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Molecular Recognition In Present Scenario

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ABSTRACT

Design and synthesis of supramolecular systems from the appropriate synthons through non covalent interactions is currently attracting the attention of chemists not only for their biological involvement but also for various technologically important applications such as molecular recognition, transport, biosensors, non linear optics and microelectronics etc. The self assembly of complementary fragments occurs through nature and plays and essential role in construction of biological superstructure. The small subunits bind together reversibly through weak, multiple noncovalent interactions. Recently, considerable efforts have been focused on the use of simple synthetic systems to probe the determinants of the natural self assembly. Indeed, a number of elegant organic self – assembling systems are now known. In the present communication a full range of noncovalent forces including π-π stacking, hydrogen bonding and hydrophobic interactions have been abstracted and described as recognition motifs.

KEYWORDS

Supramolecular;
Non-covalent interaction;
Self assembly;
Molecular recognition.

INTRODUCTION

Molecular organization and molecular interactions are the basis of the functional properties of most molecules and a detailed understanding of noncovalent chemistry is therefore fundamental to interpreting and predicting relationships between chemical structure and function.

Molecular recognition is defined by the energy and the information involved in the binding and selection of substrate by given receptor. Molecular recognition processes are influenced by many different factors which make their study complicated. Progress requires a quantitative understanding of these different factors. Some key functional group interactions such as H-bonding are well understood. H-

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bonds are strong single point interactions with very well defined geometry and their magnitude is determined by the electrostatic forces between the donor hydrogen atom and the acceptor atom. For weaker less well-defined interactions the picture is not so clear.

Molecular interactions from the basis of highly specific recognition reaction transport regulation etc that occur in biology such as substrate binding to a receptor protein enzymatic reactions assembling of multi-protein complexes immunological antigen-antibody association intermolecular reading translation and transcription of the genetic code, regulation of gene expression by DNA, binding proteins, entry of a virus into cell signal induction by neurotrasmitters, cellular recognition and so on.

The design of artificial abiotic systems capable of displaying processes of highest efficiency and selectivity requires the correct manipulation of the energetic and stereo-chemical features of the non covalent intermolecular forces within defined molecule architecture. The interaction between carbohydrate and proteins mediated a broad range of biological activities. The mechanism that govern how oligosaccharides are accommodated in binding sites of lectins, antibodies and enzymes is currently topic of major interest[1]. It is now recognized that the single molecule sugar- protein interactions are weak in nature and that multivalency is a key feature for the molecular recognition process to take place[2].The physicochemical nature of sugar-protein interactions has been matter of debate for years[3].

It has been widely recognized that arene π-stacking play crucial role in biological systems such as DNA and RNA[4], molecular recognition[5] and chemical engineering of new materials with intriguing properties including optical non-linearity[6]. Although π-stacking is common motif in life and materials sciences[7].

For examples that exclusively afford face to face interactions between aryl π-stacking system have been reported to data[8]. In the chemistry of nucleic acids Watson-Crick[9] base pairing is the most classical example of this behaviour.

The complementary hydrogen bonding structures as shown in figure 1 for adenine(A) and thymine(T) provide a vechicle for information transfer while stacking interaction between adjacent base pairs provide additional stability for the helical structure[10-15].

Figure 1: Base-pairing

Helix assembly takes place via a cooperative Zipper mechanism where the initial formation of the first few base pairs in an energetically unfavorable process. However once this nucleus is created new base pair formation leads to favourable contributions to the free energy[16].

Zimm.used the theory of melting to try to determine a value for the 'stacking free energy'-the energy gained when base pairs are stacked on each other in the helical arrangement[17-18]. The free energy was estimated to be -29 kJ/mole per base pair and double helix. Interaction between the in dividual bases and modified bases in aqueous solution have been studied by several groups[19-21]. Solvent effects have also been investigated using Raman laser temp-jump technique[22] again with conclusion that stacking interactions between the bases dominate the thermodynamics of helix formation[23].

More recently Guckian et al have looked at aromatic-stacking affinities in the context by DNA by substituting the terminal base for aromatic hydrocarbons such as benzene, naphthalene and pyrene[24]. Generally, increasing the size of the aromatic surface increased the melting temperature of the oligonucleotide.

Intercalation the interaction of small molecule with in DNA was first observed by Lerman when he studied the complex between DNA and acridine[25].

This process however causes a change in the physical characteristics of DNA as helix unwinds and bases unstack to allow the intercalator in. This leads to an increase in length of the DNA and a disruption of the regular structure. A variety of DNA intercalator have been found to reduce tumour growth animals and man and so these compounds are commonly used as anticancer agents.

In 1985 Burley and Petsko analyzed side chain interaction in proteins[26]. Two aromatic residues were considered to interact if distance between phenyl

centroids was less than 7Å. The results showed 60% of aromatic pairs and 80% of these were involved in networks of three or more interacting side chain. The most favoured distance between the rings was 5Å and most favoured dihedral angle was 90^0. Non-bonded potential energy were carried out showed a typical phenyl-phenyl interaction has an energy of between -4 and -8kJ/mol.

Hunter calculated the electrostatic interaction between two benzene molecules as function of orientation and compared it to the observed geometries of interacting phenylalanine rings in proteins with good correlation[27]. The perfectly stacked arrangement was not observed but a range of edge-to face and offset stacked geometries were found. Moreover a term like recognition bears no structural content and its expression in synthetic system requires choices concerning molecular shape complementary functionality surface type and rigidity vs flexibility.

