Chapter – I : Introduction

Compounds which do not react chemically on mixing, may not always be non-interacting. In fact, molecular non-covalent interactions do exist and they give rise to interesting physicochemical phenomena. Some well known and well established phenomena originating from such interactions are liquefaction of gases, existence of water in its liquid form, its anomalous expansion, and the formation of different conformers of peptide chains in proteins. Excess thermodynamic properties of liquid mixtures, which are of current interest among physical chemists,[1-3] are also results of intermolecular interactions. In some particular cases interaction between two different kinds of molecules forms 'molecular complexes' which are briefly discussed in the next section because the present thesis deals with such complexes involving some pharmaceutical molecules.

1.1 Molecular Complexes

When molecules of two different types form non-covalent adducts with definite stoichiometry (1:1 in most cases and sometimes 1:2) the resulting species is called a molecular complex. The known molecular complexes can be classified into the following broad types:

(1) *Charge Transfer* or *Electron Donor Acceptor Complexes.* Organic electron donor-acceptor (EDA) or charge-transfer (CT) complexes are loose molecular associations of two different molecules such that when they absorb light from the UV/Visible range an appreciable transfer of electronic charge occurs from the highest occupied molecular orbital (HOMO) of one molecule (called 'donor') to the lowest unoccupied

molecular orbital (LUMO) of the other (called 'acceptor'); in most cases, however, there is very little electron (charge) transfer in the ground state of the complex. The molecular adduct of *p*-chloranil (faintly yellow) and naphthalene (colourless) in CCl_4 medium exihibits a beautiful red colour. This is a well known example of CT complex. A new absorption band, known as CT absorption band, different from those of the components, appears almost instantaneously on mixing the component solutions. Mulliken[4,5] explained this by assuming that the ground and excited states of an EDA complex are given by the wave functions

$$\psi_G = a\,\psi_0\,(D....A) \;+\; b\,\psi_1\,(D^+ - A^-), \qquad a>>b \qquad ...(1.1)$$

$$\psi_E = a^*\,\psi_1\,(D^+ - A^-) - b^*\psi_0\,(D....A), \quad a^*>>b^* \qquad ...(1.2)$$

where $\psi_0\,(D....A)$ is the wave function of a 'no bond' structure $(D....A)$ and $\psi_1\,(D^+ - A^-)$ is that of a 'dative' structure $(D^+ - A^-)$. The 'no bond' structure is one in which the donor and acceptor molecules are held together by van der Waals types of forces and hydrogen bonds (where possible). The 'dative' structure means that one electron is completely transferred from the donor molecule to the acceptor molecule and the resulting ions are held together predominantly by electrostatic attraction. It is implied in equations (1.1) and (1.2) that both the ground and excited states of the CT complex are resonance hybrids of the 'no bond' and 'dative' structures, the former predominating in the ground state and the latter in the excited state. The energy ($h\nu_{CT}$) required for the transition

$$\psi_G \xrightarrow{h\nu_{CT}} \psi_E$$

is called 'charge transfer transition energy'. This energy usually corresponds to the UV or visible region of the electromagnetic spectrum. Experimentally, the formation of an EDA complex on mixing together the solutions of donor and acceptor is indicated by (i) the appearance of a new colour or a new absorption band in the UV region different from the

absorption bands of the component substances and (ii) formation of no new compound other than the adduct whose formation constant (K) can be determined, in case of 1:1 stoichiometry, from the equation

$$K = \frac{[AD]}{[A][D]} \qquad \ldots(1.3)$$

Here, the square brackets denote the concentrations of the enclosed species after establishment of the equilibrium, $A + D \rightleftharpoons AD$.

(2) *Hydrogen bonded molecular complex.* The widely used electrode material, Quinhydrone, is an example of such a complex of 1:1 stoichiometry. The H atoms of the phenolic –OH groups of hydroquinone form hydrogen bond with the oxygen atoms of 1,4-benzoquinone to form quinhydrone. In aqueous solution the following equilibrium exists:

1,4-benzoquinone + hydroquinone $\rightleftharpoons$ quinhydrone.

(3) *Host-guest or Inclusion complexes.* Molecules having cavities where other molecules or ions can be held by non-covalent bonds (mainly, van der Waals forces, π-π interaction and hydrogen bond) form a novel class of materials known as 'hosts'; cyclodextrins form the first of this type. They are cyclic oligosaccharides containing a minimum of six D(+) glucopyranose units attached by α-1,4 linkages. This was established by Freudenberg[6] *et. al.* Cyclodextrins are produced by the action of *Bacillus macerans* amylase on starch. The natural α-, β- and γ-cyclodextrins (α-CD, β-CD and γ-CD) consist of 6,7 and 8 units of glucose respectively. Their ability to form inclusion complexes in aqueous solution is due to the typical arrangement of glucose units as shown in Figure 1.1.

