CHAPTER 8

Electronic Spectra of Transition Metal Complexes:

❖ Spectroscopic Ground States

The spectra of transition metal complexes is not as simple as it appears from just the splitting of $d$-orbitals with electrons get promoted from the lower energy orbital set to a higher energy orbital set. Actually, energy levels of a transition metal atom or ion with a particular electronic configuration are described not only by the electronic configuration itself but also by different types of electronic interactions such as spin-spin, orbital-orbital or spin-orbital which can be categorized by some special symbols, called as term symbols. The ground state term symbol is predicted by Hund's rule. In other words, the term symbol in quantum mechanics is an abbreviated description of the total angular momentum quantum numbers in a multi-electron atom. However, the quantum mechanical states of a single electron can also be described by a term symbol.

❖ Calculation of Microstates in a Particular Electronic Configuration

The various overall-arrangements of electronic cloud around the nucleus for a particular configuration are not the same as far as the energy and angular momentum are concerned. These different electronic arrangements can be classified on the basis of overall spin, orbital or total angular momentum.

The term microstates may be defined as the overall electronic arrangements of a particular electronic configuration which can be differentiated in terms of energy or angular momentum.

The two types of electronic configurations for which the microstate calculation has to be carried out are discussed below.

1. When unpaired electrons are present in the same subshell:
   i) $p^{\uparrow}$-configuration: Let us consider that we want to study the number of ways in which a single electron can be filled in any $p$-subshell.

   \[
   \begin{array}{ccc}
   1 & \uparrow & \\
   2 & \downarrow & \\
   3 & \uparrow & \\
   4 & \downarrow & \\
   5 & \uparrow & \\
   6 & \downarrow & \\
   \end{array}
   \]

   \[
   p_x \quad p_y \quad p_z
   \]
ii) \(p^2\)-configuration: Let us consider that we want to study the number of ways in which two electrons can be filled in any \(p\)-subshell.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>↑</td>
</tr>
<tr>
<td>2</td>
<td>↑</td>
</tr>
<tr>
<td>3</td>
<td>↑</td>
</tr>
<tr>
<td>4</td>
<td>↓</td>
</tr>
<tr>
<td>5</td>
<td>↓</td>
</tr>
<tr>
<td>6</td>
<td>↓</td>
</tr>
<tr>
<td>7</td>
<td>↑</td>
</tr>
<tr>
<td>8</td>
<td>↑</td>
</tr>
<tr>
<td>9</td>
<td>↑</td>
</tr>
<tr>
<td>10</td>
<td>↑</td>
</tr>
</tbody>
</table>

Hence, the total number of ways in which one and two electrons can be arranged in the \(p\)-subshell of an atom or ion are six and fifteen, respectively. However, the calculation of the number of microstates for the configurations like \(d^2\) or \(f^2\) using the abovementioned method is quite lengthy and difficult. Moreover, as we are interested only in the number of these electronic arrangements and not in the nature; permutation and combination can be used to find out all these numbers as follows:

\[
\text{No. of microstates} = \binom{n}{r} = \frac{n!}{r!(n-r)!}
\]

Where \(n\) is twice the number of orbitals present in the subshell under consideration and \(r\) is the number of unpaired electrons in them. The formulation related to the calculation of the number of microstate in particular term symbol will be discussed later in this chapter.
Now, the number of microstates for different electronic configurations can be calculated easily.

i) For $p^1$-configuration, $n = 6$ and $r = 1$. Therefore

$$\text{No. of microstates} = \binom{6}{1} = \frac{6!}{1!(6-1)!}$$

$$\binom{6}{1} = \frac{6 \times 5 \times 4 \times 3 \times 2 \times 1}{1(5 \times 4 \times 3 \times 2 \times 1)}$$

$$= 6 \text{ microstates}$$

ii) For $p^2$-configuration, $n = 6$ and $r = 2$. Therefore

$$\text{No. of microstates} = \binom{6}{2} = \frac{6!}{2!(6-2)!}$$

$$\binom{6}{2} = \frac{6 \times 5 \times 4 \times 3 \times 2 \times 1}{2 \times 1(4 \times 3 \times 2 \times 1)}$$

$$= 15 \text{ microstates}$$

iii) For $d^1$-configuration, $n = 10$ and $r = 1$. Therefore

$$\text{No. of microstates} = \binom{10}{1} = \frac{10!}{1!(10-1)!}$$

$$\binom{10}{1} = \frac{10 \times 9 \times 8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1}{1(9 \times 8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1)}$$

$$= 10 \text{ microstates}$$

iv) For $d^2$-configuration, $n = 10$ and $r = 2$. Therefore

$$\text{No. of microstates} = \binom{10}{2} = \frac{10!}{2!(10-2)!}$$

$$\binom{10}{2} = \frac{10 \times 9 \times 8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1}{2 \times 1(8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1)}$$

$$= 45 \text{ microstates}$$

The general form of atomic term symbols considers spin-spin (S-S coupling), orbital-orbital (L-L coupling) and spin-orbital (L-S or Russell-Saunders coupling) interactions; therefore, before categorizing all the microstates in these term symbols, it is extremely important to find out all possible microstates for different electronic configurations. The total number of microstates for other different electronic configurations can be calculated using the same method and are listed below.
Table 1. The calculated microstates for different electronic configurations.

<table>
<thead>
<tr>
<th>Electronic configuration</th>
<th>No. of microstates</th>
<th>Electronic configuration</th>
<th>No. of microstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p^1$</td>
<td>6</td>
<td>$d^3$</td>
<td>120</td>
</tr>
<tr>
<td>$p^2$</td>
<td>15</td>
<td>$d^4$</td>
<td>210</td>
</tr>
<tr>
<td>$p^3$</td>
<td>20</td>
<td>$d^5$</td>
<td>252</td>
</tr>
<tr>
<td>$p^4$</td>
<td>15</td>
<td>$d^6$</td>
<td>210</td>
</tr>
<tr>
<td>$p^5$</td>
<td>6</td>
<td>$d^7$</td>
<td>120</td>
</tr>
<tr>
<td>$p^6$</td>
<td>1</td>
<td>$d^8$</td>
<td>45</td>
</tr>
<tr>
<td>$d^1$</td>
<td>10</td>
<td>$d^9$</td>
<td>1</td>
</tr>
<tr>
<td>$d^2$</td>
<td>45</td>
<td>$d^{10}$</td>
<td></td>
</tr>
</tbody>
</table>

It can be seen that the number of microstates for the same number of unpaired electrons is equal. For example, there are six microstates for $p^1$ as well as $p^5$ and forty-five microstates for both $d^2$ as well as $d^8$. It can be explained in terms of electron-hole formalism which will be discussed later in this chapter.

2. When unpaired electrons are present in different subshell:

The same approach can also be applied to calculate the microstates in the case when the electrons are present in two different subshells. Therefore, permutation and combination can be used to find out all these numbers as follows:

$$\text{No. of microstates} = \binom{n}{r} \times \binom{m}{s} = \frac{n!}{r! (n-r)!} \times \frac{m!}{s! (m-s)!}$$

Where, $n$ is twice the number of orbitals and $r$ is the number of unpaired electrons in one subshell while $m$ is twice the number of orbitals and $s$ is the number of unpaired electrons in the other subshell. Now, the number of microstates for different electronic configurations can be calculated easily.

i) $p^1 p^1$-configuration, $n = 6$, $r = 1$, $m = 6$ and $s = 1$.

$$\text{No. of microstates} = \binom{6}{1} \times \binom{6}{1} = \frac{6!}{1! (6-1)!} \times \frac{6!}{1! (6-1)!}$$

$$\binom{6}{1} \times \binom{6}{1} = \frac{6 \times 5 \times 4 \times 3 \times 2 \times 1}{1 (5 \times 4 \times 3 \times 2 \times 1)} \times \frac{6 \times 5 \times 4 \times 3 \times 2 \times 1}{1 (5 \times 4 \times 3 \times 2 \times 1)}$$

$$= 36 \text{ microstates}$$
ii) $d^1d^1$-configuration, $n = 10$, $r = 1$, $m = 10$ and $s = 1$.

\[
\text{No. of microstates} = \binom{10}{1} \times \binom{10}{1} = \frac{10!}{1!(10-1)!} \times \frac{1!(10-1)!}{1!(10-1)!} \\
\left(\frac{10}{1}\right) \times \left(\frac{10}{1}\right) = \frac{10 \times 9 \times 8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1}{1(9 \times 8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1)} \times \frac{10 \times 9 \times 8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1}{1(9 \times 8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1)} = 100 \text{ microstates}
\]

iii) $p^1d^1$-configuration, $n = 6$, $r = 1$, $m = 10$ and $s = 1$.

\[
\text{No. of microstates} = \binom{6}{1} \times \binom{10}{1} = \frac{6!}{1!(6-1)!} \times \frac{10!}{1!(10-1)!} \\
\left(\frac{6}{1}\right) \times \left(\frac{10}{1}\right) = \frac{6 \times 5 \times 4 \times 3 \times 2 \times 1}{1(5 \times 4 \times 3 \times 2 \times 1)} \times \frac{10 \times 9 \times 8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1}{1(9 \times 8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1)} = 60 \text{ microstates}
\]

The total number of microstates for different electronic configurations can be calculated using the same method and are listed below.