Strong attractive interaction between π-system have been known for over a half century. They control such diverse phenomena such as vertical base-base interactions which stabilize the double helical structure of DNA, the interaction of drugs into DNA[28] the packing of aromatic molecules in crystals[29] the tertiary structure of proteins[30], the conformational preferences and binding properties of polyaromatic macrocycles[31] complexation in many host-guest system[32] and porphyrin aggrgation[33-34].

Full levin abinito calculation have been carried out for a limited number of small systems[35] and these do reproduce the experimental results well but they do not explain the basic mechanisms of π-π interaction in a way that is helpful or predictive for the practical chemist.

π-π interaction have been found in porphyrin systems. The π-π interaction is a type of properties of the atoms in range of intermolecular contact which controls the geometry of interactions. π-π interaction were reported by Christopher A[34] in porphyrin- porphyrin system.

It is reported that the π-π interaction is enhanced by porphyrin metalation but its geometry is unaltered[36(a)]. The greater the intermolecular polarization between the porphyrin and the metal, the stronger is the π-π interaction between two porphyrins[36(b)], while coordination of the metal by a ligand reduces the magnitude of the π-π interactions in metallo-porphyrins and generally leads to disaggregation. π-π interactions of porphyrins are not restricted to self aggregation, π-stacking being observed between porphyrins and a wide variety of covalently attached π-systems in organic solvents[37-39].

For any non covalent interactions between two molecules, it involves the interplay of several different effects which can be divided into five categories[40]:

1. Vander waals interactions which are the sum of the dispersion and repulsion energy. These define the size and shape specificity of non-covalent interactions. Aromatic moieties have large planar surfaces and so a stacked arrangement maximizes the vander waals contacts.
2. Electrostatic interactions between the static charge distributions. These are particularly important in conferring specificity on molecular recognition events.
3. The induction energy which is interaction between the static molecular charge distribution of one molecule and proximity-induced charge in the charge distribution of the others.
4. Charge transfer which is stabilization due to mixing of ground state with on excited charge separated state.
5. Desolvation: Two molecules which form a complex in solution must be desolvated before complexation can occur. The solvent may complete for recognition sites there by destabilizing the complex.

There is clear experimental evidence that VDW interactions, electrostatic interactions and desolution play an important role in molecular recognition. However there is not yet any experimental evidence that induction effects are as important.

Charge effects are commonly in aromatic molecules. Indeed there is an increasing body of evidence which shows that charge transfer(CT) and electron donor-acceptor effects are negligible compared with electrostatic[41].

There are different models for π-π interactions are as given below:

(a) Solvophobic Model
(b) The Electron-Donor Acceptor Model
(c) The Atomic Charge Model

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(a) Solvophobic model

π-stacking has been attributed to solvophobic effects which are essentially entropic in origin[42-44]. In organic solvent where solvophobic effects are not important[32a]. even in water enthalpic effects can be the important driving force favouring π-π interaction[45]. In addition solvophobic effects favour the geometry of maximum π- overlap, a situation which is rarely observed .

(b) The electron donor -acceptor (EDA) model

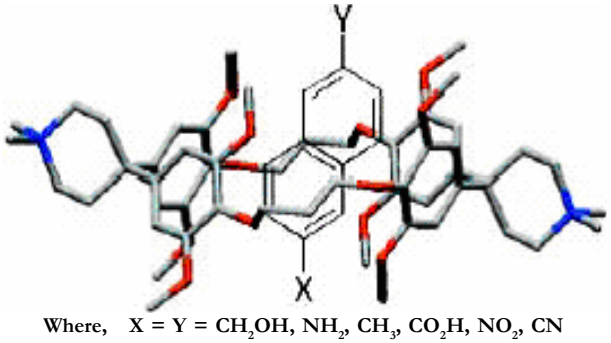
It has been suggested that the strong attraction is due to an electronic interaction between an electron donor and electron acceptor. We know that π-π* or charge transfer complexes formed between good electron donors and good electron acceptors[46,47]. However in the systems which we discuss here, no such effects are observed[32,48], even in cases where strong charge transfer interactions between two molecules are observed. Spectroscopically, the charge transfer interaction is only important in excited state and contributes relatively little to the overall energetic stability of the complex[46-48].

(c) The atomic charge model

We know that the attraction arises from the uneven charge distribution across the π-system[49]. For a particular orientation of two π- systems positively charged atoms on one molecule aligned with negatively charged atoms on the other, so that there is an attractive electrostatic interaction.

The major contributions to the interaction energy come from the electrostatic and Vander Waals components, induction generally being a second order term[35,50-52]. The apparent energy of interaction between the two molecules in solution includes association of the two molecules and displacement of solvent. However both the association and desolvation energies are likely to be associated with significant vander waals interactions.

Vander waals interaction can make an appreciable contribution to the magnitude of the π-π interaction, but since they are proportional to the area of π- overlap, they cannot be the force which controls the experimentally observed geometry of interaction. If they were, then π-overlap would be maximized and a cofacial arrangement with no offset would be observed.