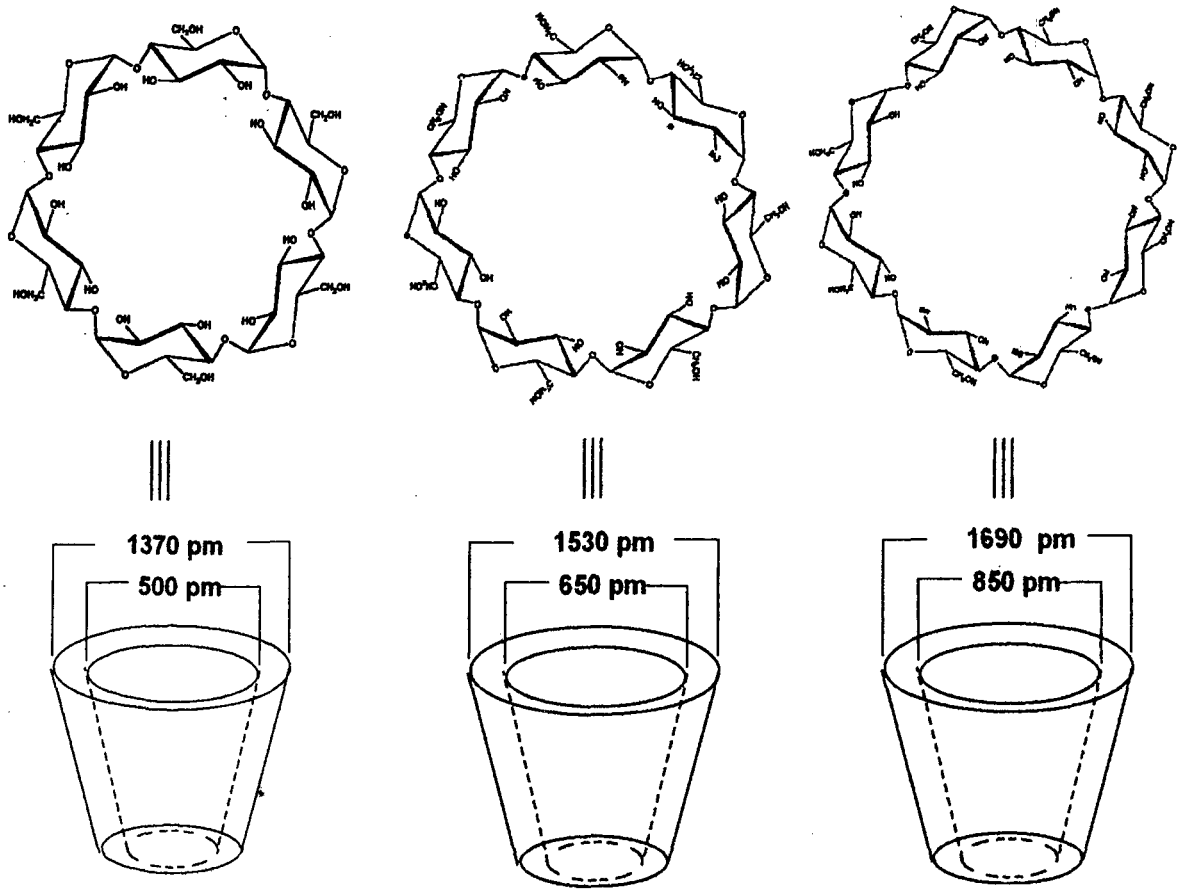

Figure 1.1

An isolated cyclodextrin molecule looks like a torus (or doughnut ring). But the molecule in aqueous solution assumes a truncated cone conformation[7,8] due to hydrogen bonding of the –OH groups with water. In such conical conformation the cone-height is about 800 pm and the inner diameter of the cavity is between 500 and 850 pm (Figure 1.1). A fascinating property of the cyclodextrins is their ability to incorporate other organic compounds into their cavity, both in the solid state and in solution. This was first recognized by Freudenberg and later substantiated through complexation studies by Cramer, Saenger and others.[9-12] Owing to non-toxicity of cyclodextrins, their ability to form inclusion complex has led to very important pharmaceutical application.

For example, an important drug molecule included[13] in γ-CD is Mytomycin C, the inclusion complex being shown in Figure 1.2. The aziridine ring (Figure 1.3) of Mytomycin C being well within the hydrophobic cavity of γ-CD, is protected[14] from degradation in acidic solution.

