/2 \\ 2 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 6$$

Eight group contains transitions form the *$2p_8$* upper level to the *$1s_2$, $1s_4$, $1s_5$* lower levels. Only two transitions are allowed.

$2p_8 \rightarrow 1s_2$ $((3/2,1/2)_2 \rightarrow (1/2,1/2)_1)$

Forbidden Transition

$2p_8 \rightarrow 1s_4$ $((3/2,1/2)_2 \rightarrow (3/2,\ 1/2)_1)$

$$=(2)(5)(3)(2)\begin{Bmatrix} 1/2 & 2 & 3/2 \\ 1 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 3C$$

$2p_8 \rightarrow 1s_5$ $((3/2,1/2)_2 \rightarrow (3/2,1/2)_2)$

$$=(2)(5)(5)(2)\begin{Bmatrix} 1/2 & 2 & 3/2 \\ 2 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 30$$

Tenth group contains transitions from the *$2p_{10}$* upper levels to the *$1s_2$, $1s_3$, $1s_4$* and $1s_5$ lower levels. Only two transitions are allowed.

$2p_{10} \rightarrow 1s_4$ $((3/2,1/2)_1 \rightarrow (3/2,\ 1/2)_1)$

$$=(2)(3)(3)(4)\begin{Bmatrix} 1/2 & 1 & 1/2 \\ 1 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1/2 & 3/2 \\ 3/2 & 0 & 1 \end{Bmatrix}^2 = 6$$

$2p_{10} \rightarrow 1s_5$ $((3/2,\ 1/2)_1 \rightarrow (3/2,1/2)_2)$

$$=(2)(3)(5)(2)\begin{Bmatrix} 1/2 & 1 & 3/2 \\ 2 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1/2 & 1/2 \\ 1/2 & 0 & 1 \end{Bmatrix}^2 = 30$$

$2p_{10} \rightarrow 1s_2$ $((3/2,\ 1/2)_1 \rightarrow (1/2,1/2)_1)$

Forbidden Transition

$2p_{10} \rightarrow 1s_3$ $((3/2,\ 1/2)_1 \rightarrow (1/2,1/2)_0)$

Forbidden Transition

LK-L'K'

$$S(LK:L'K')=[L,L',K,K',J,J']\begin{Bmatrix} K & J & s_2 \\ J' & K' & I \end{Bmatrix}^2 \begin{Bmatrix} L & K & S \\ K' & L' & I \end{Bmatrix}^2 \begin{Bmatrix} l_2 & L & l_1 \\ L' & l'_2 & I \end{Bmatrix}^2$$

To calculate the theoretical line strength in the case where the upper as well as the lower levels are represented in the *LK*-Coupling scheme.

First group contains transition from the $2p_1$ upper level to the $1s_2$, $1s_4$ lower levels. Two transitions are possible according to above formula.

$2p_1 \rightarrow 1s_2$ (S $[1/2]_0 \rightarrow$ P$[1/2]_1$)

$$=(2)(2)(3)(1)(1)(3)\begin{Bmatrix} 1/2 & 0 & 1/2 \\ 1 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 0 & 1/2 & 1/2 \\ 1/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 4$$

$2p_1 \rightarrow 1s_4$ (S $[1/2]_0 \rightarrow$ P$[3/2]_1$)

$$=(2)(4)(3)(1)(1)(3)\begin{Bmatrix} 1/2 & 0 & 1/2 \\ 1 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 0 & 1/2 & 1/2 \\ 3/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 8$$

Second group contains transitions from the $2p_2$ upper level to the $1s_2$, $1s_3$, $1s_4$, and $1s_5$ lower levels. All the four transitions are possible.

$2p_2 \rightarrow 1s_2$(P$[1/2]_1 \rightarrow$ P$[1/2]_1$)

$$=(3)(3)(2)(2)(3)(3)\begin{Bmatrix} 1/2 & 1 & 1/2 \\ 1 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1/2 & 1/2 \\ 1/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 16$$

$2p_2 \rightarrow 1s_3$ (P$[1/2]_1 \rightarrow$ P$[1/2]_0$)

$$=(3)(3)(2)(2)(3)(1)\begin{Bmatrix} 1/2 & 1 & 1/2 \\ 0 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1/2 & 1/2 \\ 1/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 8$$

$2p_2 \rightarrow 1s_4$ (P$[1/2]_1 \rightarrow$P$[3/2]_1$)

$$=(3)(3)(2)(4)(3)(3)\begin{Bmatrix} 1/2 & 1 & 1/2 \\ 1 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1/2 & 1/2 \\ 3/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 2$$

$2p_2 \rightarrow 1s_5$ (P$[1/2]_1 \rightarrow$P$[3/2]_2$)

$$=(3)(3)(2)(4)(3)(5)\begin{Bmatrix} 1/2 & 1 & 1/2 \\ 2 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1/2 & 1/2 \\ 3/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 10$$

Third group contains transitions form the $2p_3$ upper level to the $1s_2$ and $1s_4$ lower levels. Both transitions are allowed here.

$2p_3 \rightarrow 1s_2$ ($P[1/2]_0 \rightarrow P[1/2]_1$)

$$=(2)(3)(2)(3)(3)\begin{Bmatrix}1/2 & 0 & 1/2\\ 1 & 1/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1/2 & 1/2\\ 1/2 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1 & 1\\ 1 & 0 & 1\end{Bmatrix}^2=8$$

$2p_3 \rightarrow 1s_4$ ($P[1/2]_0 \rightarrow P[3/2]_1$)

$$=(2)(3)(4)(3)(3)\begin{Bmatrix}1/2 & 0 & 1/2\\ 1 & 3/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1/2 & 1/2\\ 3/2 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1 & 1\\ 1 & 0 & 1\end{Bmatrix}^2=4$$

The **fourth group** contains transitions between the $2p_4$ upper levels to the $1s_2$, $1s_4$, $1s_5$lower levels.