Where, X = Y = CH_2OH, NH_2, CH_3, CO_2H, NO_2, CN

Figure 2: Cyclophane complexes used to study substituent effects by Diederich

Therefore there must be a large electrostatic barrier to π-overlap which dominates the geometry of interaction. π-π interactions rarely cause a distortion of the UV-visible spectra of the two chromophores, so the two interacting π-systems do not distort each others molecular orbitals. Thus it should be possible to explain the phenomenon on the basis of ground-state wave functions of the two π-systems, determined in the absence of any intermolecular interaction.

Ferguson and Diederich studied the complexation of a series of 2,6-disubstituted naphthalene derivatives by cyclophanes in d 4-methanol .

The interaction between host and guest have been most favourable for guests with electron withdrawing substituents such as X=CO_2H, NO_2 and CN and least favourable for those with electron donating substituents such as X=CH_2OH, NH_2 and CH_3[53]. The cyclophane can be thought of as a donor host with 4-phenyl rings substituted with electron donating methoxy groups. The most stable complexes were formed with electron poor guests, and this suggests that electrostatic interactions are the major factor determining the stability of the complexes.

No charge-transfer bands were observed in the UV–visible absorption spectra,indicating CT have not played any role in the stability of such complexes. This work demonstrated the importance of electronic complementary in the complexation of aromatic guests. Guests prefer the axial arrangement since this allows highly solvated polar substituents to poke out into the surrounding solvent minimizing any unfavourable desolvation. Analysis of the complexation induced shifts of the protons of the guest implied that naph-

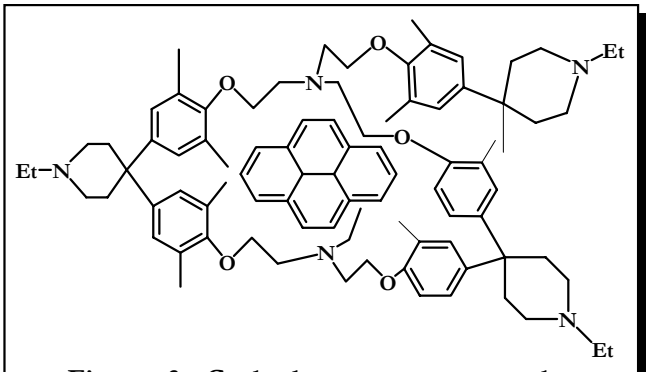


Figure 3: Cyclophane - pyrene complex

thalene molecules bearing electron accepting substituents are located more deeply within the cavity than those with donor substituents. The experiments were repeated in d6-dimethyl sulfoxide and the same trends in complexation strength were observed which suggests the differences between guests are not due to solvent effects.

The effect of solvent on aromatic interactions was also studied by Smithrud and Diederich using the complexation of pyrene by a different cyclophane[54].

Diederich's model describes the solvent properties which appear to be most important in determining the strength of a polar host-guest complexation. Binding is strongest in polar solvents possessing low molecular polarisability and high cohesive factors. Solvents with high cohesive interactions interact more strongly with "like" bulk solvent than with the a polar surfaces of the host and guest molecules, so when complexation takes place, free energy is gained upon the release of surface-solvating molecules to bulk solvent. Thus water is the best solvent for a polar binding Whitlock et al. designed a macrocyclic host to bind nitrophenol, K=9.6×104 M^{-1}[55, 56].

A combination of aromatic stacking interactions and hydrogen bonding was responsible for tight binding. Use of a more flexible linker reduced the binding constant to 6×10^3 M^{-1} indicating the importance of preorganisation.

Dougherty and co-workers used the system to examine the contributions of aromatic and ion-quadrupole interactions to complexation in aqueous media[57].

Hosts **(3)** and **(4)** have similar dimensions and comparable degrees of preorganisation. If the hydrophobic effect was dominant, then the cyclohexyl derivative should show the strongest binding

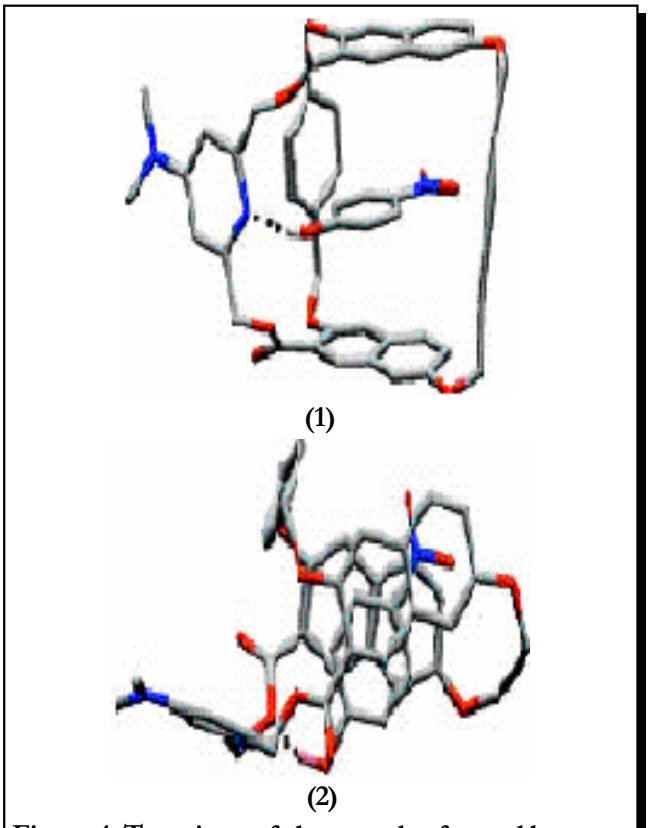


Figure 4: Two views of the complex formed between whitlock's bicycle and p-nitrophenol

The directionality of the cation-p effect was studied by Schwabacher and co-workers[58]. The cationic **(15)** and anionic **(16)** hosts were designed to study the interaction of charges with the edge of a bound aromatic ring.