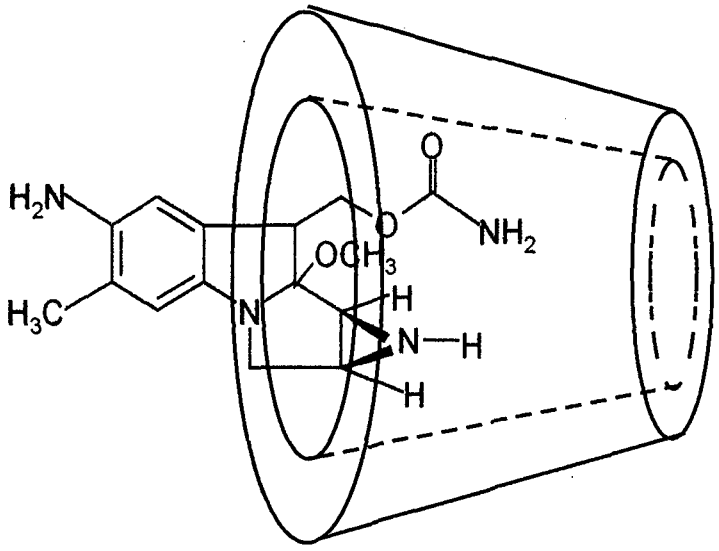

Figure 1.2

Mytomycin C included in γ-CD

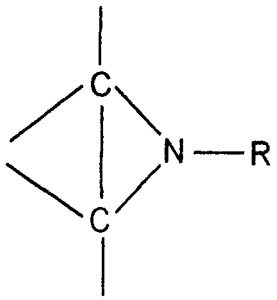

Figure 1.3

Aziridine ring

Cyclodextrins are studied as solubilizing and stabilizing agents in pharmaceutical dosage forms. Lach[15-16] *et. al* utilised the complexing ability of cyclodextrins to trap, stabilize and solubilize sulphonamides, tetracyclines, morphine, aspirin, benzocaine, ephedrine, reserpin and testosterone. The aqueous solubility of retionic acid (0.5 mg dm^{-3}), a drug used topically in the treatment of acne,[17] is increased to 160 $mg.dm^{-3}$ by

complexation with β-CD. Dissolution rate plays an important role in bio-availability of drugs, fast dissolution usually favouring absorption. Thus, the dissolution rate of famotidine,[18] a potent drug in the treatment of gastric and duodenal ulcer and tolbutamide, an oral antidiabetic drug, are both increased by complexation[19] with β-CD. If some –OH groups are alkylated, the resulting cyclodextrin has been reported to be useful in sustained drug release. Thus, ethylated β-CD has been used[20] to retard, through inclusion complex formation, the delivery of isosorbide dinitrate, a vasodilator.

Some other known host molecules are crown ethers, calix[n]arenes and resorcin[n]arenes. While crown ethers are best known for their capacity to form complexes with metal ions, all these three types of hosts have been reported to include [60]- and [70]fullerenes in their cavity.[21,22] Recently three resorcin[4]arene capped porphyrines have been synthesized and shown[23] to include water, methane and benzene, and to inhibit the oxidation of Co(II) to Co(III). A number of chiral resorcin[4]arenes have been synthesized and their enantioselectivity through cavity effects have been shown recently by Botta *et.al.*[24-27] Three resorcin[5]arenes decamethyl ethers containing cyanomethyl side chains have recently been synthesized by the same group.[28] Such macrocyles are of great importance in molecular recognition studies through inclusion complex formation with selective guests.

1.2 Absorption spectrometric method for determination of formation constants of molecular (CT) complexes

Several methods (such as those involving solubility measurement,[29]calorimetry,[30] nuclear magnetic resonance[31] etc.) are

known for determination of formation constants of molecular complexes. However, the spectrophotometric method is the most widely used. In this method, solutions of the component substances are mixed at known concentrations and the absorbances of the mixtures are measured at suitable wavelengths against appropriate references. The first equation for employing spectrophotometric data for determination of formation constant (K_{DA}) and molar absorptivity (ϵ_D) of a 1:1 molecular complex was derived by Benesi and Hildebrand.[32] The equation is,

$$\frac{[A]_0}{d} = \frac{K_{DA}\,\epsilon_{DA}}{[D]_0} + \frac{1}{\epsilon_{DA}} \qquad \ldots (1.4)$$

where $[A]_0$ and $[D]_0$ are concentrations of the acceptor and donor respectively in the mixture before complexation, the optical path length of the cell used is 1 cm, d is the absorbance of the mixture, and ϵ_{DA} is the molar absorptivity of the complex at the wavelength of measurement. The equation is based on the following assumptions:

(a) Only the complex absorbs at the wavelength of measurement

(b) $[D]_0 >> [A]_0$

Ketelaar[33] modified this equation, for cases where the acceptor also absorbs at the wavelength of measurement, to the form

$$\frac{1}{(\epsilon_a - \epsilon_A)} = \frac{1}{(\epsilon_{DA} - \epsilon_A)K_{DA}} \cdot \frac{1}{[D]_0} + \frac{1}{(\epsilon_{DA} - \epsilon_A)} \qquad \ldots (1.5)$$

(for measurement in a cell of 1 cm path-length)

where $\epsilon_a - \epsilon_A$ = apparent extinction coefficient of the mixture = $d/[A]_0$

In applying any of the equations (1.4) and (1.5), the wavelength is so chosen that the donor does not absorb significantly and the donor solution at concentration $[D]_0$ is used as reference. The molar extinction coefficient of the acceptor (ϵ_A) at the wavelength for measurement is either known or measured separately. The plot of $[A]_0/d$ or $1/(\epsilon_a - \epsilon_A)$ against $1/[D]_0$ should be linear; dividing the intercept by the slope, values of K_{DA} can be determined.

Several objections may be raised to the equations (1.4) and (1.5). Firstly, evaluation of K_{DA} requires the intercept, i.e. extrapolation of the line to $[D]_0 \rightarrow \infty$. To get rid of this, Scott[34] rearranged the Benesi-Hildebrand equation, by multiplying equation (1.4) by $[D]_0$, to the form

$$\frac{[A]_0[D]_0}{d} = \frac{[D]_0}{\epsilon_{DA}} + \frac{1}{K_{DA}\,\epsilon_{DA}} \qquad \ldots(1.6)$$

In this equation, extrapolation to dilute solutions ($[D]_0 \rightarrow 0$) is required. Foster [35] *et. al.* suggested the rearrangement

$$\frac{d}{[D]_0} = -K_{DA}d + K_{DA}\,\epsilon_{DA}\,[A]_0 \qquad \ldots(1.7)$$

which requires no such extrapolation and gives K_{DA} from the slope directly.

Secondly, Drago and Rose[36] pointed out that under the condition $[D]_0 >> [A]_0$ the solution to the final equation depends on the differences in the sets of experimental data; for example, if $[D]_0^1$, $[D]_0^2$, ..., $[D]_0^{15}$ be the donor concentrations used in an experiment to generate 15 data points keeping $[A]_0$ fixed (which is the usual practice) then the result depends on the differences $[D]_0^1 - [D]_0^2$, $[D]_0^2 - [D]_0^3$, and so on .

An equation free from these objections which does not impose any concentration condition on the method of measurement has been derived by Rose and Drago.[37] This equation is

$$\frac{1}{K_{DA}} = \frac{[A]_0[D]_0(\epsilon_{DA} - \epsilon_A)}{d - d_A^0} - [A]_0 - [D]_0 + \frac{d - d_A^0}{\epsilon_{DA} - \epsilon_A} \qquad \ldots(1.8)$$

where $d^0_A = [A]_0 \epsilon_A$ and the other symbols have meanings already defined. The authors themselves gave a graphical procedure for solving this equation. This consisted of random selection of ϵ_{DA} values and calculation of $1/K_{DA}$ using equation (1.8) from one set of experimental data (i.e. with one particular value of $[A]_0$ and $[D]_0$), plotting $1/K_{DA}$ as a function of ϵ_{DA}, repetition of this procedure with other sets and finally evaluating K_{DA} and ϵ_{DA} from the common point of intersection of the curves which are in most cases linear. But making the initial guess of a series of ϵ_{DA} values for each set of experimental data is difficult and renders this graphical method laborious and sometimes impossible to employ. In addition, in many cases the Rose-Drago plot shows a wide scatter[36] in the values of K_{DA} and ϵ_{DA}. Sometimes the Rose-Drago curves constructed for a set of experimental data may be parallel giving no intersection at all.[38a] Aranaud and Bonnier[39] gave an iterative method for solving the Rose-Drago equation. But this method requires an intuitive guess value of K_{DA} to start with, for the iteration to converge. One graphical method, which is more direct and less laborious than Rose and Drago's original method was developed by Seal[38b] *et. al.*; the same authors gave a numerical method for solving the Rose-Drago equation (1.8). It is however, known that when $[D]_0$ is more than 10^2 times higher than $[A]_0$, the Benesi-Hildebrand equation gives the same result as that given by the Rose-Drago equation.