$2p_4 \rightarrow 1s_2$ ($D\ [3/2]_2 \rightarrow P[1/2]_1$)

$$=(4)(5)(3)(2)(3)(3)\begin{Bmatrix}3/2 & 2 & 1/2\\ 1 & 1/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 3/2 & 1/2\\ 1/2 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1 & 1\\ 1 & 0 & 1\end{Bmatrix}^2=10$$

$2p_4 \rightarrow 1s_4$ ($D\ [3/2]_2 \rightarrow P[3/2]_1$)

$$=(4)(5)(3)(4)(3)(3)\begin{Bmatrix}3/2 & 2 & 1/2\\ 1 & 3/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 3/2 & 1/2\\ 3/2 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1 & 1\\ 1 & 0 & 1\end{Bmatrix}^2=5$$

$2p_4 \rightarrow 1s_5$ ($D\ [3/2]_2 \rightarrow P[3/2]_2$)

$$=(4)(5)(5)(4)(2)(3)\begin{Bmatrix}3/2 & 2 & 1/2\\ 2 & 3/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 3/2 & 1/2\\ 3/2 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1 & 1\\ 1 & 0 & 1\end{Bmatrix}^2=45$$

Fifth group contains transitions form the $2p_5$ upper level to the $1s_2$, $1s_3$, $1s_4$ and $1s_5$ lower levels.

$2p_5 \rightarrow 1s_2$ ($P[3/2]_1 \rightarrow P[1/2]_1$)

$$=(4)(3)(3)(2)(3)(3)\begin{Bmatrix}3/2 & 1 & 1/2\\ 1 & 1/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 3/2 & 1/2\\ 1/2 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1 & 1\\ 1 & 0 & 1\end{Bmatrix}^2=2$$

$2p_5 \rightarrow 1s_3$ ($P[3/2]_1 \rightarrow P[1/2]_0$)

$$=(4)(3)(2)(3)(3)\begin{Bmatrix}3/2 & 1 & 1/2\\ 0 & 1/2 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 3/2 & 1/2\\ 1/2 & 1 & 1\end{Bmatrix}^2\begin{Bmatrix}1 & 1 & 1\\ 1 & 0 & 1\end{Bmatrix}^2=4$$

2p₅→1s₄ (P[3/2]₁→P[3/2]₁)

$$= (4)(3)(3)(4)(3)(3)\begin{Bmatrix} 3/2 & 1 & 1/2 \\ 1 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 1/2 \\ 3/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 25$$

2p₅→1s₅ (P[3/2]₁→P[3/2]₂)

$$= (4)(3)(5)(4)(3)(3)\begin{Bmatrix} 3/2 & 1 & 1/2 \\ 2 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 3/2 & 1/2 \\ 3/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 5$$

Sixth group contains transitions from the $2p_6$ upper level to the $1s_2$, $1s_4$, $1s_5$lower levels.

2p₆→1s₂ (P[3/2]₁→P[1/2]₁)

$$= (4)(5)(3)(2)(5)(3)\begin{Bmatrix} 3/2 & 2 & 1/2 \\ 1 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 2 & 3/2 & 1/2 \\ 1/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 2 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 50$$

2p₆→1s₄ (P[3/2]₁→P[3/2]₁)

$$= (4)(5)(3)(4)(3)(5)\begin{Bmatrix} 3/2 & 2 & 1/2 \\ 1 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 2 & 3/2 & 1/2 \\ 3/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 1$$

2p₆→1s₅ (P[3/2]₁→P[3/2]₂)

$$= (4)(5)(5)(4)(5)(3)\begin{Bmatrix} 3/2 & 2 & 1/2 \\ 2 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 2 & 3/2 & 1/2 \\ 3/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 9$$

Seventh group contains transitions from the $2p_7$ upper level to the $1s_2$, $1s_3$, $1s_4$, and$1s_5$ lower levels.

2p₇→1s₂ (D [3/2]₁→P[1/2]₁)

$$= (4)(3)(3)(2)(5)(3)\begin{Bmatrix} 3/2 & 1 & 1/2 \\ 1 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 2 & 3/2 & 1/2 \\ 1/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 10$$

2p₇→1s₃ (D [3/2]₁→P[1/2]₀)

$$= (4)(3)(2)(5)(3)\begin{Bmatrix} 3/2 & 1 & 1/2 \\ 0 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 2 & 3/2 & 1/2 \\ 1/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 20$$

2p₇→1s₄ (D [3/2]₁→P[3/2]₁)

$$= (4)(3)(3)(4)(5)(3)\begin{Bmatrix} 3/2 & 1 & 1/2 \\ 1 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 2 & 3/2 & 1/2 \\ 3/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 5$$

2p$_7$→1s$_5$ (D [3/2]$_1$→P[3/2]$_2$)

$$= (4)(3)(5)(4)(5)(3)\begin{Bmatrix} 3/2 & 1 & 1/2 \\ 2 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 2 & 3/2 & 1/2 \\ 3/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 1$$

Eight group contains transitions from the *2p$_8$* upper level to the *1s$_2$, 1s$_4$, 1s$_5$* lower levels.

2p$_8$→1s$_4$ (D [5/2]$_2$→P[3/2]$_1$)

$$= (6)(5)(3)(4)(3)(5)\begin{Bmatrix} 5/2 & 2 & 1/2 \\ 1 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 2 & 5/2 & 1/2 \\ 3/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 54$$

2p$_8$→1s$_5$ (D [5/2]$_2$→P[3/2]$_2$)

$$= (6)(5)(5)(4)(5)(3)\begin{Bmatrix} 5/2 & 2 & 1/2 \\ 2 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 2 & 5/2 & 1/2 \\ 3/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 6$$

Tenth group contains transition from the*2p$_{10}$* upper levels to the *1s$_2$, 1s$_3$, 1s$_4$* and *1s$_5$* lower levels.