Schneider and co-workers had previously shown enhanced binding of aromatic guests by cationic cyclophanes over anionic analogues[59].

In 1987, Hamilton and co-workers reported the synthesis of a class of thymine receptors which showed edge-to-face or stacked aromatic interactions depending on the electronic properties of the substituents[60-61] Macrocycle **(21)** formed a 1:1 complex with 1-butylthymine **(23)** (K=570 M^{-1} in chloroform). NMR studies indicated a stacked geometry which was confirmed by an X-ray crystal structure of figure 7(a) and 7(c).

Tetraether macrocycle **(22)** bound more weakly (K=138M^{-1}). MNDO calculations indicated a mismatch in the charge distributions for this system, and NMR spectroscopy and the X-ray crystal structure showed that an edge-to-face interaction is used to

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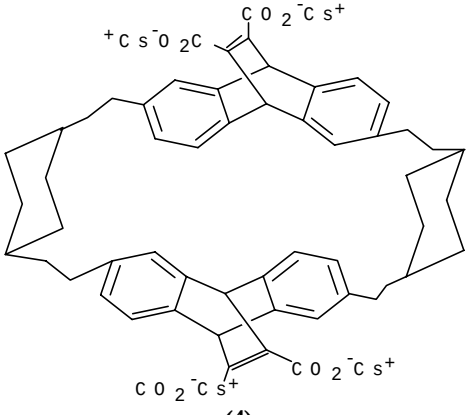
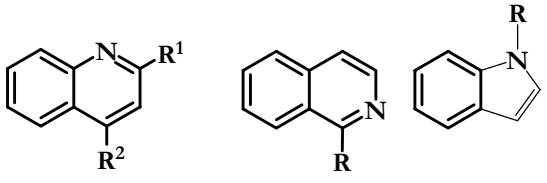
(3)



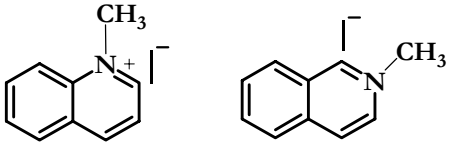
(4)



(5) $R^1=R^2=H$
(6) $R^1=CH_3$, $R^2=H$
(7) $R^1=H$, $R^2=CH_3$

(8) R=H
(9) $R=CH_3$

(10) R=H
(11) $R=CH_3$



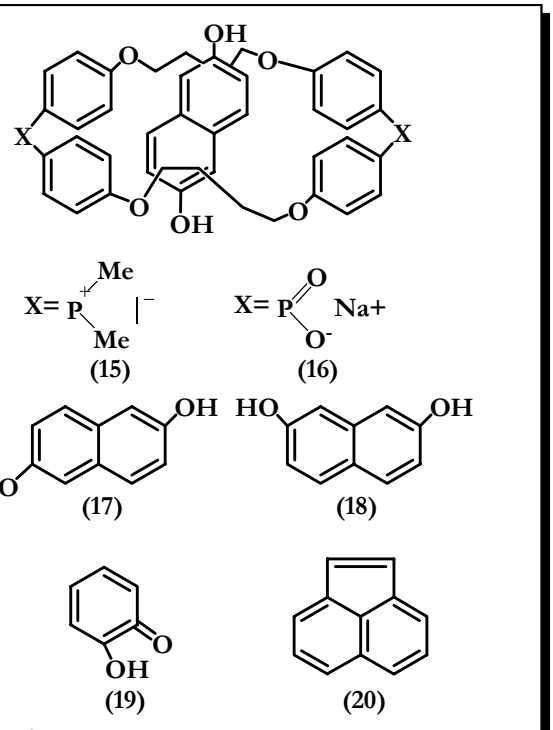
(12) (13)

Figure 5: Dougherty's phenyl host 3(X-ray structure) and cyclohexyl host 4 which binds guest molecules 5-13 in water

avoid stacking figure 7(b).

Rebek and Nemeth designed a molecular cleft **(24)** to bind aromatic guests figure 8[62] The binding of **(24)** to heterocyclic diamines was studied using 1H NMR spectroscopy. For pyrazine **(25)**, the binding constant was 1.4×103M^{-1} in chloroform.

Quinoxaline **(26)** showed a 15-fold enhancement



(15) (16)

(17) (18)

(19) (20)

Figure 6: Schwabacher's cationic (15) and anionic (16) cyclophane complexes and aromatic guests 17-20

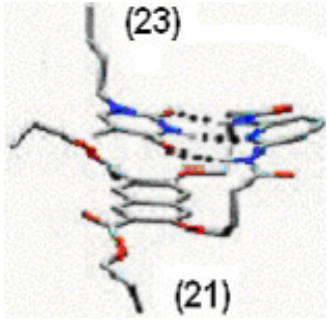
in binding (K=2.3×104 M^{-1}), due to a stacking interaction with the anthracene group which was revealed by up.eld shifts of the quinoxaline protons.