<table>
<thead>
<tr>
<th>Electronic configuration</th>
<th>No. of microstates</th>
<th>Electronic configuration</th>
<th>No. of microstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p^1p^1$</td>
<td>36</td>
<td>$d^1d^1$</td>
<td>2025</td>
</tr>
<tr>
<td>$p^1p^2$</td>
<td>90</td>
<td>$d^1d^1$</td>
<td>5400</td>
</tr>
<tr>
<td>$p^2p^3$</td>
<td>225</td>
<td>$p^1d^1$</td>
<td>60</td>
</tr>
<tr>
<td>$p^2p^3$</td>
<td>300</td>
<td>$p^1d^2$</td>
<td>270</td>
</tr>
<tr>
<td>$d^1d^1$</td>
<td>100</td>
<td>$p^2d^1$</td>
<td>675</td>
</tr>
<tr>
<td>$d^1d^2$</td>
<td>450</td>
<td>$p^2d^2$</td>
<td>1800</td>
</tr>
</tbody>
</table>

This table can further be extended for the remaining combination of $p-p$, $d-d$, $p-d$ or their combinations with $f$-subshell. The number of microstates in particular configuration can be distributed to various electronic states, represented by atomic term symbols. The distribution of these microstates in different term symbols will be discussed later in this section.
Atomic Term Symbols

Atomic term symbols may be defined as the symbolic representations of various electronic states having different resultant angular momentums resulting from spin-spin, orbital-orbital or spin-orbital interactions and the transitions between two different atomic states may also be represented using their term symbols, to which certain rules apply.

The general form of any atomic term symbol that is used to represent any electronic state resulting from inter-electronic repulsion is:

\[
\begin{align*}
2S+1 & \quad L_j \\
\end{align*}
\]

Where,

\[
2S+1 = \text{spin multiplicity} \\
S = \text{resultant spin angular momentum quantum number} \\
L = \text{resultant orbital angular momentum quantum number} \\
J = \text{resultant total angular momentum quantum number}
\]

Just like in the case of atomic orbitals, where \( l \) represents the individual orbital angular momentums; \( L \) represents the resultants orbital angular momentum of an electronic state and gives the base designation of any atomic term symbol.

\[
\begin{array}{cccccccc}
L & = & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\text{State} & = & S & P & D & F & G & H & I & K \\
\end{array}
\]

The calculation of resultant spin and orbital angular momentum involves the concepts of space quantization and vector interactions. A somewhat simplified approach for the calculation of resultant orbital angular momentum quantum number (L), resultant spin angular momentum quantum number S and resultant total angular momentum quantum number (J) can be given by understanding the spin-spin, orbital-orbital and spin-orbital couplings schemes.

1. **Orbital-orbital coupling (\( l-l \) interaction):** Consider a multielectron system, then the resultant orbital angular momentum quantum number can be deduced as:

\[
L = (l_1 + l_2), (l_1 + l_2 - 1), ..., |l_1 - l_2|
\]

Where \( l_1 \) and \( l_2 \) are the individual orbital angular momentum quantum numbers for electrons and modulus sign shows that the value of resultant orbital angular momentum quantum number is always positive. Given the eigenstates of \( l_1 \) and \( l_2 \), the construction of eigenstates of \( L \) (which still is conserved) is the coupling of the angular momenta of electrons 1 and 2.
i) For $p^1p^1$-configuration, $l_1 = 1$ and $l_2 = 1$, therefore

$$L = (1 + 1), \ (1 + 1 - 1), \ (1 - 1)$$

$$L = 2, 1, 0$$

States = D, P, S

Similarly,

ii) For $d^1d^1$-configuration, $l_1 = 2$ and $l_2 = 2$, therefore

$$L = (2 + 2), \ (2 + 2 - 1) \ldots \ldots (2 - 2)$$

$$L = 4, 3, 2, 1, 0$$

States = G, F, D, P, S

Although the above-mentioned procedure provides the resultant orbital angular momentum number ($L$) quite easily, the exact concept of orbital–orbital coupling can be understood only after knowing the concepts of space quantization. One thing that is totally clear is that these symbols are nothing but the mathematical shorthand of the electronic arrangements around the nucleus. The quantization of individual orbital angular momentums can be used to calculate the resultant value as follows:

i) For $p^1p^1$-configuration, $l_1 = 1$ and $l_2 = 1$, therefore orbital angular momentum for each of the electron is $\sqrt{2}$ and it is a well-known fact from the quantum mechanics that $\sqrt{2}$ angular momentum can be oriented in space with three different ways (+1, 0 and −1). The different combinations of orbital angular momentum can be calculated as

$$l_1(z) = +1 \quad +1 \quad +1 \quad 0 \quad 0 \quad 0 \quad -1 \quad -1 \quad -1$$

$$l_2(z) = +1 \quad 0 \quad -1 \quad -1 \quad 0 \quad -1 \quad +1 \quad 0 \quad -1$$

$$L_z = +2 \quad +1 \quad 0 \quad +1 \quad 0 \quad -1 \quad 0 \quad -1 \quad -2$$

Hence, the orbital angular momentums of two $p$-electrons can interact in nine ways, creating nine combinations; out of which, three quantum-mechanically allowed series can be fashioned.

$$L_z = (+2, +1, 0, -1, -2), \ (+1, 0, -1), \ (0)$$

or

$$L = 2, 1, 0$$

Hence

States = D, P, S

Therefore, we can say that there are nine ways in which the orbital motion can interact.
Similarly,

ii) For $d^1d^1$-configuration, $l_1 = 2$ and $l_2 = 2$, therefore orbital angular momentum for each of the electron is $\sqrt{6}$
and it is a well-known fact from the quantum mechanics that $\sqrt{6}$ angular momentum can be oriented in space
with five different ways ($+2, +1, 0, -1$ and $-2$). The different combinations of orbital angular momentum can
be calculated as:

\[ l_1 (z) = \begin{array}{cccccccc}
+2 & +2 & +2 & +2 & +1 & +1 & +1 & +1 \\
\end{array} \]

\[ l_2 (z) = \begin{array}{cccccccc}
+2 & +1 & 0 & -1 & -2 & +2 & +1 & 0 & -1 & -2 \\
+4 & +3 & +2 & +1 & 0 & +3 & +2 & +1 & 0 & -1 \\
\end{array} \]

L = \begin{array}{cccccccc}
+4 & +3 & +2 & +1 & 0 & +3 & +2 & +1 & 0 & -1 \\
+2 & +1 & 0 & -1 & -2 & +2 & +1 & 0 & -1 & -2 \\
\end{array} \]

and

\[ l_1 (z) = \begin{array}{cccccccc}
0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 & -1 \\
0 & -1 & -2 & -3 & -4 & 0 & -1 & -2 & -3 & -4 \\
\end{array} \]

Hence, the orbital angular momentums of two $d$-electrons can interact in twenty-five ways, creating twenty-five combinations; out of which, five quantum-mechanically allowed series can be fashioned.

\[ L_z = \begin{array}{cccccccc}
+4, +3, +2, +1, 0, -1, -2, -3, -4, +3, +2, +1, 0, -1, -2, -3, +2, +1, 0, -1, -2, +1, 0, -1, 0, 0 \\
\end{array} \]

or

\[ L = 4, 3, 2, 1, 0 \]