2p$_{10}$→1s$_2$ (S [1/2]$_1$→P[1/2]$_1$)

$$= (2)(3)(3)(2)(3)\begin{Bmatrix} 1/2 & 1 & 1/2 \\ 1 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 0 & 1/2 & 1/2 \\ 1/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 8$$

2p$_{10}$→1s$_3$ (S [1/2]$_1$→P[1/2]$_0$)

$$= (2)(3)(2)(3)\begin{Bmatrix} 1/2 & 1 & 1/2 \\ 0 & 1/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 0 & 1/2 & 1/2 \\ 1/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 4$$

2p$_{10}$→1s$_4$ (S [1/2]$_1$→P[3/2]$_1$)

$$= (2)(3)(3)(4)(3)\begin{Bmatrix} 1/2 & 1 & 1/2 \\ 1 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 0 & 1/2 & 1/2 \\ 3/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 4$$

2p$_{10}$→1s$_5$ (S [1/2]$_1$→P[3/2]$_2$)

$$= (2)(3)(5)(4)(3)\begin{Bmatrix} 1/2 & 1 & 1/2 \\ 2 & 3/2 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 0 & 1/2 & 1/2 \\ 3/2 & 1 & 1 \end{Bmatrix}^2 \begin{Bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \end{Bmatrix}^2 = 20$$

All these calculations using different coupling schemes are collected in the Table – 4.4. The last column shows the experimentally determined line strengths.

Table 4.4: Comparison of Experimental and Theoretical Line Strength

Transitions	*LS-LS*	*LS-LK*	*LK-LK*	*Jk-Jk*	*jj-jj*	*JK-jj*	*Present Experiment*
$2p_1$-$1s_2$	12	4	4	12	12	12	**11.6**
$1s_4$	……	8	8	……	……	……	**0.4**
Total	**12**	**12**	**12**	**12**	**12**	**12**	**12**
$2p_2$-$1s_2$	……	6	16	24	24	24	**17.07**
$1s_3$	12	12	8	12	12	12	**7.18**
$1s_4$	9	3	2	……	……	……	**3.69**
$1s_5$	15	15	10	……	……	……	**8.06**
Total	**36**	**36**	**36**	**36**	**36**	**36**	**36**
$2P_3$-$1s_2$	…	8	8	……	……	……	**0.39**
$1s_4$	12	4	4	12	12	12	**11.61**
Total	**12**	**12**	**12**	**12**	**12**	**12**	**12**
$2p_4$-$1s_2$	……	10	10	60	60	60	**29.86**
$1s_4$	15	5	5	……	……	……	**16.56**
$1s_5$	45	45	45	……	……	……	**13.58**
Total	**60**	**60**	**60**	**60**	**60**	**60**	**60**
$2p_5$-$1s_2$	36	12	2	12	12	12	**20.11**
$1s_3$	……	……	4	24	24	24	**12.07**
$1s_4$	……	24	25	……	……	……	**0.67**
$1s_5$	……	……	5	……	……	……	**3.16**
Total	**36**	**36**	**36**	**36**	**36**	**36**	**36**
$2p_6$-$1s_2$	60	20	50	……	……	……	**27.08**
$1s_4$	……	40	1	6	30	6	**6.31**
$1s_5$	……	……	9	54	30	54	**26.61**
Total	**60**	**60**	**60**	**60**	**60**	**60**	**60**
$2p_7$-$1s_2$	……	10	10	……	……	……	**1.99**
$1s_3$	20	20	20	……	……	……	**10.92**
$1s_4$	15	5	5	30	30	30	**21.76**
$1s_5$	1	1	1	6	6	6	**1.33**
Total	**36**	**36**	**36**	**36**	**36**	**36**	**36**
$2p_8$-$1s_2$	……	30	……	……	……	……	**4.51**
$1s_4$	45	30	54	54	30	54	**34.94**
$1s_5$	15	……	6	6	30	6	**20.55**
Total	**60**	**60**	**60**	**60**	**60**	**60**	**60**
$2p_{10}$-$1s_2$	……	8	8	……	……	……	**0.39**
$1s_3$	4	4	4	……	……	……	**4.86**
$1s_4$	12	4	4	6	6	6	**11.77**
$1s_5$	20	20	20	30	30	30	**18.98**
Total	**36**	**36**	**36**	**36**	**36**	**36**	**36**

4.5 Comparison of the Theoretical and Experimental Line Strengths:

Equations presented by *Cowan and Andrew* [25] and by *Warner* [11] have been used in calculating the theoretical line strength in various coupling schemes. By applying all the coupling transformation, we calculate the theoretical line strength for each line in the multiplet. These calculated values were compared against the experimentally observed values with the hope that at least one of the coupling schemes would give the values in agreement with those experimental values. For coupling transformation we use the formulas of Brain Warner, which gives the theoretical line strength for each pair. All formulas of coupling transformation involve the *3j, 6j, 9j* symbols [17].The numerical values of these *6j* and *9j* symbols can be calculated with the help of listed values in some dedicated books or using *369j*-calculation calculators available on the net.

There are four levels associated with the $2p^5 3s$ configuration, namely $^3P_{2,1,0}$ and $^1P_1$describedin *LS-Coupling* scheme. There are ten levels associated with the $2p^5 3p$ configuration namely $^3D_{3,2,1}$, $^3P_{2,1,0}$, $^3S_1$ and $^1D_2$, $^1P_1$ and $^1S_0$ represented in *LS* coupling scheme. In the *LS*-coupling scheme, the transitions from singlet to triplet levels are forbidden which restricts the number of allowed transitions that can be experimentally observed. However, we have observed all the transitions connecting the ten upper levels with the four lower levels following the $\Delta J = 0, \pm 1$ selection rules. This experimental evidence of the transitions and their observed intensities tempted us to find out which coupling scheme is more appropriate to describe the levels in these configurations in neon.

There are two lines observed due to transitions from the $2p_1$ upper to the lower levels and their intensities show a slight departure from the *LS*-coupling; may be the *LK*-coupling is more appropriate for the level designations.