Rebek et al. later developed a synthetic system that can recognise adenine using Watson-Crick or Hoogsten hydrogen bonding and aromatic interactions figure 9[52].

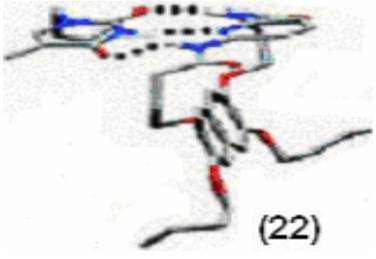
Kemp's triacid formed the basis of the receptor which could be substituted with a variety of aromatic groups of varying size and electronic properties. The phenyl and naphthalene systems show only a small increase in the association constant compared to the control methyl amide, whereas anthracene shows a nearly six-fold increase in binding constant which corresponds to a stacking interaction of 4.2 kJ mol^{-1}.

Chen and Whitlock first defined molecular tweezers as synthetic receptors containing two complexing aromatic chromophores connected by a single spacer[63]. Bisfunctional derivatives of caffeine **(32)** showed an increase in association constant relative to simple caffeine derivatives when complexed with planar aromatic guests such as 2,6 dihydroxybenzoate and 1,3-dihydroxy-2-naphthoate

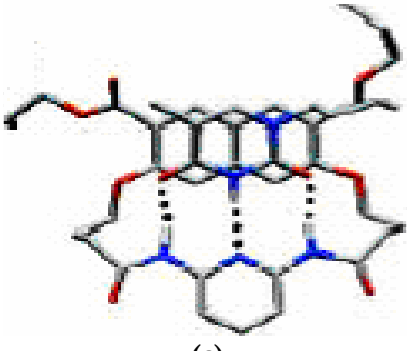
Since then, molecular tweezers have been the subject of an extensive study by zimmerman. In



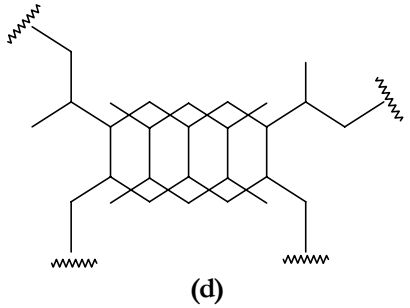
(a)



(b)



(c)



(d)

Figure 7: Hamilton's thymine receptors (a) Ester substituents lead to a stacking interaction.(b) Alkoxy substituents prevent stacking.(c)The geometry of the stacking interaction in (a).(d) The alignment of charges which leads to the attractive interaction in (a)

1987, he described a molecular tweezer in which a rigid spacer enforced a syncofacial arrangement of two acridine chromophores as shown by the X-ray structure[54] in (i). The spacer holds the chromophores

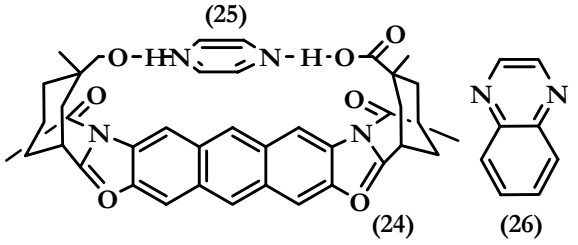


Figure 8: The complex formed between Rebek's cleft 24 and pyrazine 25

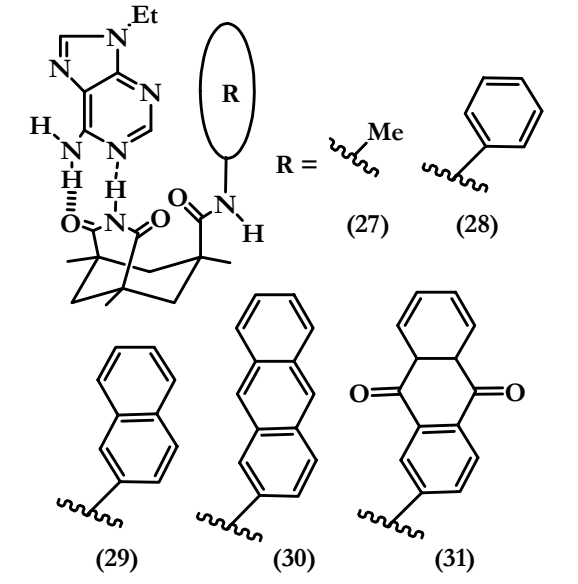


Figure 9: Complexes used to investigates stacking interactions with adenine

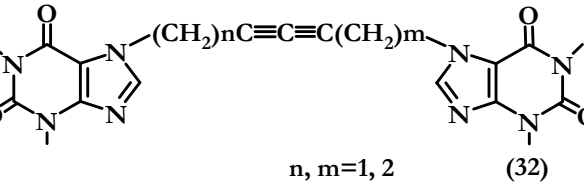


Figure 10: Whitlock's molecular tweezer

approximately 7Å apart, ideal for a planar aromatic guest. Complexation studies were carried out inchloroform solution by ^{1}HNMR spectroscopy, and the tweezer shown (i) binds 2,4,7-trinitro fluoren-9-one(TNF) with an association constant of 172M^{-1}. Large upfield shifts observed for the TNF resonances suggest the TNF carbonyl isdirected towards the spacer. Electron donor–acceptor effects were probed using the tweezers **(33-36)**.