Which means

States = G, F, D, P, S

2. Spin-spin coupling (s-s interaction): Consider a multielectron system, then the resultant spin angular momentum quantum number can be deduced as:

\[ S = (s_1 + s_2), (s_1 + s_2 - 1) \ldots \ldots |s_1 - s_2| \]

Where $s_1$ and $s_2$ are the individual spin angular momentum quantum numbers for electrons and modulus sign shows that the value of resultant spin angular momentum quantum number is always positive.
i) For $p^1p^1$ or $d^1d^1$-configuration, $s_1 = 1/2$ and $s_2 = 1/2$, therefore

$$ S = (1/2 + 1/2), (1/2 - 1/2) $$

or

$$ S = 1, 0 $$

Which means

$$ \text{Multiplicity} = (2S + 1) = 3 \text{ and } 1 $$

The aforementioned procedure offers the resultant spin angular momentum quantum number ($S$) quite easily but the exact concept of spin-spin interaction can be understood only after knowing the concepts of space quantization. The quantization of individual spin angular momentums can be used to calculate the resultant value as follows:

i) For $p^1p^1$ or $d^1d^1$-configuration, $s_1 = 1/2$ and $s_2 = 1/2$, therefore spin angular momentum for each of the electrons is $\sqrt{0.75}$ and it is a well-known fact from the quantum mechanics that $\sqrt{0.75}$ angular momentum can be oriented in space with two different ways (+1/2 and −1/2). The different combinations of spin angular momentum can be calculated as:

\[
\begin{array}{c|c|c|c}
\text{s}_1 (z) & +1/2 & +1/2 & -1/2 \\
\text{s}_2 (z) & +1/2 & -1/2 & +1/2 \\
\text{S}_z & +1 & 0 & -1
\end{array}
\]

Hence, the spin angular momentums of two $p$ or $d$-electrons can interact in four ways, creating four combinations; out of which, two quantum-mechanically allowed series can be fashioned.

$$ S = (1, 0), (-1, 0) $$

or

$$ S = 1, 0 $$

$$ \text{Multiplicity} = (2S + 1) = 3 \text{ and } 1 $$

The multiplicity actually represents the number of orientations possible for the total spin relative to the total orbital angular momentum $L$, and thus to the number of near-degenerate levels that differ only in their spin-orbit coupling energy. For example, the ground state of the carbon atom is a $^3P$ state. The superscript of three specifies that the multiplicity $2S+1 = 3$ i.e. triplet, so that the total spin $S = 1$. This spin is due to two unpaired electrons, as a result of Hund's rule which favors the single filling of degenerate orbitals. The spin multiplicity is a primary factor in governing the overall energy of an electronic state and maybe summarised for different electron combination.
Table 3. Spin multiplicities for the different number of unpaired electron in an electronic configuration.

<table>
<thead>
<tr>
<th>Unpaired Electrons</th>
<th>S</th>
<th>2S+1</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>Singlet</td>
</tr>
<tr>
<td>1</td>
<td>1/2</td>
<td>2</td>
<td>Doublet</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>3</td>
<td>Triplet</td>
</tr>
<tr>
<td>3</td>
<td>3/2</td>
<td>4</td>
<td>Quartet</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>5</td>
<td>Quintet</td>
</tr>
</tbody>
</table>

3. Spin-orbital coupling (L-S interaction): In a multi-electron system, the resultant orbital angular momentum (L) and resultant spin angular momentum (S) interact with each other to give total angular momentum which is defined by the quantum number J.

\[ J = (L + S), (L + S - 1), \ldots, |L - S| \]

Where L and S are the quantum numbers for resultant orbital angular momentum and resultant spin angular momentum, respectively. The modulus sign shows that the value of the resultant total angular momentum quantum number is always positive. The value of J is assigned as the subscripts of the overall term symbol.

i) For \( \text{p}^1 \text{p}^1 \)-configuration, 9 combinations given by orbital orbital coupling (\( L = 2, 1, 0 \)) and 4 combinations given by spin-spin coupling (\( S = 1, 0 \)) combine to create a total of 36 microstates, therefore

\[ L = 0, 1, 2 \text{ and } S = 1, 0 \]

States = \( 3^S, \ 3^P, \ 3^D, \ 1^S, \ 1^P, \ 1^D \)

The summarization of spin-orbital coupling for \( \text{p}^1 \text{p}^1 \)-configurations is given below.

Table 4. Splitting of the term symbols for \( \text{p}^1 \text{p}^1 \)-configuration due to L-S coupling.

<table>
<thead>
<tr>
<th>State</th>
<th>Value L and S</th>
<th>Value of J</th>
<th>States after L-S coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>3^S</td>
<td>L = 0 and S = 1</td>
<td>J = (0 + 1) = 1</td>
<td>3^S_1</td>
</tr>
<tr>
<td>3^P</td>
<td>L = 1 and S = 1</td>
<td>J = (1 + 1) \ldots (1 - 1) = 2, 1, 0</td>
<td>3^P_2, 3^P_1, 3^P_0</td>
</tr>
<tr>
<td>3^D</td>
<td>L = 2 and S = 1</td>
<td>J = (2 + 1) \ldots (2 - 1) = 3, 2, 1</td>
<td>3^D_3, 3^D_2, 3^D_1</td>
</tr>
</tbody>
</table>

Table 4. Continued on the next page...
ii) For $d^4d^4$-configuration, 25 combinations given by orbital-orbital coupling ($L = 4, 3, 2, 1, 0$) and 4 combinations given by spin-spin coupling ($S = 1, 0$) couple to create a total of 100 microstates. therefore

$$L = 4, 3, 2, 1, 0$$

$$S = 1, 0$$

States = $^3S, ^3P, ^3D, ^3F, ^3G, ^1S, ^1P, ^1D, ^1F, ^1G$

The summarization of spin-orbital coupling for $d^4d^4$-configurations is given below.

Table 5. Splitting of the term symbols for $d^4d^4$-configuration due to L-S coupling.

<table>
<thead>
<tr>
<th>State</th>
<th>Value of L and S</th>
<th>Value of J</th>
<th>States after L-S coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3S$</td>
<td>$L = 0$ and $S = 0$</td>
<td>$J = (0 + 0) = 0$</td>
<td>$^3S_0$</td>
</tr>
<tr>
<td>$^3P$</td>
<td>$L = 1$ and $S = 0$</td>
<td>$J = (1 + 0) = 1$</td>
<td>$^3P_1$</td>
</tr>
<tr>
<td>$^3D$</td>
<td>$L = 2$ and $S = 0$</td>
<td>$J = (2 + 0) = 2$</td>
<td>$^3D_2$</td>
</tr>
<tr>
<td>$^3F$</td>
<td>$L = 3$ and $S = 0$</td>
<td>$J = (3 + 0) = 3$</td>
<td>$^3F_3$</td>
</tr>
<tr>
<td>$^3G$</td>
<td>$L = 4$ and $S = 0$</td>
<td>$J = (4 + 0) = 4$</td>
<td>$^3G_4$</td>
</tr>
<tr>
<td>$^1S$</td>
<td>$L = 0$ and $S = 0$</td>
<td>$J = (0 + 0) = 0$</td>
<td>$^1S_0$</td>
</tr>
<tr>
<td>$^1P$</td>
<td>$L = 1$ and $S = 0$</td>
<td>$J = (1 + 0) = 1$</td>
<td>$^1P_1$</td>
</tr>
<tr>
<td>$^1D$</td>
<td>$L = 2$ and $S = 0$</td>
<td>$J = (2 + 0) = 2$</td>
<td>$^1D_2$</td>
</tr>
<tr>
<td>$^1F$</td>
<td>$L = 3$ and $S = 0$</td>
<td>$J = (3 + 0) = 3$</td>
<td>$^1F_3$</td>
</tr>
<tr>
<td>$^1G$</td>
<td>$L = 4$ and $S = 0$</td>
<td>$J = (4 + 0) = 4$</td>
<td>$^1G_4$</td>
</tr>
</tbody>
</table>
The quantization of individual orbital angular momentums can be used to calculate the resultant value as follows: For $^3P$ state of $p^1p^1$-configuration, $L = 1$ and $S = 1$. Therefore, the different combinations of resultant orbital angular momentum and resultant spin angular momentum can be calculated:

$$
L_z = +1 \quad +1 \quad +1 \quad 0 \quad 0 \quad 0 \quad -1 \quad -1 \quad -1 \\
S_z = +1 \quad +1 \quad 0 \quad 0 \quad -1 \quad -1 \quad +1 \quad 0 \quad -1 \\
J_z = +2 \quad +1 \quad 0 \quad +1 \quad 0 \quad -1 \quad 0 \quad -1 \quad -2
$$