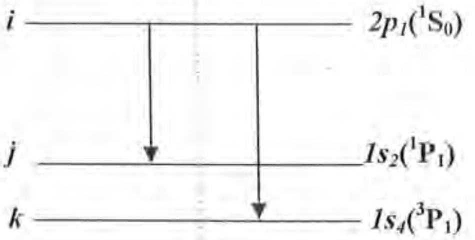
Four transitions have been observed from the $2p_2$ upper level and their lines intensities are close to the situation if the upper as well as lower levels are represented in the *LK*-coupling.

There are two lines observed due to transition from the $2p_3$ upper level to the lower level and their intensities show a slight departure from the *LS*-Coupling.

Therefore, the homogeneous *LS* coupling suggested for the $2p_1$ and $2p_{10}$ transitions; this does indeed yields results in relatively good agreement with the experimentally observed intensities. However for the $2p_2$ through the $2p_9$upper levels, not a single pure-coupling scheme gives intensities of the levels that are close to the experimental values. Thus it seems that no pure coupling scheme will give the general agreement with experiment and thus more sophisticated techniques must be used to describe the levels of neon. One such technique is the intermediate coupling scheme. The overall results show that the level designation coupling lies between *LS* and *LK* schemes.

4.6 Absolute transition probabilities

We have calculated the absolute transition probabilities for all the observed lines of neon using the relations mentioned above. The calculations of transition probabilities for all the ten upper levels are given below. The **First group** contains transitions between $2p^5 3p\ ^1S_0 \rightarrow 2p^5 3s\ ^1P_1$ and $^3P_1$ have been observed at 585.4 nm and 540.2 nm respectively represented in LS coupling designation and in Paschen notation from the $2p_1$ upper level and $1s_2$, $1s_4$ as the lower level. The transitions and the calculated transition probabilities are given in the table below and the procedure of calculations is also listed:



Transitions	*Wavelength*	*Intensity*	$A\times10^6$
$2p_1 \rightarrow 1s_2$	*585.3*	*998.8*	**65.93**
$\rightarrow 1s_4$	*540.1*	*46.03*	**3.03**
Total			**68.96**

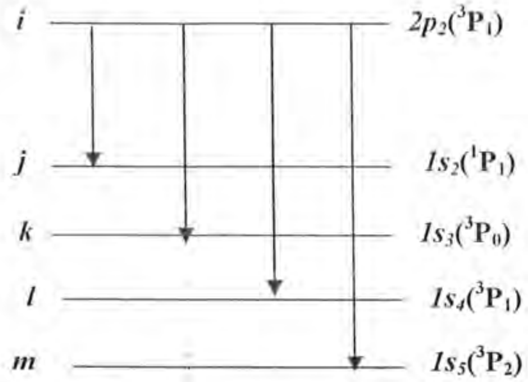
$2p_1 \rightarrow 1s_2\ (^1S_0 \rightarrow {}^1P_1)$

$A_{ij} = [\tau_i\,(1+I_{ij}/I_{ik})]^{-1} = [14.5\times10^{-9}(1+655.3/27.3)]^{-1} = 65.932\times10^6$

$2p_1 \rightarrow 1s_4\ (^1S_0 \rightarrow {}^3P_1)$

$A_{ik} = [\tau_i\,(1+I_{ij}/I_{ik})]^{-1} = [14.5\times10^{-9}(1+27.3/655.3)]^{-1} = 3.03\times10^6$

Second group involve transitions from $2p_2$ as upper level and $1s_2$, $1s_3$, $1s_4$, and $1s_5$ as the lower level.The transitions, their wavelengths and the calculated transition probabilities are given below along with the detailed calculation procedure.



Transitions	*Wavelength*	*Intensity*	$A\times10^6$
$2p_2\rightarrow1s_2$	*659.9*	*1054.31*	***21.93***
$\rightarrow1s_3$	*616.4*	*544.11*	***11.32***
$\rightarrow1s_4$	*603.0*	*298.94*	***6.22***
$\rightarrow1s_5$	*588.2*	*701.36*	***14.59***
Total			***54.06***

$2p_2\rightarrow1s_2(^3P_1\rightarrow{}^1P_1)$

$A_{ij}=[\tau_i(1+I_{ik}/I_{ij}+I_{il}/I_{ij}+I_{im}/I_{ij})]^{-1}$

$=[18.5\times10^{-9}(1+544.11/1054.31+298.94/1054.31+701.36/1054.31)]^{-1}=21.93\times10^6$

$2p_2\rightarrow1s_3\,(^3P_1\rightarrow{}^3P_0)$

$A_{ik}=[\tau_i(1+I_{ij}/I_{ik}+I_{il}/I_{ik}+I_{im}/I_{ik})]^{-1}$

$=[18.5\times10^{-9}(1+1054.31/544.11+298.94/544.11+701.36/544.11)]^{-1}=11.32\times10^6$

$2p_2\rightarrow1s_4\,(^3P_1\rightarrow{}^3P_1)$

$A_{il}=[\tau_i(1+I_{ik}/I_{il}+I_{ij}/I_{il}+I_{im}/I_{il})]^{-1}$

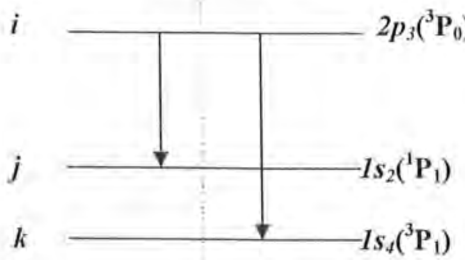
$=[18.5\times10^{-9}(1+544.11/298.94+1054.31/298.94+701.36/298.94)]^{-1}=6.22\times10^6$