If at the absorption peak λ_{CT} of the complex DA, the donor and the acceptor both have small but appreciable absorption and the measurement is done with the solvent as reference, the above equations have to be used with corrections for the absorbances of the donor and acceptor. Thus, if d is the observed absorbance of the equilibrium mixture containing the complex and the uncomplexed donor and acceptor, then

$$d = \epsilon_{DA}[DA] + \epsilon_D[D] + \epsilon_A[A]$$ (for measurement with a cell of 1 cm optical length)

$$= \epsilon_{DA}[DA] + \epsilon_D([D]_0 - [DA]) + \epsilon_A([A]_0 - [DA])$$

$$= (\epsilon_{DA} - \epsilon_D - \epsilon_A)[DA] + \epsilon_D[D]_0 + \epsilon_D[A]_0$$

$$= (\epsilon_{DA} - \epsilon_D - \epsilon_A)[DA] + \epsilon_D[D]_0 + \epsilon_D[A]_0$$

$$= (\epsilon_{DA} - \epsilon_D - \epsilon_A)[DA] + d^0_D + d^0_A \quad \ldots(1.9)$$

where d^0_D and d^0_A are respectively the absorbances of the donor and acceptor solutions at their initial concentrations before complexation; these can be measured separately at λ_{CT} using the pure donor and acceptor solutions at concentrations $[D]_0$ and $[A]_0$. One can now define a corrected absorbance d' as follows:

$$d' = d - d^0_D - d^0_A$$

$$= (\epsilon_{DA} - \epsilon_D - \epsilon_A)[DA]$$

$$= \epsilon'[DA] \quad \ldots.(1.10)$$

where $\epsilon' = (\epsilon_{DA} - \epsilon_D - \epsilon_A)$ $\ldots.(1.11)$

With these definitions the Benesi-Hildebrand equation retains the same form as equation (1.6), only d and ϵ_{DA} are to be replaced by d' and ϵ' respectively; similarly, the Rose-Drago equation retains the same form

as equation (1.8) with replacement of $d - d^0_A$ and $\epsilon_{DA} - \epsilon_A$ by d' and ϵ' respectively.

1.3 Areas of occurrence and application of CT complexes

CT complexes occur in a wide variety of systems and have found a variety of applications as discussed in the following paragraphs.

(1) In *biological systems.* There are ample evidences[40,41] for the occurrence of CT complexes in biological systems. The action of a drug in a biological system is ultimately the result of physicochemical interactions[42,43] between the drug molecule and the functionally important molecules known as 'receptors' present in living systems.[44,45] According to the Michaelis-Menten mechanism[46] of enzyme catalysis, the enzyme (E) forms an adduct with the substrate which may sometimes involve CT interaction.[47,48] Some other biologically important CT complexes are those of 1,3,7,9-tetramethyluric acid[49] and various amino acids[50] with the semiquinone derived from riboflavin. Birks and Slifkin[51] have shown the importance of quinones as models in many biochemical reactions in living systems and Pryor[52] *et. al.* have shown that among the carcinogenic cigarette tars the predominant one is a complex between 1,4-benzoquinone and hydrocarbon groups in a polymeric matrix.

Involvement of CT complex formation in bioelectrochemical energy transfer processes is a subject of current research activity.[53-57] A detailed

review of biological systems involving EDA complexes may be found in references.[58,59]

(2) As *reaction intermediates*. In many nucleophilic and electrophilic substitution reactions molecular complexes of CT type have been reported to act as intermediates. For example, the observed rate of the reaction between 2,4-dinitrochlorobenzene (N) and aniline (An) in ethanol medium has been explained[60] by assuming the following two paths:

$$N + An \rightarrow \text{products}$$

$$N + An \rightleftharpoons N{\cdot}An \rightarrow \text{products}$$

Here, owing to the presence of strongly electron-withdrawing nitro groups, N is an electron acceptor while aniline is a known electron donor and the assumption of the EDA intermediate (N·An) is quite plausible. The rate of acetolysis of 2,4,7-trinitro-9-fluorenyl-*p*-toluene sulphonate (an electron acceptor) has been shown to be enhanced[61] by π-electron donors like hexamethylbenzene, phenanthrene and anthracene; the observed catalysis in this case has been interpreted in terms of CT complex formation between the π-donors and the trinitrofluorene derivative in the activated state rather than in the ground state. Detailed discussion about CT complexes occuring as reaction intermediates may be found in references.[62-66]

(3) For *measuring solvent polarity*. The EDA complex between 1-ethyl 4-carbomethoxypyridinium cation and iodide ion shows a CT transition energy which is very sensitive to change in solvent polarity. Its transition energy (Z, in Kcal / mol) in a particular solvent is used as an empirical measure of the polarity of that solvent.[67-69]

(4) For *determination of molar mass*. Molar masses of aromatic hydrocarbons and some amines have been determined[70] spectrophotometrically through CT complex formation with suitable acceptors (e.g. 1,3,5-trinitrobenzene in case of aromatic hydrocarbons).

(5) In *chromatographic separations*. The selective adsorption of different donor species on chromatographic stationary phases containing electron acceptors (or the converse phenomenon) has been utilised[71] for separation of mixtures of donors / acceptors.