Hence, the resultant orbital angular momentums and resultant spin angular momentums of $^3P$ can interact in nine ways, creating nine microstates; out of which, three quantum-mechanically allowed series can be fashioned.

$$
J_z = (+2, +1, 0, -1, -2), (+1, 0, -1), (0)
$$

or

$$
J = 2, 1, 0
$$

Which means

States $= ^3P_2, ^3P_1, ^3P_0$

### Derivation of the Term Symbols for Unpaired Electrons in the Same Subshell

In the previous section, we have distributed all the 36 microstates for $p^1p^1$-configuration in six electronic states labeled by $^3S, ^3P, ^3D, ^1S, ^1P$ and $^1D$ term symbols. However, for $p^2$-configuration (both of the unpaired electrons in same subshell), many microstates that were possible in $p^1p^1$-configuration cannot exist if they violate the Pauli exclusion principle. Therefore, there are only 15 microstates (complying with Pauli principle) for $p^2$-configuration which can be distributed in three electronic states labeled by $^1S, ^3P$ and $^1D$ term symbols.

Similarly, all the 100 microstates for $d^1d^1$-configuration ($^1S, ^3P, ^1D, ^3F, ^1G, ^3S, ^1P, ^1D, ^1F$ and $^1G$) cannot exist if they both the electrons are present in the same $d$-subshell. Therefore, there are only 45 microstates (complying with Pauli principle) for $d^2$-configuration which can be distributed in five electronic states labeled by $^1S, ^3P, ^1D, ^3F$ and $^1G$ term symbols.

Term symbols for electronic configurations with unpaired electrons in the same subshell can be derived using “pigeon hole” diagrams. The principal steps for such operations are:

1. Create vertical columns for all allowed orientation or effect of individual orbital angular momentum in the reference direction. For example, $+1$, $0$ and $-1$ are the allowed orientations of the orbital angular momentum corresponding to $l = 1$ value.

2. Fill up the electrons in these columns by exhausting all the possibilities of parallel, paired and opposite orientations.
3. Sum-up all the $l_z$ values of every column to find out the resultant $L_z$ values.

4. Quantum mechanically allowed series set-up should be carried out for different parallel, paired and opposite orientation, which in turn can be used to provide the resultant orbital angular momentum quantum number $L$ for particular resultant spin quantum number $S$.

5. Combine the values of $L$ and $S$ to find out the term symbols for allowed electronic states.

1. $s^1$-configuration:

\[
\begin{array}{c|c}
  l_z & \uparrow \\
  \hline
  0 & \uparrow \\
  L_z & 0 \\
\end{array}
\]

As $L_z = 0$, the value of resultant orbital angular momentum quantum number $L = 0$. There is only one unpaired electron, therefore $S = 1/2$.

From $L = 0$, the state is $S$; and from $S = 1/2$, the multiplicity is 2. Thus, the overall term symbol is $^2S$.

2. $s^2$-configuration:

\[
\begin{array}{c|c|c}
  l_z & \uparrow \downarrow & \uparrow \\
  \hline
  0 & \uparrow \downarrow & \uparrow \\
  L_z & 0 & 0 \\
\end{array}
\]

As $L_z = 0$, the value of resultant orbital angular momentum quantum number $L = 0$. There are no unpaired electrons, therefore $S = 0$.

From $L = 0$, the state is $S$; and from $S = 0$, the multiplicity is 1. Thus, the overall term symbol is $^1S$.

3. $p^1$ and $p^5$-configuration:

\[
\begin{array}{c|c|c}
  l_z & \uparrow & \uparrow \\
  \hline
  -1 & \uparrow & \uparrow \\
  0 & \uparrow & \uparrow \\
  +1 & \uparrow & \uparrow \\
  L_z & +1 & 0 & -1 \\
\end{array}
\]

As $L_z = +1$, 0, −1; the value of resultant orbital angular momentum quantum number $L = 1$. There is one unpaired electron, therefore $S = 1/2$.

From $L = 1$, the state is $P$; and from $S = 1/2$, the multiplicity is 2. Thus, the overall term symbol is $^3P$. Hence, all the 6 microstates for $p^1$ and $p^5$-configurations are distributed in $^3P$ term symbol.
4. \( p^2 \) and \( p^4 \)-configuration:

For parallel arrangements,

\[
\begin{array}{c|ccc}
L_z & -1 & 0 & +1 \\
\hline
-1 & \uparrow & \uparrow & \uparrow \\
0 & \uparrow & \uparrow & \\
+1 & \uparrow & \uparrow & \\
\end{array}
\]

As \( L_z = +1, 0, -1 \); the value of resultant orbital angular momentum quantum number \( L = 1 \).

There are two unpaired electrons, therefore \( S = 1 \).

From \( L = 1 \), the state is \( P \).

From \( S = 1 \), the multiplicity is 3.

Thus, the overall term symbol is \( ^3P \).

Similarly,

For paired and opposite arrangements,

\[
\begin{array}{c|ccc}
L_z & -2 & -1 & 0 & +1 \\
\hline
-2 & & & \uparrow & \\
-1 & & & \uparrow & \\
0 & & & \uparrow & \\
+1 & & & \uparrow & \\
\end{array}
\]

Out of six values of \( L_z \) (resultant orbital angular momentum in reference direction), two quantum-mechanically allowed series can be setup. One with \( L_z = +2, +1, 0, -1, -2 \); giving resultant orbital angular momentum quantum number \( L = 2 \). The second series with \( L_z = 0 \); giving resultant orbital angular momentum quantum number \( L = 0 \).

There are zero unpaired electrons, therefore \( S = 0 \).

From \( L = 2 \) and 0; the states are \( D \) and \( S \), respectively.

From \( S = 0 \), the multiplicity is 1.

Thus, the overall term symbols are \( ^1D \) and \( ^1S \).

Hence, all the 15 microstates for \( p^2 \) and \( p^4 \) electronic configurations which can be distributed in \( ^1S, ^3P \) and \( ^1D \) term symbols.
5. \( p^3 \)-configuration:

\[
\begin{array}{c|ccccc}
L_z & 0 & +2 & +1 & -1 & -2 \\
\hline
-1 & \uparrow & & & & \\
0 & \uparrow & \uparrow \downarrow & \uparrow \downarrow & \uparrow & \downarrow \\
+1 & \uparrow \downarrow & \uparrow \downarrow & \uparrow & \uparrow & \uparrow \\
\end{array}
\]

For parallel arrangements,

As \( L_z = 0 \); the value of resultant orbital angular momentum quantum number \( L = 0 \). There are three unpaired electrons, therefore \( S = 3/2 \).

From \( L = 0 \), the state is \( S \); and from \( S = 3/2 \), the multiplicity is 4. Thus, the overall term symbol is \( ^4S \).

For paired and opposite arrangements,

Out of eight values of \( L_z \), two quantum-mechanically allowed series can be setup. One with \( L_z = +2, +1, 0, -1, -2 \); giving resultant orbital angular momentum quantum number \( L = 2 \). The second series with \( L_z = +1, 0, -1 \); giving resultant orbital angular momentum quantum number \( L = 1 \). There is one unpaired electron, therefore \( S = 1/2 \).

From \( L = 2 \) and 1 the states are \( D \) and \( P \), respectively.

From \( S = 1/2 \), the multiplicity is 2.

Thus, the overall term symbols are \( ^2D \) and \( ^2P \).

Hence, all the 20 microstates for \( p^3 \)-configurations are distributed in \( ^4S, ^2P \) and \( ^2D \) term symbols.