$2p_2\rightarrow1s_5\,(^3P_1\rightarrow{}^3P_2)$

$A_{im}=[\tau_i(1+I_{ij}/I_{im}+I_{ik}/I_{im}+I_{il}/I_{im})]^{-1}$

$=[18.5\times10^{-9}(1+1054.31/701.36+544.11/701.36+298.94/701.36)]^{-1}=14.59\times10^6$

Third group involves transitions from the $2p_3$ as upper level and $1s_2$, $1s_4$ as the lower level. Schematic transitions, wavelengths, observed line intensities and calculated transitions probabilities are given below:



Transitions	*Wavelength*	*Intensity*	$A\times10^6$
$2P_3\rightarrow1s_2$	*665.2*	*23.86*	*1.53*
$\rightarrow1s_4$	*607.5*	*865.66*	*55.61*
Total			*57.14*

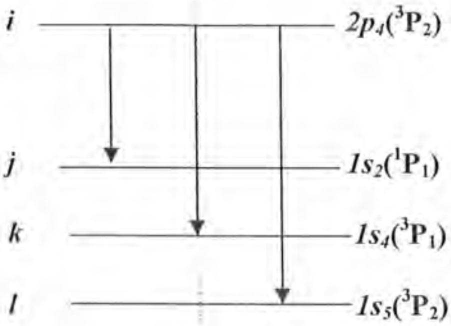
$2p_3 \rightarrow 1s_2\ (^3P_0 \rightarrow {}^1P_1)$

$A_{ij}= [\tau_i(1+ I_{ik}/I_{ij})]^{-1}=[17.5\times10^{-9}(1+862/22)]^{-1}=1.53\times10^6$

$2p_3 \rightarrow 1s_4\ (^3P_0 \rightarrow {}^3P_1)$

$A_{ik}= [\tau_i(1+ I_{ij}/I_{ik})]^{-1}=[17.5\times10^{-9}(1+22/862)]^{-1}=55.61\times10^6$

Fourth group involve transitions from the$2p_4$ as the upper level and $1s_2$, $1s_4$, $1s_5$ as the lower levels. Measurements of both these transitions involving different wavelengths including intensities at each wavelength are given below



Transitions	*Wavelength*	*Intensity*	***A×10⁶***
$2p_4 \rightarrow 1s_2$	*667.8*	*1567.39*	***21.71***
$\rightarrow 1s_4$	*609.6*	*1143.6*	***15.84***
$\rightarrow 1s_5$	*594.5*	*1010.94*	***14***
Total			***51.55***

$2p_4 \rightarrow 1s_2\ (^3P_2 \rightarrow {}^1P_1)$

$A_{ij}= [\tau_i(1+ I_{ik}/I_{ij}+I_{il}/I_{ij})]^{-1}=[19.4\times10^{-9}(1+1143.6/1567.39+1010.94/1567.39)]^{-1}=21.71\times10^6$

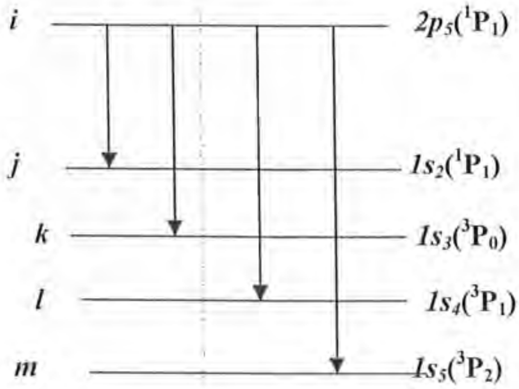
$2p_4 \rightarrow 1s_4\ (^3P_2 \rightarrow {}^3P_1)$

$A_{ik}= [\tau_i(1+ I_{ij}/I_{ik}+I_{il}/I_{ik})]^{-1}=[19.4\times10^{-9}(1+1567.39/1143.6+1010.94/1143.6)]^{-1}=15.84\times10^6$

$2p_4 \rightarrow 1s_5\ (^3P_2 \rightarrow {}^3P_2)$

$A_{im}= [\tau_i(1+ I_{ij}/I_{il}+I_{ik}/I_{il})]^{-1}=[19.4\times10^{-9}(1+1567.39/1010.94+1143.6/1010.94)]^{-1}=14\times10^6$

Fifth group involve $2p_5$ transitions from the upper level and $1s_2$, $1s_3$, $1s_4$, and $1s_5$ as the lower level. Transition probabilities for all these transitions are given below



Transitions	*Wavelength*	*Intensity*	***A×10⁶***
$2p_5 \rightarrow 1s_2$	*671.7*	*986.78*	***25.17***
$\rightarrow 1s_3$	*626.6*	*729.51*	***18.61***
$\rightarrow 1s_4$	*612.8*	*43.23*	***1.11***
$\rightarrow 1s_5$	*597.6*	*220.39*	***5.62***
Total			***50.51***

$2p_5 \rightarrow 1s_2\,(^1P_1 \rightarrow {}^1P_1)$

$A_{ij}= [\tau_i(1+ I_{ik}/I_{ij}+I_{il}/I_{ij}+ I_{im}/I_{ij})]^{-1}$

$=[19.8\times10^{-9}(1+729.51/986.78+43.23/986.78+220.39/986.78)]^{-1}=25.17\times10^{6}$

$2p_5 \rightarrow 1s_3\,(^1P_1 \rightarrow {}^3P_0)$

$A_{ik}= [\tau_i(1+ I_{ij}/I_{ik}+I_{il}/I_{ik}+ I_{im}/I_{ik})]^{-1}$

$=[19.8\times10^{-9}(1+986.78/729.51+43.23/729.51+220.29/729.51)]^{-1}=18.61\times10^{6}$