As the electron density of the host π-system increases, the association constant increases. The use

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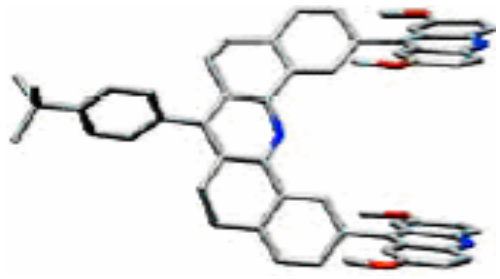
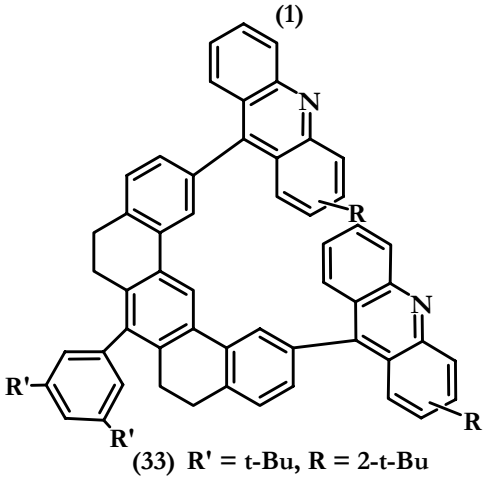
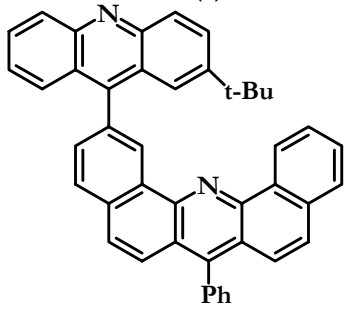


(1)



(33) R' = t-Bu, R = 2-t-Bu
(34) R' = t-Bu, R = 4 - OMe
(35) R' = t-Bu, R = 4,7 - OMe
(36) R' = t-Bu, R = NM

(2)



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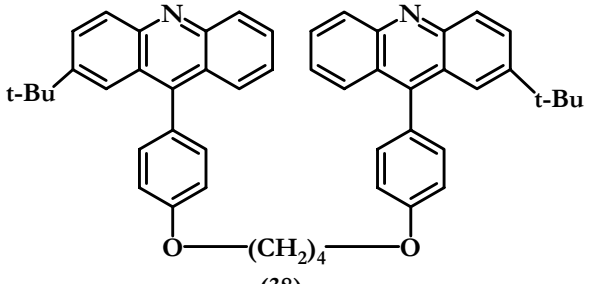


(38)

Figure 11: (1) X- Ray structure of Zimmerman's molecular tweezer. (2) The structure of tweezer derivatives 33-36. (3) Control compounds 37 and 38

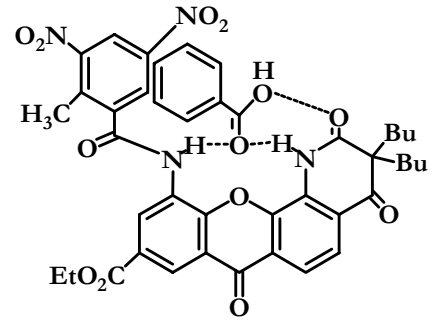


Figure 12: Crego' clefts bind benzoic acid derivatives

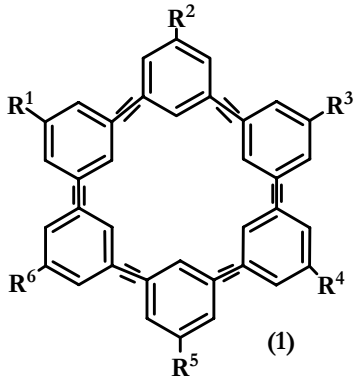
of donor solvents, THF and 1,4-dioxane, which solvate TNF better than chloroform greatly reduced the association constants.

A cleft type receptor for aromatic acids was reported by Crego et al.[61] The receptor **(39)** relies on stacking interactions and hydrogen bonding and binds a variety of substituted aromatic acids and amides. Generally, the binding constants increase with increasing π-electron density on the guest.

Moore and co-workers prepared hexakis(phenyla cetylene) molecules(PAMs) with varying degrees of electron withdrawing(ester) and donating (alkyl ether) substituents and studied their aggregation properties by ^{1}H NMR in chloroform figure 13(1)[62,63]. The chemical shifts of the aromatic protons depend strongly on concentration, and dimerisation through aromatic stacking interactions was proposed to account for this. Compounds **(40)**, **(41)** and **(42)** show dimerisation constants of 60, 18 and 26 M^{-1} respectively. Compounds **(43)** and **(44)** show no aggregation behaviour. These results indicate that the aromatic substituents have a significant influence on the stacking interaction. tert-Butyl ester substituents prevent aggregation, indicating that the interaction is due to face-to-face stacking which is hindered by the bulky groups. Non-planar pentakisand heptakis(phenyl- acetylene) molecules also have reduced association constants.