6. \( p^6 \)-configuration:

\[
\begin{array}{c|c}
L_z & 0 \\
\hline
-1 & \uparrow \downarrow \\
0 & \uparrow \downarrow \\
+1 & \uparrow \downarrow \\
\end{array}
\]

As \( L_z = 0 \), the value of resultant orbital angular momentum quantum number \( L = 0 \); and zero unpaired electrons, therefore \( S = 0 \). Thus, the overall term symbol is \( ^1S \) which contains the one and only microstate of \( p^6 \)-electronic configuration.
7. \(d^1\) and \(d^9\)-configuration:

\[
\begin{array}{cccccccc}
L_z & -2 & -1 & 0 & +1 & +2 \\
\hline
-2 & & & & & & & \\
-1 & & & & & & & \\
0 & & & & & & & \\
+1 & & & & & & & \\
+2 & & & & & & & \\
\end{array}
\]

As \(L_z = +2, +1, 0, -1, -2\); the value of resultant orbital angular momentum quantum number \(L = 2\).

There is only one unpaired electron, therefore \(S = \frac{1}{2}\).

From \(L = 2\), the state is \(D\); and from \(S = \frac{1}{2}\), the multiplicity is also \(2\).

Thus, the overall term symbol is \(^2D\).

Hence, all the 10 microstates for \(d^1\) and \(d^9\)-configurations are distributed in \(^2D\) term symbols.

8. \(d^2\) and \(d^8\)-configuration:

For parallel arrangements,

\[
\begin{array}{cccccccc}
L_z & -3 & -2 & -1 & 0 & +1 & +2 \\
\hline
-3 & & & & & & & \\
-2 & & & & & & & \\
-1 & & & & & & & \\
0 & & & & & & & \\
+1 & & & & & & & \\
+2 & & & & & & & \\
\end{array}
\]

Out of ten values of \(L_z\), two quantum-mechanically allowed series can be setup. One with \(L_z = +3, +2, +1, 0, -1, -2, -3\); giving resultant orbital angular momentum quantum number \(L = 3\). The second series with \(L_z = +1, 0, -1\); giving resultant orbital angular momentum quantum number \(L = 1\). There are two unpaired electrons, therefore \(S = 1\).

From \(L = 3\) and 1, the states are \(F\) and \(P\), respectively. From \(S = 1\), the multiplicity is 3. Thus, the overall term symbols are \(^3F\) and \(^3P\).
Out of fifteen values of $L_z$, three quantum-mechanically allowed series can be setup. First with $L_z = +4, +3, +2, +1, 0, −1, −2, −3, −4$; giving resultant orbital angular momentum quantum number $L = 4$. Second series with $L_z = +2, +1, 0, −1, −2$; giving resultant orbital angular momentum quantum number $L = 2$. The third series with $L_z = 0$; giving resultant orbital angular momentum quantum number $L = 0$. There are zero unpaired electrons, therefore $S = 0$.

From $L = 4, 2$ and $0$ the states are $^4G, ^2D$ and $^4S$, respectively. From $S = 0$, the multiplicity is $1$. Thus, the overall term symbols are $^4G, ^2D$ and $^4S$.

Hence, all the 45 microstates for $d^2$ and $d^8$-configurations are distributed in $^1S, ^3P, ^1D, ^3F$ and $^1G$ term symbols.

9. $d^3$ and $d^7$-configuration:

For parallel arrangements,

<table>
<thead>
<tr>
<th>$L_z$</th>
<th>+3</th>
<th>+2</th>
<th>+1</th>
<th>0</th>
<th>−1</th>
<th>−3</th>
<th>+1</th>
<th>−1</th>
<th>−2</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>−2</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>−1</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>0</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>+1</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>+2</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
</tbody>
</table>

Out of ten values of $L_z$, two quantum-mechanically allowed series can be setup.

One with $L_z = +3, +2, +1, 0, −1, −2, −3$; giving resultant orbital angular momentum quantum number $L = 3$.

The second series with $L_z = +1, 0, −1$; giving resultant orbital angular momentum quantum number $L = 1$. There are three unpaired electrons, therefore $S = 3/2$. 
From $L = 3$ and 1; the states are $F$ and $P$, respectively. From $S = 3/2$, the multiplicity is 4. Thus, the overall term symbols are $^4F$ and $^4P$.

For paired and opposite arrangements, the states are $H$, $G$, $F$, $D$, $D$ and $P$, respectively. From $S = 1/2$, the multiplicity is 2.
Thus, the overall term symbols are $^2\text{H}$, $^2\text{G}$, $^2\text{F}$, $^2\text{D}$, $^2\text{D}$ and $^2\text{P}$.

Hence, all the 120 microstates for $d^3$ and $d^7$-configurations are distributed in $^4\text{F}$, $^4\text{P}$, $^2\text{H}$, $^2\text{G}$, $^2\text{F}$, $^2\text{D}$, $^2\text{D}$ and $^2\text{P}$ term symbols.

**10. $d^4$ and $d^6$-configuration:**

For parallel arrangements,

\[
\begin{array}{c|cccc}
 l_z & -2 & -1 & 0 & 1 \\
\hline
\uparrow & \uparrow & \uparrow & \uparrow \\
\hline
\uparrow & \uparrow & \uparrow & \uparrow \\
\hline
\uparrow & \uparrow & \uparrow & \uparrow \\
\hline
\uparrow & \uparrow & \uparrow & \uparrow \\
\hline
\end{array}
\]

Out of five values of $l_z$, only one quantum-mechanically allowed series can be set up with $l_z = +2, +1, 0, -1, -2$; giving resultant orbital angular momentum quantum number $L = 2$.

There are four unpaired electrons, therefore $S = 2$.

From $L = 2$, the state is $^2\text{D}$.

From $S = 2$, the multiplicity is 5.

Thus, the overall term symbol is $^5\text{D}$.

For two electrons paired or opposite arrangement,

\[
\begin{array}{c|cccccc}
 l_z & -2 & -1 & 0 & +1 & +2 & +3 \\
\hline
\uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
\hline
\uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
\hline
\uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
\hline
\uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
\hline
\end{array}
\]

and
Out of forty-five values of $L_z$, seven quantum-mechanically allowed series can be setup as. First with $L_z = +5, +4, +3, +2, +1, 0, -1, -2, -3, -4, -5$; giving resultant orbital angular momentum quantum number $L = 5$. Second series with $L_z = +4, +3, +2, +1, 0, -1, -2, -3, -4$; giving resultant orbital angular momentum quantum number $L = 4$. The third and fourth series with $L_z = +3, +2, +1, 0, -1, -2, -3$; giving resultant orbital angular momentum quantum number $L = 3$ and 3. Fifth series with $L_z = +2, +1, 0, -1, -2$; giving resultant orbital angular momentum quantum number $L = 2$. The sixth and seventh series is consisted of $L_z = +1, 0, -1$; giving resultant orbital angular momentum quantum number $L = 1$ and 1, respectively.

There are two unpaired electrons, therefore $S = 1$.

From $L = 5, 4, 3, 2, 1$ and 1; the states are $H, G, F, F, D, P$ and $P$, respectively.

From $S = 1$, the multiplicity is 3.

Thus, the overall term symbols are $^3H, ^3G, ^3F, ^3D, ^3P$ and $^3P$.