$2p_5 \rightarrow 1s_4\,(^1P_1 \rightarrow {}^3P_1)$

$A_{il}= [\tau_i(1+ I_{ik}/I_{il}+I_{ij}/I_{il}+ I_{im}/I_{il})]^{-1}$

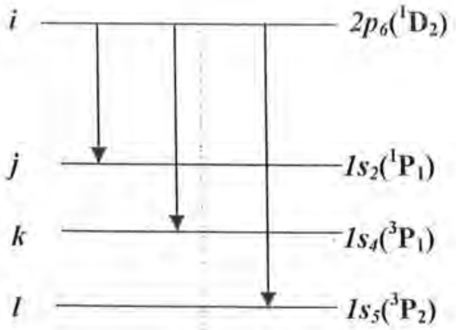
$=[19.8\times10^{-9}(1+729.51/43.23+986.78/43.23+220.29/43.23)]^{-1}=1.11\times10^{6}$

$2p_5 \rightarrow 1s_5\,(^1P_1 \rightarrow {}^3P_2)$

$A_{im}= [\tau_i(1+ I_{ij}/I_{im}+I_{ik}/I_{im}+ I_{il}/I_{im})]^{-1}$

$= [19.8\times10^{-9}(1+986.78/220.29+729.51/220.29+43.23/220.29)]^{-1}=5.62\times10^{6}$

Sixth group involve transitions $2p_6$ as upper level and $1s_2$, $1s_4$and $1s_5$as lower level. Measurement of these transition probabilities at different wavelengths are given below



Transitions	*Wavelength*	*Intensity*	$A\times10^{6}$
$2p_6 \rightarrow 1s_2$	692.9	988.35	18.77
$\rightarrow 1s_4$	630.5	305.37	5.79
$\rightarrow 1s_5$	614.3	1393.09	26.45
Total			51.01

$2p_6 \rightarrow 1s_2\,(^1D_2 \rightarrow {}^1P_1)$

$A_{ij}= [\tau_i(1+ I_{ik}/I_{ij}+I_{il}/I_{ij})]^{-1}$

$=[19.6\times10^{-9}(1+988.35/305.37+1393.09/305.37)]^{-1}=18.77\times10^{6}$

$2p_6 \rightarrow 1s_4\,(^1D_2 \rightarrow {}^3P_1)$

$A_{ik}= [\tau_i(1+ I_{ij}/I_{ik}+I_{il}/I_{ik})]^{-1}$

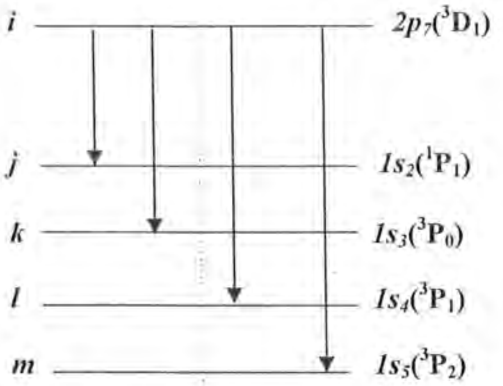
$=[19.6\times10^{-9}(1+988.35/305.37+1393.09/305.37)]^{-1}=5.79\times10^{6}$

$2p_6 \rightarrow 1s_5\ (^1D_2 \rightarrow {}^3P_2)$

$A_{im} = [\tau_i(1 + I_{ij}/I_{il} + I_{ik}/I_{il})]^{-1}$

$= [19.6\times10^{-9}(1+988.35/1393.09+305.37/1393.09)]^{-1} = 26.45\times10^{6}$

Seventh group contain transitions from the $2p_7$ as upper level and $1s_2$, $1s_3$, $1s_4$ and $1s_5$ as the lower levels. Absolute transition probabilities for all these transitions are given below



Transitions	*Wavelength*	*Intensity*	$A\times10^6$
$2p_7 \rightarrow 1s_2$	*703.3*	*84.79*	***2.19***
$\rightarrow 1s_3$	*653.3*	*577.52*	***14.92***
$\rightarrow 1s_4$	*638.3*	*1232.55*	***31.83***
$\rightarrow 1s_5$	*621.7*	*80.83*	***2.08***
Total			***51.02***

$2p_7 \rightarrow 1s_2\ (^3D_1 \rightarrow {}^1P_1)$

$A_{ij} = [\tau_i(1 + I_{ik}/I_{ij} + I_{il}/I_{ij} + I_{im}/I_{ij})]^{-1}$

$= [19.6\times10^{-9}(1+577.52/84.79+1232.55/84.79+80.83/84.79)]^{-1} = 2.19\times10^{6}$

$2p_7 \rightarrow 1s_3\ (^3D_1 \rightarrow {}^3P_0)$

$A_{ik} = [\tau_i(1 + I_{ij}/I_{ik} + I_{il}/I_{ik} + I_{im}/I_{ik})]^{-1}$

$= [19.6\times10^{-9}(1+84.79/577.52+1232.55/577.52+80.83/577.52)]^{-1} = 14.92\times10^{6}$

$2p_7 \rightarrow 1s_4\ (^3D_1 \rightarrow {}^3P_1)$

$A_{il} = [\tau_i(1 + I_{ik}/I_{il} + I_{ij}/I_{il} + I_{im}/I_{il})]^{-1}$

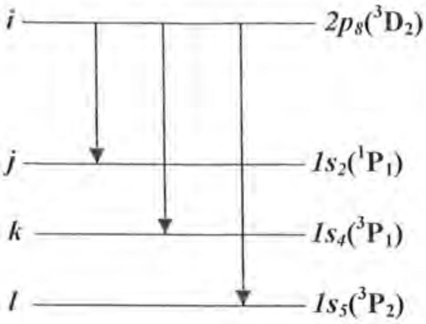
$= [19.6\times10^{-9}(1+577.52/1232.55+84.79/1232.55+80.83/1232.55)]^{-1} = 31.83\times10^{6}$

$2p_7 \rightarrow 1s_5\ (^3D_1 \rightarrow {}^3P_2)$

$A_{im} = [\tau_i(1 + I_{ij}/I_{im} + I_{ik}/I_{im} + I_{il}/I_{im})]^{-1}$

$= [19.6\times10^{-9}(1+986.78/220.29+729.51/220.29+43.23/220.29)]^{-1} = 2.08\times10^{6}$