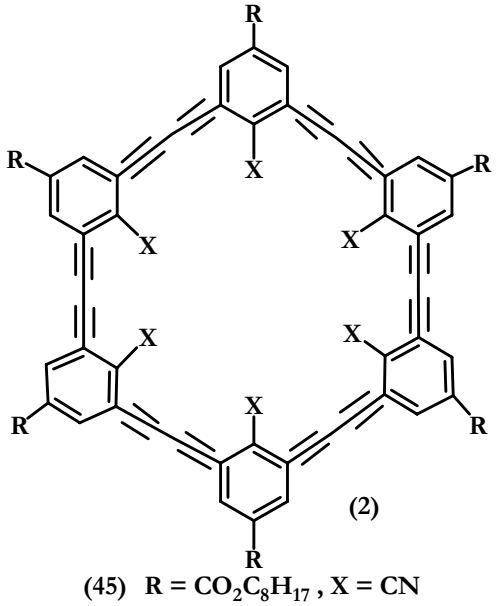
Tobe et al. designed a PAM system capable of heteroaggregation and binding metal ions figure 13 (2)[64] Compounds **(45)** and **(46)** form a 1:1 heteroaggregate but **(45)** does not self-associate. The electron withdrawing cyano-substituents appear to enhance aromatic stacking interactions in the heteroaggregate.

PAMs which fold in acetonitrile Jimenez-Barbero



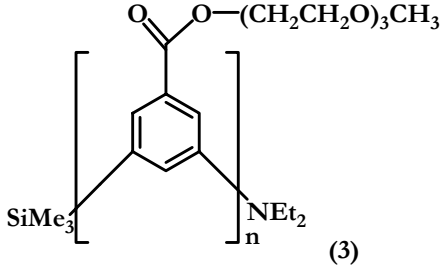
(1)

(40) $R_{1\text{-}6}$ = CO_2n-Bu
(41) R_1,3,5 = CO_2n-Bu, R_2,4,6 = On-Bu
(42) R_1,2,3 = CO_2n-Bu, R_4,5,6 = On-Bu
(43) $R_{1\text{-}6}$ = On-Bu
(44) $R_{1\text{-}6}$ = CH_2On-Bu



(2)

(45) R = $CO_2C_8H_{17}$, X = CN
(46) R = $CO_2C_8H_{17}$, X = H



(3)

n= 2,4,6,8,10,12,14,16,18

Figure 13: (i) Moore's macrocylic Phenylacetylene Molecules (PAMS). (ii) Tobe's macrocyclic PAMs. (iii) Moore's open chain

used a similar approach to investigate stacking interactions in benzene using ester linked aromatic units[71] **(47-52)**. The ^{1}HNMR spectrum of the symmetrical diesters **(48)** and **(50)** and corresponding control monoesters **(47)** and**(49)** are very similar, indicating there is no intramolecular interaction. However, the spectrum of the unsymmetrical diester **(51)** shows upfield shifts of between 0.1 and 0.5ppm on both the anthracene and dinitrophenyl rings. A stacked intramolecular complex was proposed.

If vander waals interactions were dominant in the complex, the greatest effect would be in the symmetrical anthracene derivative, as it would provide the largest vander waals contact. No charge transfer bands in the UV spectra were observed. Hence the interaction was attributed to electrostatic quadrupole interactions, as the quadrupole moments of the dinitrophenyl and anthracene groups have opposite signs.

To draw some general conclusions about the preferred geometries of π–π interactions. We use the set of three rules for non-polarised π- systems.

(a) π–π repulsion dominates in a face- to- face π-stacked geometry .
(b) π–σ attraction dominates in an edge-on or T-shaped geometry. And
(c) π–σ attraction dominates in an offset π-stacked geometry.

Two types of geometry are generally observed edge on relationships which give rise to the characterstic herring bone pattern and offset stacked relationship.

The crystal structure of Kekulene and[18] annulene illustrate this point:in one dimension the π-system are parallel stacked and offset so that the π-system of one molecule lies over the π-cavity at the centre of its nearest neighbour as shown in figure **15 (1)** & **(2)**.

In the other dimensions the molecules are aligned to give perpendicular edge on interactions with their neighbours[70-71].

To predict geometries for whole molecules using the model we sum the electrostatic interactions over all the atoms.

The model predicts geometry of such stacking interactions with high degree of accuracy, it is the **p-π** interactions which dominate the geometry of the

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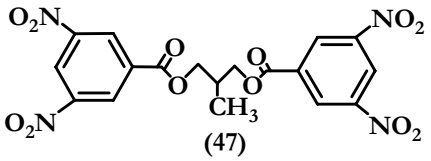
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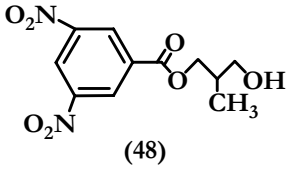
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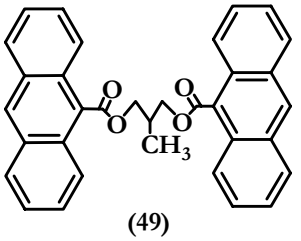
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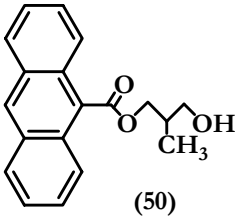
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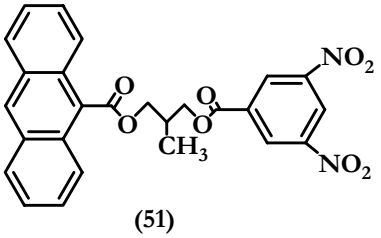
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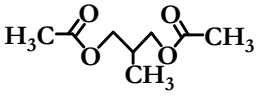
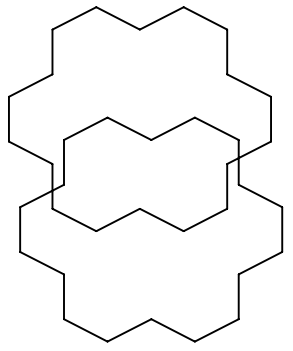