Similarly,

For all electrons paired or opposite arrangement,
<table>
<thead>
<tr>
<th>$l_z$</th>
<th>$-2$</th>
<th>$-1$</th>
<th>$0$</th>
<th>$+1$</th>
<th>$+2$</th>
<th>$+3$</th>
<th>$+4$</th>
<th>$+6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
</tr>
<tr>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
</tr>
<tr>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow$</td>
<td>$\uparrow$</td>
<td>$\uparrow$</td>
<td>$\uparrow$</td>
<td>$\uparrow$</td>
</tr>
<tr>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
</tr>
</tbody>
</table>

and

<table>
<thead>
<tr>
<th>$l_z$</th>
<th>$-2$</th>
<th>$-1$</th>
<th>$0$</th>
<th>$+1$</th>
<th>$+2$</th>
<th>$+3$</th>
<th>$+4$</th>
<th>$+6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
</tr>
<tr>
<td>$\uparrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
</tr>
<tr>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
</tr>
<tr>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
</tr>
</tbody>
</table>

and

<table>
<thead>
<tr>
<th>$l_z$</th>
<th>$-2$</th>
<th>$-1$</th>
<th>$0$</th>
<th>$+1$</th>
<th>$+2$</th>
<th>$+3$</th>
<th>$+4$</th>
<th>$+6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
</tr>
<tr>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
</tr>
<tr>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
</tr>
<tr>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
</tr>
</tbody>
</table>

and

<table>
<thead>
<tr>
<th>$l_z$</th>
<th>$-2$</th>
<th>$-1$</th>
<th>$0$</th>
<th>$+1$</th>
<th>$+2$</th>
<th>$+3$</th>
<th>$+4$</th>
<th>$+6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
</tr>
<tr>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
</tr>
<tr>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
</tr>
<tr>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
<td>$\uparrow \downarrow$</td>
</tr>
</tbody>
</table>

and
Out of fifty values of $L_z$, eight quantum-mechanically allowed series can be setup as. First with $L_z = +6$, $+5$, $+4$, $+3$, $+2$, $+1$, $0$, $-1$, $-2$, $-3$, $-4$, $-5$, $-6$; giving resultant orbital angular momentum quantum number $L = 6$. Second and third series with $L_z = +4$, $+3$, $+2$, $+1$, $0$, $-1$, $-2$, $-3$, $-4$; giving resultant orbital angular momentum quantum number $L = 4$ and $4$, respectively. The fourth series with $L_z = +3$, $+2$, $+1$, $0$, $-1$, $-2$, $-3$; giving resultant orbital angular momentum quantum number $L = 3$: Fifth and sixth series with $L_z = +2$, $+1$, $0$, $-1$, $-2$; giving resultant orbital angular momentum quantum number $L = 2$ and $2$, respectively. The seventh and eighth series is consisted of $L_z = 0$; giving resultant orbital angular momentum quantum number $L = 0$ and $0$, respectively. There are zero unpaired electrons, therefore $S = 0$. From $L = 6$, $4$, $4$, $3$, $2$, $0$ and $0$, the states are $^1I$, $^1G$, $^1G$, $^1D$, $^1D$, $^1S$ and $^1S$, respectively. From $S = 0$, the multiplicity is 1. Thus, the overall term symbols are $^1I$, $^1G$, $^1G$, $^1D$, $^1D$, $^1S$ and $^1S$. Hence, all the 210 microstates for $d^4$ and $d^6$-configurations are distributed in $^5D$, $^3H$, $^3G$, $^3F$, $^3F$, $^3D$, $^3P$, $^3P$, $^1I$, $^1G$, $^1F$, $^1D$, $^1D$, $^1S$ and $^1S$ term symbols.

11. $d^5$-configuration:

For parallel arrangements,

<table>
<thead>
<tr>
<th>$L_z$</th>
<th>$-2$</th>
<th>$-1$</th>
<th>$0$</th>
<th>$+1$</th>
<th>$+2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_z$</td>
<td>$↑$</td>
<td>$↑$</td>
<td>$↑$</td>
<td>$↑$</td>
<td>$↑$</td>
</tr>
</tbody>
</table>
As \( L_z = 0 \); the value of resultant orbital angular momentum quantum number \( L = 0 \). There are five unpaired electrons, therefore \( S = 5/2 \).

From \( L = 0 \), the state is \( S \). From \( S = 5/2 \), the multiplicity is 6. Thus, the overall term symbol is \(^6S\).

For two electrons paired or opposite arrangement,

\[
\begin{array}{cccccccccccc}
 L_z & \downarrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
-2 & & & & & & & & & & & \\
-1 & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
0 & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
+1 & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
+2 & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
& \hline
& +4 & +3 & +2 & +1 & +3 & +2 & +1 & -1 & +2 & +1 & -1 \\
& +3 & +2 & +1 & 0 & -1 & -2 & -3 & 0 & -4 & -3 & -2 \\
\end{array}
\]

Out of twenty-four values of \( L_z \), four quantum-mechanically allowed series can be setup as. First with \( L_z = +4, +3, +2, +1, 0, -1, -2, -3, -4 \); giving resultant orbital angular momentum quantum number \( L = 4 \). Second series with \( L_z = +3, +2, +1, 0, -1, -2, -3 \); giving resultant orbital angular momentum quantum number \( L = 3 \). The third series with \( L_z = +2, +1, 0, -1, -2 \); giving resultant orbital angular momentum quantum number \( L = 3 \). The fourth series is consisted of \( L_z = +1, 0, -1 \); giving resultant orbital angular momentum quantum number \( L = 1 \).

There are three unpaired electrons, therefore \( S = 3/2 \).

From \( L = 4, 3, 2 \) and 1; the states are \( G, F, D \) and \( P \), respectively.

From \( S = 3/2 \), the multiplicity is 4.

Thus, the overall term symbols are \(^4G, ^4F, ^4D \) and \(^4P\).
For four electrons paired or opposite arrangement,

\[
\begin{array}{cccccccccccc}
L_z & -2 &  &  &  &  &  &  &  &  &  &  \\
     &   & \uparrow &   &   & \uparrow &   &   & \uparrow &   &   & \uparrow \\
-1  &   &   & \uparrow &   & \uparrow & \uparrow & \downarrow & \downarrow & \downarrow & \uparrow & \uparrow \\
0   &   & \uparrow &   & \uparrow & \uparrow & \uparrow & \downarrow & \uparrow & \uparrow & \uparrow & \uparrow \\
+1  &   & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \downarrow & \uparrow & \uparrow & \uparrow & \uparrow \\
+2  &   & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\

L_z & +6 & +5 & +4 & +3 & +2 & +2 & +1 & +1 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{array}
\]

and

\[
\begin{array}{cccccccccc}
L_z & -2 &  &  &  &  &  &  &  &  &  \\
     &   & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
-1  &   & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \downarrow & \uparrow & \uparrow & \uparrow \\
0   &   & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
+1  &   & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
+2  &   & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\

L_z & +2 & 0 & -2 & 0 & -2 & 0 & -3 & 0 & -4 & -2 & -3 & -5 & -4 & -5 & -6 \\
\end{array}
\]

and

\[
\begin{array}{cccccccccc}
L_z & -2 &  &  &  &  &  &  &  &  &  \\
     &   & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\
-1  &   & \downarrow & \uparrow & \uparrow & \downarrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
0   &   & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
+1  &   & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\
+2  &   & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\

L_z & +4 & +3 & +2 & +1 & +3 & +2 & +1 & +1 & -1 & -2 & +1 & -1 & -2 & -1 & -2 \\
\end{array}
\]
Out of seventy-five values of \( L_z \), eleven quantum-mechanically allowed series can be setup. First with \( L_z = +6 \), \(+5\), \(+4\), \(+3\), \(+2\), \(+1\), \(0\), \(-1\), \(-2\), \(-3\), \(-4\), \(-5\), \(-6\); giving resultant orbital angular momentum quantum number \( L = 6 \). Second series with \( L_z = +5\), \(+4\), \(+3\), \(+2\), \(+1\), \(0\), \(-1\), \(-2\), \(-3\), \(-4\), \(-5\); giving resultant orbital angular momentum quantum number \( L = 5 \). The third and fourth series with \( L_z = +4\), \(+3\), \(+2\), \(+1\), \(0\), \(-1\), \(-2\), \(-3\), \(-4\); giving resultant orbital angular momentum quantum number \( L = 4 \). Fifth and sixth series with \( L_z = +3\), \(+2\), \(+1\), \(0\), \(-1\), \(-2\), \(-3\); giving resultant orbital angular momentum quantum number \( L = 3 \) and 3, respectively. The seventh, eighth and ninth series are consisted of \( L_z = +2\), \(+1\), \(0\), \(-1\), \(-2\); giving resultant orbital angular momentum quantum number \( L = 2 \), 2 and 2, respectively. The tenth and eleventh series are consisted of \( L_z = +1\), \(0\), \(-1\) and \( L_z = 0 \); giving resultant orbital angular momentum quantum number \( L = 1 \) and 0, respectively.

There is one unpaired electron which \( S = 1/2 \).