(6) As *new materials in the solid state*. In the solid state, some CT complexes have been found to be electrically conducting. For example,[72] the complex between tetracyanoquinodimethane (TCNQ, an acceptor) and tetrathiafulvalene (TTF, a good π-electron donor) has a conductivity, $\sigma = 1.47 \times 10^4$ S / cm at 66 K, a conductivity approaching that of metals (Cu at 298 K has $\sigma = 6 \times 10^5$ S / cm). Calvin and co-workers[73,74] found that complexes of *o*-chloranil i.e., 3,4,5,6-tetrachloro 1,2-benzoquinone) with phthalocyanine and violanthrene show a large increase in electrical conductivity compared to the sum of the conductivities of the individual donors and acceptors. They have also detected photoconduction in thin films of these CT complexes. A photovoltaic effect has been shown[75] with thin films containing porphyrene-*o*-chloranil CT complexes and involvement of such complexes in storage and conversion of solar energy is an important field of research.[76] In the solid state the properties of CT complexes cannot be completely explained by the simple Mulliken theory; a detailed analysis of solid state properties (like specific heat, magnetic properties etc) has been done theoretically by Soos and Klein .[77]

(7) In *micellar media*. Some studies of CT complexes in micellar media have been reported.[78-80] Because of the intrinsic importance of such media themselves, these studies are of potential technological value.

(8) As *initiators in polymerization.* CT complexes of quinoline, isoquinoline, lepidine and N,N-dimethylaniline as donors and halogens, benzophenone and benzenesulphonyl chloride as acceptors have been shown to photo-initiate polymerization reactions.[81,82]

(9) In *inclusion phenomena* (host-guest complexation). A good number of inclusion complexes have been shown where [60]-and [70]fullerenes act as guest as well as electron acceptor.[21,22]

(10) *In devising molecular machines.* Designing molecular shuttles by utilization of the phenomenon of electron (charge) transfer is a current field of research.[83-86] Such molecular machines are either electro-chemically driven or photo-induced. They are of immense potential utility in making use of solar energy

References

1. W. Marczak, *Phys. Chem. Chem. Phys.* **2002**, *4*, 1889
2. A.Pal and H.Kumar, *Physics and Chemistry of Liquids* **2003**,*41*,405
3. A.Pal , *Indian J. Chem A,* **2007**, *46*, 755
4. R. S. Mulliken, *J. Am. Chem. Soc.*,**1952**, *74*, 811
5. . R. S. Mulliken, *J. Phys. Chem.*, **1952**, *56*, 801
6. K. Freudenberg and F. Cramer, *Z. Naturforsch., Teil B*, **1948**, *3*, 464
7. K. Cabrera and G. Schwinn, *American Laboratory,* June, **1990**, 22
8. D. Duchene and D. Wouessidjewe, *Pharm. Tech.*, June, **1990**, 26
9. F. Cramer and H. Hettler, *Naturwissenschaften*, **1967**, *54*, 625
10. W. Saenger, *Angew. Chem.*, **1980**, *92*, 343
11. W. Saenger, in *Inclusion Compounds*, Vol. 2 (J. L. Atwood, J. E. D. Davies and D. D. MacNicol, Eds.) Academic Press, London, **1984**
12. J. Szejtli, *Kontakte (Darmstadt)*, **1988**, No. 1, 31
13. O. Beckers, *Int. J. Pharm.*, **1989**, *52*, 240
14. O. Beckers, J. H. Beijnen, E. H. G. Bramel, M. Otasgiri, A. Bult and W. J. M. Undurberg, *Int. J. Pharm.*, **1989**, *52*, 239
15. J. L. Lach and J. Cohen, *J. Pharm. Sci.*, **1963**, *52*, 137
16. W. A. Pauli and J. Lach, *J. Pharm. Sci.*, **1965**, *54*, 1945
17. J. Lach, and W. A. Pauli *J. Pharm. Sci.*, **1966**, *55*, 32
18. D. Amdidouche, H. Darrouzet, D. Duchêne and M.-C. Poelman, *Int. J. Pharm.*, **1989**, *54*, 175
19. M. A. Hassan, M. S. Suleiman and N. M. Najib, *Int. J. Pharm.*, **1990**, *58*, 19
20. F. Hirayama, N. Hirashima, K.Abe, K.Uekama, T. Ijitsu and M. Ueno, *J. Pharm.Sci*, **1988**, *77*, 233
21. K.Datta, M. Banerjee, A.K. Mukherjee, *J. Phys. Chem.* B, **2004,** *108*, 16100