(52)

Figure 14: Compounds used to probe intramolecular aromatic interactions in benzene

intermolecular interaction so crystal packing forces must be relatively weak. This implies that the study of crystal structures may be very fruitful source of information on π-π interactions between more complicated polarized aromatic molecules.

Lehn etel have observed an attractive electron acceptor-acceptor interaction, but the geometry of interaction has not been completely defined. In one orientation p-overlap is stabilized by specific charge-charge interactions between the negatively charged guest oxygen and positively charged carbonyl carbons


(1) [18] annulene

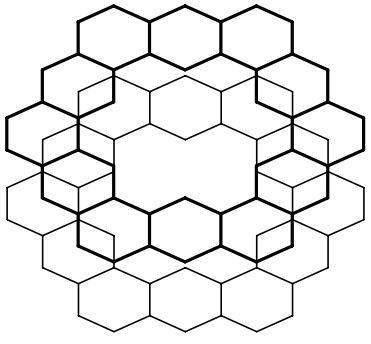

(2) Kekulene

Figure 15

of the host[72] The donor-acceptor stacks in Stoddart's systems also clearly show offset and cross-interactions.

Highly polarized π-deficient molecules such as tetra nitro fluorene form stable π-stacked complexes with a range of π-systems due to the reduced π-electron density at the site of π-overlap and favourable charge-charge interactions.

This explains why Zimmerman's molecular tweezers work. The π-π interactions in these systems are most likely to be associated with an offset geometry, crystal structures show that two tweezers can mutually complex one another, but that the stacking interactios are associated with minimal π-overlap[73].

Hamilton et. al. have observed π-π interactions in complexes of 1-butyl thymine and diamidopyridene receptors[74-75] In contrast electron with drawing substituents decreases the naphthalene π-electron density so that electronic repulsion is reduced and the stacked arrangement is favoured[74].

Hamilton et al. pointed out that there are also specific charge-charge interactions in these two systems which stabilized the stacked geometry for the π-deficient naphthalene and destabilize it for the π

rich one. More recently it has emerged that attractive interactions of a different type exist between aromatic moieties devoid of polar substituents. These 'edge to face' interactions though modest in energy terms can play an important role in molecular recognition processes[40,76-78].

Edge- to-face packing appears to have been first noted by Co et al. (1958) in single crystals of benzene[79]. Recent X-ray crystallography and NMR evidence indicates that relatively weak intermolecular edge-to-face interactions between aromatic rings can affect or determine the conformation of organic molecule in the solid state and in solution.

Experimental estimates indicate that this interactions[80-83] are energetically attractive by ca 1.5Kcal/mol but disfavoured in solution.

Hunter etal have modelled DNA base stacking interactions and the result correlate well with oligonucleotide X-ray crystal structures[84].This approach has been used to parametrise a complete model for predicting the sequence-dependent structure of DNA. Structures calculated for dodecamers agree with X-ray crystal structure to within 1Å rms difference in the position of heavy atoms. Thus theorectical models of aromatic stacking interactions are beginning to contribute to our understanding of complex biological processes[85,86] Stacking interactions play a key role in determining the material properties of molecular solids. Perhaps the best studied cases are the semi-conducting charge-transfer complexes based on tetra thiofulvalene and tetracyanoquinone derivatives semiconducting properties are obtained provided the molecules can be persuaded to form segregated stacks.Important aromatic interactions have been found in synthetic catalytic systems.

Sharpless etal used the ligand in combination with osmium tetraoxide to influence transition states in osmium-catalysed asymmetric dihydroxylation reactions[87].

The ligand adopts a U-shaped geometry with the naphthyl groups forming a tweezer-like binding pocket, which sandwiches aromatic substituents. On olefins and holds the double bond in the perfect position to react with the osmium tetraoxide.

Aromatic substrates react faster than aliphatic ones, and increasing the size of the aromatic group

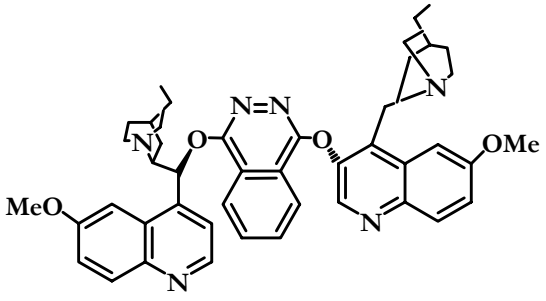


Figure 16: The sharpless ligand used for the asymmetric dihydroxylation of olefins

in both ligand and substrate leads to larger rate constants due to favourable, stacking interactions in the binding pocket.

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