From \( L = 6\), \(5\), \(4\), \(3\), \(2\), \(2\), \(1\) and \(0\); the states are \( I, H, G, F, D, D, D, P \) and \( S \), respectively. From \( S = 1/2 \), the multiplicity is 2. Thus, the overall term symbols are \( ^2I, ^2H, ^2G, ^2F, ^2D, ^2D, ^2P \) and \( ^2S \). Hence, all the 252 microstates for \( d^5 \)-configurations are distributed in \( ^2I, ^2H, ^2G, ^2F, ^2D, ^2D, ^2D, ^2P, ^2S, ^4G, ^4F, ^4D, ^6P \) and \( ^6S \) term symbols.
12. $d^{10}$-configuration:

\[
\begin{array}{c|c}
L_z & \uparrow\downarrow \\
-2 & \\
-1 & \uparrow\downarrow \\
0 & \uparrow\downarrow \\
+1 & \uparrow\downarrow \\
+2 & \\
\hline
L_z & 0 \\
\end{array}
\]

As $L_z = 0$; the value of resultant orbital angular momentum quantum number $L = 0$. There are no unpaired electrons, therefore $S = 0$.

From $L = 0$, the state is $S$. From $S = 0$, the multiplicity is 1. Thus, the overall term symbol is $^1S$ which contains the only microstate of $d^{10}$-configuration.

It can clearly be seen that the number of microstates, as well as the term symbols for $dn$ and $d10-n$ configurations, are the same. This is due to the fact that the number of unpaired electrons is the same for both of the configurations. In other words, the possible arrangements for unpaired electrons in less than half-filled or for holes in more than half-filled configurations are the same. The same analogy is true for $s$, $p$ or $f$-subshell.

Moreover, the number of microstates distributed in any term symbol can be calculated using the following relations:

1. Term symbols without $J$-value: $(2L+1) \times (2S+1)$
2. Term symbols without $J$-value: $(2J+1)$

Let us tally the number of microstates for $p^2$ electronic configuration with term symbols distribution.

\[
\begin{align*}
(2L+1) \times (2S+1) & \quad (2J+1) \\
^1S & = (2\times0+1) \times (2\times0+1) = 1 & ^1S_0 & = 2\times0 + 1 = 1 \\
^3P & = (2\times1+1) \times (2\times1+1) = 9 & ^3P_2 & = 2\times2 + 1 = 5 \\
^1D & = (2\times2+1) \times (2\times0+1) = 5 & ^3P_1 & = 2\times1 + 1 = 3 \\
\end{align*}
\]

Buy the complete book with TOC navigation, high resolution images and no watermark.
Determination of Spectroscopic Ground State Term

In a particular configuration, the classification of various microstates in different term symbols also distinguishes them energetically. It can be explained in terms of the effect of spin-spin, orbital-orbital and spin-orbital coupling. There are two different approaches, both are based upon some conclusive results from quantum mechanics, to find out the term symbol for ground electronic state.

1. From correlation diagram: This approach is based on the correlation of all the free ion term of a particular atom or ion and then the ground state term is calculated with the help of certain rules.

i) The energy of different terms (electronic states) depends primarily on the Hund’s rule, which states that the most stable state should have the highest multiplicity. Hence, triplet states are more stable than the singlet one. In other words, the higher the value of 2S+1, the greater will be the stability.

ii) If the value of spin multiplicities for two different states is the same, the value of resultant angular momentum will be the deciding factor in the determination of the lower energy term. A higher value of L gives the lower energy state and the vice-versa is also true.

iii) The energy dependence of different terms upon total angular momentum is configuration-specific in nature. The perturbed Hamiltonian of spin-orbital interaction can have both types of effect, stabilization or destabilization, over the energy states and depends upon the magnitude of J-value. It has been proved that the interaction of spin-orbital motion destabilizes the less than half-filled configuration and stabilizes the more than half-filled. Hence, a lower J-value for less than half-filled and a higher J-value of more than half will give the lower energy.

Let us apply this procedure to find out the ground state term symbol for $p^2$-configuration:

![Figure 1. Splitting of free ion terms in the carbon atom.](image)
The effect of spin-spin interaction makes the triplet (3P) state more stable in comparison to the singlet (1D or 1S). Furthermore, the stabilization of 1D state after the consideration of orbital-orbital interaction can be attributed to the higher value of orbital angular momentum. Finally, as the p²-configuration is less than half-filled; the splitting of 3P state goes with 3P₀ as the ground state term symbol.

2. Using L-S coupling scheme: This procedure is applicable only to find out the ground state term symbol. We do not need to calculate all the microstates but only present in the ground electronic state. Various steps involved in this procedure are:

1. The electron filling in the valence subshell should be carried out in such a way that a maximum spin multiplicity (2S+1) is produced.
2. Maximize the value of resultant orbital angular momentum component by filing electrons first in the orbitals with the positive component of individual orbital angular momentum.
3. Select maximum J-value for more than half-filled and minimum J-value for less than half-filled configuration.

Let us determine the ground state term symbol for carbon atom. The electronic configuration for carbon is 1s², 2s², 2p².

\[
\begin{pmatrix}
  l_z & +1 & 0 & -1 \\
  2p & \uparrow & \uparrow & \uparrow \\
\end{pmatrix}
\]

From the total component of orbital and spin angular momentum, \( L = (+1) + (0) = 1 \) and \( S = 1/2 + 1/2 = 1 \).

From L-S coupling, \(|L+S| \ldots \ldots |L-S|\): \((1+1) \ldots \ldots (1-1) = 2, 1, 0 \).

Now, as the configuration is less than half-filled, the lower J-value is selected for lower energy. Thus, this gives rise to a 3P₀ state.

For nitrogen atom, the determination of the ground state term symbol can be calculated through the same route. The electronic configuration for nitrogen is 1s², 2s², 2p³.

\[
\begin{pmatrix}
  l_z & +1 & 0 & -1 \\
  2p & \uparrow & \uparrow & \uparrow \\
\end{pmatrix}
\]

From the total component of orbital and spin angular momentum, \( L = (+1) + (0) + (-1) = 0 \) and \( S = 1/2 + 1/2 + 1/2 = 3/2 \).

From L-S coupling, \(|L+S| \ldots \ldots |L-S|\): \((0 + 3/2) = 3/2 \).

Now, as the configuration is half-filled, the only J-value is bound to be selected for lower energy. Thus, this gives rise to a 4S_{3/2} state.

For trivalent vanadium ion (V³⁺), the electronic configuration can be given as is 1s², 2s², 2p⁶, 3s², 3p⁶, 4s², 3d⁶.
From the total component of orbital and spin angular momentum, \( L = (+2) + (+1) = 3 \) and \( S = 1/2 + 1/2 = 1 \).

From L-S coupling, \(|L+S| .... \ldots \) \(|L-S| = 4, 3, 2 \). Now, as the configuration is less than half-filled, the lower J-value is selected for lower energy. Thus, this gives rise to a \( ^3F_2 \) state. However, the ground state term symbol for \( d^8 \)-configuration will be \( ^3F_4 \).

All the free ions terms (including ground states) for different electronic configurations are summarized in the following table. However, it must be kept in mind that the ground state term symbol after L-S coupling will be different for more than half-filled and less than half-filled counterparts.

**Table 6.** The free ion terms and the corresponding ground electronic states for different types of electronic configuration.

<table>
<thead>
<tr>
<th>Electronic configuration</th>
<th>Free ion terms</th>
<th>Ground State</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s^1 )</td>
<td>( ^2S )</td>
<td>( ^2S )</td>
</tr>
<tr>
<td>( s^2 )</td>
<td>( ^1S )</td>
<td>( ^1S )</td>
</tr>
<tr>
<td>( p^1, p^5 )</td>
<td>( ^3P )</td>
<td>( ^3P )</td>
</tr>
<tr>
<td>( p^2, p^4 )</td>
<td>( ^3D )</td>
<td>( ^3D )</td>
</tr>
<tr>
<td>( p^3 )</td>
<td>( ^4S )</td>
<td>( ^4S )</td>
</tr>
<tr>
<td>( p^6 )</td>
<td>( ^2P )</td>
<td>( ^2P )</td>
</tr>
<tr>
<td>( d^1, d^9 )</td>
<td>( ^3S, ^3P, ^1D, ^3F, ^1G )</td>
<td>( ^3P )</td>
</tr>
<tr>
<td>( d^2, d^8 )</td>
<td>( ^4F, ^4P, ^2H, ^2G, ^2F, ^2D, ^2D, ^2D, ^2D )</td>
<td>( ^4F )</td>
</tr>
<tr>
<td>( d^3, d^7 )</td>
<td>( ^5D, ^3H, ^1G, ^3F, ^3D, ^3P, ^3P, ^1I, ^1G, ^1G, ^1F, ^1D, ^1D, ^1S, ^1S )</td>
<td>( ^5D )</td>
</tr>
<tr>
<td>( d^4, d^6 )</td>
<td>( ^6S )</td>
<td>( ^6S )</td>
</tr>
<tr>
<td>( d^5 )</td>
<td>( ^2I, ^2H, ^2G, ^2G, ^2F, ^2D, ^2D, ^2D, ^2P, ^3S, ^4G, ^4D, ^4P, ^6S )</td>
<td>( ^2I )</td>
</tr>
<tr>
<td>( d^{10} )</td>
<td>( ^1S )</td>
<td>( ^1S )</td>
</tr>
</tbody>
</table>