Eight groups contains transitions from the $2p_8$ as upper level and $1s_2$, $1s_4$, and $1s_5$. Transition probabilities for all these three transitions are given below



Transitions	*Wavelength*	*Intensity*	*A×10^6*
$2p_8 \rightarrow 1s_2$	717.4	163.6	2.69
$\rightarrow 1s_4$	650.6	1701.42	28.02
$\rightarrow 1s_5$	633.5	1083.14	17.84
Total			48.55

$2p_8 \rightarrow 1s_2\,(^3D_2 \rightarrow {}^1P_1)$

$A_{ij}= [\tau_i(1+ I_{ik}/I_{ij}+I_{il}/I_{ij})]^{-1}$

$=[19.6\times10^{-9}(1+1701.42/163.6+1083.14/163.6)]^{-1}=2.69\times10^{6}$

$2p_8 \rightarrow 1s_4(^3D_2 \rightarrow {}^3P_1)$

$A_{ik}= [\tau_i(1+ I_{ij}/I_{ik}+I_{il}/I_{ik})]^{-1}$

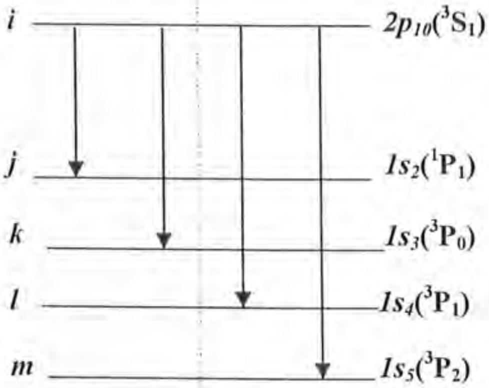
$=[19.6\times10^{-9}(1+163.6/1701.42+1083.14/1701.42)]^{-1}=28.02\times10^{6}$

$2p_8 \rightarrow 1s_5\,(^3D_2 \rightarrow {}^3{}_2)$

$A_{il}= [\tau_i(1+ I_{ij}/I_{il}+I_{ik}/I_{il})]^{-1}$

$= [19.6\times10^{-9}(1+163.6/1083.14+1701.42/1083.14)]^{-1}=17.84\times10^{6}$

Eight group contains transitions from the $2p_{10}$ as upper level and $1s_2$, $1s_3$, $1s_4$, and $1s_5$ as the lower level. Measurements of these absolute transitions are given below



Transitions	*Wavelength*	*Intensity*	*A×10^6*
$2p_{10} \rightarrow 1s_2$	808.3	23.49	0.29
$\rightarrow 1s_3$	743.9	379.53	4.77
$\rightarrow 1s_4$	724.5	982.58	12.36
$\rightarrow 1s_5$	703.3	1683.57	21.18
Total			38.6

$2p_{10} \rightarrow 1s_2\,(^3S_1 \rightarrow {}^1P_1)$

$A_{ij}= [\tau_i(1+ I_{ik}/I_{ij}+I_{il}/I_{ij}+ I_{im}/I_{ij})]^{-1}$

$= [26.45\times10^{-9}(1+411.51/26+1078.62/26+1902.49/26)]^{-1}=.29\times10^{6}$

$2p_{10}\rightarrow 1s_3\ (^3S_1\rightarrow {}^3P_0)$

$A_{ik}= [\tau_i(1+ I_{ij}/I_{ik}+I_{il}/I_{ik}+ I_{im}/I_{ik})]^{-1}$

$= [26.45\times10^{-9}(1+26/411.51+1078.62/411.51+1902.49/411.51)]^{-1}=4.77\times10^6$

$2p_{10}\rightarrow 1s_4\ (^3S_1\rightarrow {}^3P_1)$

$A_{il}= [\tau_i(1+ I_{ik}/I_{il}+I_{ij}/I_{il}+ I_{im}/I_{il})]^{-1}$

$=[26.45\times10^{-9}(1+411.51/1078.62+26/1078.62+1902.49/1078.62)]^{-1}=12.36\times10^6$

$2p_{10}\rightarrow 1s_5\ (^3S_1\rightarrow {}^3P_2)$

$A_{im}= [\tau_i(1+ I_{ij}/I_{im}+I_{ik}/I_{im}+ I_{il}/I_{im})]^{-1}$

$= [26.45\times10^{-9}(1+26/1902.49+411.51/1902.49+1078.62/1902.49)]^{-1}=21.18\times1$

All these calculations of absolute transition probabilities are collected in the Table – 4.5. We compare our calculated results with the results of the previous papers.