22. A.Saha, S.K.Nayak, S. Chattopadhyay, A.K. Mukherjee, *J. Phys. Chem.* B, **2003,** *107*, 11889

23. B. Botta, P.Ricciardi, C. Galeffi, M.Botta, A. Tafi, R. Pogni, R.Iacovino, I.Garella, B.D. Blasio and G.D. Monache *Org. Biomol. Chem.*, **2003,** *1*, 3131

24. B. Botta, M.Botta, A. Filippi, A. Tafi, G.D. Monache, M. Speranza, *J. Am. Chem. Soc.*, **2002,** *124*, 7658

25. A. Tafi, B. Botta , M.Botta, G.D. Monache, A. Filippi, M. Speranza, *Chemistry*, **2004**,*10*, 4126

26. B. Botta, G.D. Monache, P.Ricciardi, G. Zappia,C. Seri, E. Gacs-Baitz, P. Csokasi, D. Misiti, *Euro. J. Org. Chem.*, **2000,** 841

27. B. Botta, D. Subissati, A. Tafi, G.D. Monache, A. Filippi, M. Speranza, *Angew. Chem. Int. Ed. Engl.* **2004**, *43*, 4767

28. I. D' Acquarica, L. Nevola, G.D. Monache, E. Gacs-Baitz, C. Massera, F. Ugozzoli, G. Zappia, B. Botta, *Euro. J. Org. Chem.* **2006**, 3652

29. L. J. Andrews and R. M. Keefer, *J. Am. Chem. Soc.*, **1949,** *71*, 3644; **1950,** *72*, 3113, 5034

30. T. F. Bolles and R. S. Drago, *J. Am. Chem. Soc.*, **1965**, *87*, 5015

31. C. J. Creswell and A. L. Allred, *J. Phys. Chem.*, **1962**, *66*, 1469

32. H. A. Benesi and J. H. Hildebrand, *J. Am. Chem. Soc.*, **1949**, *71*, 2703

33. J. A. A. Ketelaar, C. Van de stolpe, A. Goudsmidt and W. Dzcubas, *Rec. Trav. Chim.*, **1952**, *71*, 1104

34. R. L. Scott, Proc. Int. conf. on coordination compounds Amsterdam. **1955,** p. 265 ; Recl. Trav. Chim. Pays- Bas Belg., **1956**, *75*, 787

35. R. Foster, D. Ll.Hammick and A. A. Wardley, *J. Chem. Soc.*, **1953**, 3817

36. N. J. Rose and R.S. Drago, *J. Am. Chem. Soc.*,**!959**, *81*, 6138

37. R.S. Drago and N. J. Rose. *J. Am. Chem. Soc.*,**!959**, *81*, 6141

38. (a) B. K. Seal, A. K. Mukherjee and D. C. Mukherjee, *Bull. Chem. Soc. Japan,* **1979**, *52*, 2088

(b) B.K. Seal, A. K. Mukherjee and D. C. Mukherjee, *Z. Phys. Chemie (Leipzig)*, **1984**, *265*, 353

39. R. Arnaud and J. M. Bonnier, *J. Chim. Phys.*, **1969**,*66*, 954

40. A. Szent-Gyorgyi, *Bioenergetics*, Academic Press, New York, **1957**; *Introduction to a Submolecular Biology*, Academic Press, New York, **1961**; *Bioelectronics*, Academic Press, New York, **1968**

41. R. Foster, *J. Phys. Chem.*, **1980**, *84*, 2135

42. A. Goldstein, L. Aronow and S. Kaplan *Principle of Drug Action*: *The basis of pharmacology,* Second.edition. Wiley, New York, **1974,** chapter 1

43. A. Albert, *Selective Toxicity,* 6th edn., Chapman and Hall, London, **1979**, chapter 2

44. A. Korolkovas, *Essentials of Medicinal Chemistry,* 2nd.edn., Wiley, New York, **1988**, chapter 3

45. R. Mandal (Karan) and S.C. Lahiri, *J. Indian Chem. Soc.,* **1999**, *76*, 347

46. L. Michaelis and M.L. Menten, *Biochem.*, **1913**, *49*, 333

47. J. G. Heathcot and M. A. Slifkin, *Biochim. biophys. Acta,* **1968**, *158*, 167

48. A.K Mukherjee and A. K. Chattopadhyay, *J. C. S. Perkin Trans.* **2**, **1992**, 1081

49. M. A. Slifkin, *Biochim. biophys. Acta,* **1965**, *109*, 617

50. M. A. Slifkin, *Nature,* **1963**, *197*, 275

51. J. B. Birks and M. A. Slifkin, *Nature*, **1963**, *197*, 42

52. W. A. Pryor, B. J. Habes, P. I. Premovic and D. F. Church, *Science,* **1983**, *220*, 425

53. M.J. Frost, *Phys. Chem. Chem. Phys.*, **2003**, 5, 3169

54. Y.-B. Wang, Z. Lin, *J. Am. Chem. Soc.*, **2003**, 125, 6072

55. D. M. Guldi, C. Luo, M. Prato, A. Troisi, F. Zerbetto, M. Scheloske, E. Dietel, W. Bauer, A. Hirsch, *J. Am. Chem. Soc.*, **2001**, 123, 9166