It is also worthy to note that the ground state term symbol for all fully-filled subshells like \( s^2, p^6 \), or \( d^{10} \) is \( ^1S \) always which also includes the one and only microstate available.
LEGAL NOTICE
This document is an excerpt from the book entitled “A Textbook of Inorganic Chemistry – Volume 1 by Mandeep Dalal”, and is the intellectual property of the Author/Publisher. The content of this document is protected by international copyright law and is valid only for the personal preview of the user who has originally downloaded it from the publisher’s website (www.dalalinstitute.com). Any act of copying (including plagiarizing its language) or sharing this document will result in severe civil and criminal prosecution to the maximum extent possible under law.

This is a low resolution version only for preview purpose. If you want to read the full book, please consider buying.

Buy the complete book with TOC navigation, high resolution images and no watermark.
Home: https://www.dalalinstitute.com/
Classes: https://www.dalalinstitute.com/classes/
Books: https://www.dalalinstitute.com/books/
Videos: https://www.dalalinstitute.com/videos/
Location: https://www.dalalinstitute.com/location/
Contact Us: https://www.dalalinstitute.com/contact-us/
About Us: https://www.dalalinstitute.com/about-us/

Postgraduate Level Classes
(NET-JRF & IIT-GATE)

Admission
Regular Program
Test Series
Distance Learning
Result

Undergraduate Level Classes
(M.Sc Entrance & IIT-JAM)

Admission
Regular Program
Test Series
Distance Learning
Result

A Textbook of Inorganic Chemistry – Volume 1

“A Textbook of Inorganic Chemistry – Volume 1 by Mandeep Dalal” is now available globally; including India, America and most of the European continent. Please ask at your local bookshop or get it online here.

READ MORE

Join the revolution by becoming a part of our community and get all of the member benefits like downloading any PDF document for your personal preview.

Sign Up
A TEXTBOOK OF INORGANIC CHEMISTRY

Volume I

MANDEEP DALAL

First Edition

DALAL INSTITUTE
# Table of Contents

CHAPTER 1 ..................................................................................................................................... 11

**Stereochemistry and Bonding in Main Group Compounds:** ........................................................ 11
- VSEPR Theory ................................................................................................................................ 11
- $d\pi-p\pi$ Bonds .................................................................................................................................... 23
- Bent Rule and Energetic of Hybridization ....................................................................................... 28
- Problems .......................................................................................................................................... 42
- Bibliography .................................................................................................................................... 43

CHAPTER 2 ..................................................................................................................................... 44

**Metal-Ligand Equilibria in Solution:** ................................................................................................. 44
- Stepwise and Overall Formation Constants and Their Interactions ............................................... 44
- Trends in Stepwise Constants .......................................................................................................... 46
- Factors Affecting Stability of Metal Complexes with Reference to the Nature of Metal Ion and Ligand .............................................................................................................................................. 49
- Chelate Effect and Its Thermodynamic Origin ................................................................................ 56
- Determination of Binary Formation Constants by pH-metry and Spectrophotometry .................... 63
- Problems .......................................................................................................................................... 68
- Bibliography .................................................................................................................................... 69

CHAPTER 3 ..................................................................................................................................... 70

**Reaction Mechanism of Transition Metal Complexes – I:** ............................................................. 70
- Inert and Labile Complexes ............................................................................................................. 70
- Mechanisms for Ligand Replacement Reactions ............................................................................ 77
- Formation of Complexes from Aquo Ions ....................................................................................... 82
- Ligand Displacement Reactions in Octahedral Complexes- Acid Hydrolysis, Base Hydrolysis .... 86
- Racemization of Tris Chelate Complexes ....................................................................................... 89
- Electrophilic Attack on Ligands ...................................................................................................... 92
- Problems .......................................................................................................................................... 94
- Bibliography .................................................................................................................................... 95
CHAPTER 4 ..................................................................................................................................... 96

Reaction Mechanism of Transition Metal Complexes – II: .......................................................... 96
  ❖ Mechanism of Ligand Displacement Reactions in Square Planar Complexes ....................... 96
  ❖ The Trans Effect ...................................................................................................................... 98
  ❖ Theories of Trans Effect ......................................................................................................... 103
  ❖ Mechanism of Electron Transfer Reactions – Types; Outer Sphere Electron Transfer Mechanism and Inner Sphere Electron Transfer Mechanism ......................................................... 106
  ❖ Electron Exchange ................................................................................................................ 117
  ❖ Problems ............................................................................................................................. 121
  ❖ Bibliography ......................................................................................................................... 122

CHAPTER 5 ................................................................................................................................... 123

Isopoly and Heteropoly Acids and Salts: ...................................................................................... 123
  ❖ Isopoly and Heteropoly Acids and Salts of Mo and W: Structures of Isopoly and Heteropoly Anions ........................................................................................................................................123
  ❖ Problems ............................................................................................................................. 152
  ❖ Bibliography ......................................................................................................................... 153

CHAPTER 6 ................................................................................................................................... 154

Crystal Structures: ....................................................................................................................... 154
  ❖ Structures of Some Binary and Ternary Compounds Such as Fluorite, Antifluorite, Rutile, Antirutile, Crystobalite, Layer Lattices - CdI$_2$, BiI$_3$, ReO$_3$, Mn$_2$O$_3$, Corundum, Pervoskite, Ilmenite and Calcite.............................................................................................................................................154
  ❖ Problems ............................................................................................................................. 178
  ❖ Bibliography ......................................................................................................................... 179

CHAPTER 7 ................................................................................................................................... 180

Metal-Ligand Bonding: ................................................................................................................ 180
  ❖ Limitation of Crystal Field Theory.......................................................................................... 180
  ❖ Molecular Orbital Theory – Octahedral, Tetrahedral or Square Planar Complexes.............. 184
  ❖ π-Bonding and Molecular Orbital Theory ............................................................................. 198
  ❖ Problems ............................................................................................................................. 212
  ❖ Bibliography ......................................................................................................................... 213
CHAPTER 11 ................................................................................................................................. 426

Metal-Π Complexes: ......................................................................................................................... 426

Metal Carbonyls: Structure and Bonding ...................................................................................... 426

Vibrational Spectra of Metal Carbonyls for Bonding and Structure Elucidation .......................... 439

Important Reactions of Metal Carbonyls .................................................................................... 446

Preparation, Bonding, Structure and Important Reactions of Transition Metal Nitrosyl, Dinitrogen and Dioxygen Complexes ......................................................................................... 450

Tertiary Phosphine as Ligand ........................................................................................................ 463

Problems ........................................................................................................................................ 469

Bibliography .................................................................................................................................. 470

INDEX ............................................................................................................................................. 471
Mandeep Dalal is an Indian research scholar who is primarily working in the field of Science and Philosophy. He received his Ph.D in Chemistry from Maharshi Dayanand University, Rohtak, in 2018. He is also the Founder and Director of "Dalal Institute", an India-based educational organization which is trying to revolutionize the mode of higher education in Chemistry across the globe. He has published more than 40 research papers in various international scientific journals, including mostly from Elsevier (USA), IOP (UK) and Springer (Netherlands).

Other Books by the Author

A TEXTBOOK OF INORGANIC CHEMISTRY - VOLUME I, II, III, IV
A TEXTBOOK OF PHYSICAL CHEMISTRY - VOLUME I, II, III, IV
A TEXTBOOK OF ORGANIC CHEMISTRY - VOLUME I, II, III, IV