Table 4.5: Absolute Transition Probabilities

Transitions	Wavelength A^0	Intensity a.u	Present Experiment $A*10^6$	Nodwell[27] $A*10^6$	Ellis[3] $A*10^6$	Wiese[5] $A*10^6$	Miller[8] $A*10^6$	Holmes[9] $A*10^6$	Life Time[12] τ(ns)
$2p_1$-$1s_2$	585.25	998.77	**65.93**	65.8	68.68	68.6	73	68.2	**14.5**
$1s_4$	540.056	46.03	**3.03**	…	0.76	0.88	0.13	0.9	
Total			**68.96**	**65.8**	**69.44**	**69.48**	**73.13**	**69.1**	
$2p_2$-$1s_2$	659.89	1054.31	**21.93**	22.4	23.45	23	24.4	23.2	**18.5**
$1s_3$	616.36	544.11	**11.32**	13.5	14.94	14.4	17.3	14.6	
$1s_4$	602.99	298.94	**6.22**	…	4.46	5.23	6.2	5.61	
$1s_5$	588.19	701.36	**14.59**	10.34	10.34	10.4	12.2	11.5	
Total			**54.06**	**46.24**	**53.19**	**53.03**	**60.1**	**54.91**	
$2P_3$-$1s_2$	665.21	23.86	**1.53**	0.85	0.85	0.33	…	0.29	**17.5**
$1s_4$	607.44	865.66	**55.61**	58	55.82	56.5	59	60.3	
Total			**57.14**	**58.85**	**56.67**	**56.83**	**59**	**60.59**	
$2p_4$-$1s_2$	667.83	1567.39	**21.71**	21	25.01	23.1	26.4	23.3	**19.4**
$1s_4$	609.62	1143.6	**15.84**	16.8	16.61	18	17.2	18.1	
$1s_5$	594.48	1010.94	**14**	9.9	10.73	11.3	10.7	11.3	
Total			**51.55**	**47.7**	**52.35**	**52.4**	**54.3**	**52.7**	
$2p_5$-$1s_2$	671.71	986.78	**25.17**	20	21.99	21.2	25.6	21.7	**19.8**
$1s_3$	626.65	729.51	**18.61**	20.3	24.2	24.9	23.5	24.9	
$1s_4$	612.85	43.23	**1.11**	…	0.57	0.68	…	0.67	
$1s_5$	597.55	220.39	**5.62**	…	3.5	3.41	3.9	3.51	
Total			**50.51**	**40.3**	**50.26**	**50.19**	**53**	**50.78**	
$2p_6$-$1s_2$	692.95	988.35	**18.77**	16.5	17.89	17.6	21.1	17.4	**19.6**
$1s_4$	630.48	305.37	**5.79**	4.8	3.99	4.27	4.9	4.16	
$1s_5$	614.31	1393.09	**26.45**	22	28.88	28.8	27.6	28.2	
Total			**51.01**	**43.3**	**50.76**	**50.67**	**53.6**	**49.76**	
$2p_7$-$1s_2$	703.24	84.79	**2.19**	…	1.87	1.95	…	1.89	**19.6**
$1s_3$	653.29	577.52	**14.92**	…	9.87	10.6	15.4	10.8	
$1s_4$	638.3	1232.55	**31.83**	29.7	30.73	31.6	22.9	32.1	
$1s_5$	621.73	80.83	**2.08**	7	7.77	6.02	9.5	6.37	
Total			**51.02**	**36.7**	**50.24**	**50.17**	**47.8**	**51.16**	
$2p_8$-$1s_2$	717.39	163.6	**2.69**	…	3.29	3.17	4.5	2.87	**20.6**
$1s_4$	650.65	1701.42	**28.02**	30.81	30.81	29.5	25.4	30	
$1s_5$	633.44	1083.14	**17.84**	3.29	16.41	17.8	14.6	16.1	
Total			**48.55**	**34.1**	**50.51**	**50.47**	**44.5**	**48.97**	
$2p_9$-$1s_5$	640.48	2390.74	**52.08**	…	…	**50.6**	…	**50.6**	**19.2**
$2p_{10}$-$1s_2$	808.25	23.49	**0.29**	…	0.42	0.13	…	0.12	**25.9**
$1s_3$	743.89	379.53	**4.77**	…	3.34	2.58	3.8	2.31	
$1s_4$	724.52	982.58	**12.36**	9.6	9.11	10.7	9.5	9.35	
$1s_5$	703.24	1683.57	**21.18**	19.8	27.46	27	20.6	25.3	
Total			**38.6**	**29.4**	**40.33**	**40.41**	**33.9**	**37.08**	

By combining the branching ratio data as obtained above with the life time values that we take from the literature we have deduced the experimental transitions proababilities of *30* spectral lines of neon for the $2p^5 3p$-$2p^5 3s$ configuration and compared our values with the avaiable data in the literature (*Nodwel et al*[27], *Wiese*[5], *Miller et al* [4], *Ellis et al*[3]and *Holmes et al* [6]). The transition probabilities have been determined by using the *eq (8)* in the previous chapter.We apply the summation of *eq (8)* in the same way as we apply it to calculate the relative line strenght. Summation in that relation applies in such a way that the denominator remains fix and the summation applies on the numinator. The life times for the upper levels have been taken from *Fujimoto* [12]. For the $^3D_3$ level we just have one transition $(^3D_3 \rightarrow {}^3P_2)$ and to evaluate the transition probability of this transition we just take the inverse of the life time for that level, which gives the transition probability for that level. If we sum up all the transitions for each level and then take its inverse, we can determine the life time for that level using the relation:

$$\tau_i = \frac{1}{\sum_j A_{ij}}$$

The intensities of each spectral line have also been given in above table. The intensities that we have extracted from spectrum also gives us the idea about their transition probability. We note that the transitions which possess higher intensities are the most probable transitions i.e. have larger transition probabilities.

4.7 Conclusion

Branching ratios of intensities for *30* spectral lines of neon are measured from the laser of the produced neon plasma. These measured intensities are transformed into relative line strengths. The relative line strengths have been compared with the previously reported values. The experimental line strengths have also been compared with the *J-File* Sum Rule, that are in good agreement with the theoretically calculated values. In addition, we have determined the theoretical line strengths by using the Warner [11] *and Cowan Andrew* [14] relations involving *3j, 6j, 9j* [17] symbols. Using same or different coupling schemes for the upper level as well as the lower level, we have calculated the line strengths which are compared with the experimentally determined line strengths. From this comparison, we can predict the best coupling scheme to be used for the level designations in neon for these transitions. It is found that the *LK* coupling for the lower level as well as for the upper level gives better line strengths than any other combination of coupling schemes. The relative line strength also gives us the information about the absolute transition probabilities; the transitions which are intense are the most probable transitions. Absolute transition probabilities of *30* spectral lines of *Ne* can be determined by using two methods. The first method involves the life time of upper level and branching ratios of intensities, and finally the inverse of product of branching ratios and life time gives us the transition probability. The second method involves the experimentally measured relative line strengths and calculated R_{ij} in Coulomb Approximation (Bates et al) reported in the literature. In this thesis, we have used the first method and determined the absolute transition probabilities for *30* allowed spectral lines of neon by using the known life times of the upper levels.

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