56. D. M. Guldi, C. Luo, M. Prato, E. Dietel, W. Bauer, A. Hirsch, *J. Chem. Soc., Chem. Commun.*, **2000**, 373

57. H. Nakayama, H. Ohno, Y. Okahata, *J. Chem. Soc., Chem. Commun.*, **2001**, 2300

58. R. Foster, Organic Charge Transfer Complexes, Academic Press, London, **1969**, chapter 12

59. M. A. Slifkin, *Charge Transfer Interaction in Biomolecules,* Academic Press, London, **1971**

60. S. D. Ross and I. Kuntz, *J. Am. Chem. Soc.*, **1954**, *76*, 3000

61. A. K. Colter and S. S. Wang, *J. Am. Chem. Soc.*, **1963**, *85*, 114

62. L. J. Andrews and R. M. Keefer, *Molecular Complexes in Organic Chemistry,* Holden-Day, Inc., London, **1964**, pp.146-180

63. R. S. Davidson in *Molecular Association*, Vol 1, edited by R. Foster, Academic Press New York, **1975**, chapter 4

64. T. Roy, K. Datta, M. K. Nayak, A. K. Mukherjee, M. Banerjee, and B. K. Seal, *Perkin Trans 2,* **1999**, 2219

65. K. Datta, A. K. Mukherjee, M. Banerjee, and B. K. Seal, *Spectrochim Acta A*, **1997**, 53, 2587

66. M. Krishnamurthy, K. Surendrababu and U. Muralikrishna, *Indian J. Chem. A,* **1988**, *27*, 669

67. E. M. Kosower and E. P. Klinedinst, *J. Am. Chem. Soc.,* **1956**, *78*, 3493

68. E. M. Kosower, *J. Am. Chem. Soc.,* **1956**, *78*, 5700

69. E. M. Kosower, *J. Am. Chem. Soc.,* **1958**, *80*, 3253

70. J. C. Godfrey, *Analyt. Chem.* **1959**, *31*, 1087

71. M. Frank-Neumann and P. Jossang, *J. Chromat,* **1964**, *14*, 280

72. F. Vögtle, *Supramolecular Chemistry : An introduction*, (John Wiley & Sons, New York), **1991**, chapter 10 and references cited therein

73. D. R. Kears, G. Tollin and M. Calvin, *J. Chem. Phys.*, **1960,** *32*, 1020

74. D. R. Kears, and M. Calvin, *J. Am. Chem. Soc.*, **1961**, *83*, 2110

75. K. Takahashi, K. Horino, T. Komura and K. Murata, *Bull. Chem. Soc. Japan*, **1993**, *66*, 733

76. See Special Issue on Photochemical Conversion and Storage of Solar Energy, *Proc. Indian Acad. Sci. (Chem. Sci)* **1997,** *109*

77. Z. G. Soos and D. J. Klein in *Molecular Association,* **Vol. 1** edited by R. Foster, Academic Press, New York, **1975**, chapter 1

78. B. B. Bhowmik and M. Mukhopadhyay, *Colloid Polym. Sci.* **1988**, *266*, 672

79. M. Mukhopadhyay, C. Senvarma and B. B Bhowmik, *Colloid Polymer Sci.*, **1990**, *268*, 447

80. B. K. Paul, D. C. Mukherjee and S. P. Moulik, *J. Photochem. Photobiol. A: Chem.*, **1996**, *94*, 53

81. P. Ghosh and S. Chakraborty, *Macromol. Chem.*, **1980**,*181*, 2697

82. L. P. Nayak and S. Nayak, *J. polym. Sci. Polym. Chem. Ed.*, **1984**,*22*, 429

83. A. Mateo-Alonso , G. Fioravanti , M. Marcaccio , F. Paolucci , G. M. A. Rahman , C. Ehli , D. M. Guldi, M. Prato, *Chem Commun.* **2007**, 1945

84. D. M. Guldi, *Phys Chem Chem Phys.* **2007**, *9*, 1400

85. T. Torres, A. Gouloumis, D. Sanchez-Garcia, J. Jayawickramarajah, W. Seitz , D. M. Guldi , J. L. Sessler, *Chem. Commun.* **2007,** 292

86. C. Pol, M. Bryce, M. Wielopolski, C. Atienza-Castellanos , D. M. Guldi, S. Filippone , N. Martin, *J. Org. Chem.*, **2007**, *72*, 6662