Photoactive metallocyclodextrins: sophisticated supramolecular arrays for the construction of light activated miniature devices

Johanna M. Haider and Zoe Pikramenou*

Received 17th August 2004
First published as an Advance Article on the web 5th January 2005
DOI: 10.1039/b203904b

The introduction of photoactive metal centres onto cyclodextrin receptors opens up new possibilities for the design of sensors, wires and energy conversion systems. This *tutorial review* focuses on strategies involving such metallocyclodextrins for the construction of supramolecular arrays with light-activated functions. The assembly procedures for building such arrays are presented, together with the features required for their functions both as sensors for ion or small molecule detection and as wires for photoinduced long-range energy or electron transport. Systems for metal ion sensing are described where the cyclodextrin plays a mediating role in influencing the luminescence properties of an organic probe, responsive to metal binding. Small molecule sensing by the cyclodextrin cavity is realised using luminescent lanthanide or transition metal functionalised cyclodextrins. The light signal of the photoactive metal is *switched on* or *off* upon binding an analyte in the cyclodextrin cavity. The metallocyclodextrin systems that function as wires are distinguished by the controlled assembly of transition metal polypyridine and metalloporphyrin units. These units have inherent photoactivity that defines the vectorial direction of energy or electron transfer processes through the wire.

1. Introduction

The design of supramolecular systems, where the different molecular components are held together *via non-covalent* interactions, is progressing towards more sophisticated architectures where covalent bond synthesis cannot compete due to the high molecular complexity involved.[1] The elegance of the supramolecular approach is realised in photochemical systems where selective tuning of the properties of the molecular components can encode advanced functions in miniature devices.[2] Light activated supramolecular systems have received much attention, in particular for the development of information storage systems in the nanotechnology field.[3] In this context, it is attractive to design photomolecular devices with functions such as sensing, energy transport or storage, or directional electron transfer that have potential for optical and electronic applications in switches, molecular wires or energy conversion systems. Molecular receptors are popular building blocks for functional architectures. There are two principal reasons for this. Firstly, the structural features that determine

---

*z.pikramenou@bham.ac.uk

Johanna M. Haider received her ''Magistra der Naturwissenschaft'' from the University of Innsbruck, Austria. She subsequently joined the group of Zoe Pikramenou at the University of Edinburgh where she obtained a PhD on research of photoactive metallocyclodextrins. She extended the work carrying out half a year of post-doctoral research within the same group at the University of Birmingham elucidating the photophysics of metal–metal communication via cyclodextrin cavities. She then moved to the industrial sector where she is currently working as an agrochemical formulation scientist.


Johanna M. Haider

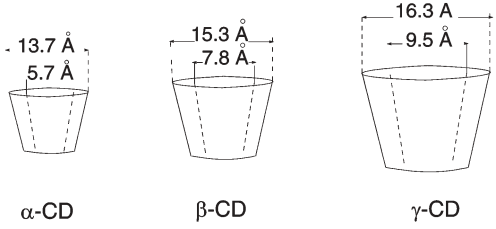
Zoe Pikramenou obtained her BSc from the University of Athens in Greece. She was then awarded an Academy of Athens scholarship to carry out PhD studies in the USA where she joined the group of Professor Daniel G. Nocera (currently at MIT) at Michigan State University to develop optical supramolecules as sensors for aromatic pollutants. Upon completion of the degree she moved to France to join the group of Professor Jean-Marie Lehn as a Marie Curie fellow and later as a Collége de France research fellow to work on photochromic systems based on photoinduced proton transfer. She then moved to the UK to take up an appointment as a lecturer at the University of Edinburgh before she moved to the University of Birmingham where she is currently a Senior Lecturer in Chemistry. Her research interests involve the design of functional supramolecular systems with emphasis on light-activated functions, lanthanide chemistry and photophysics and cyclodextrin chemistry.


Zoe Pikramenou

their molecular recognition properties for inclusion can be modified for selective binding of differently sized molecules. This is particularly desirable in the design of sensors and switches. Secondly, the size and bulkiness of receptors may vary; it can be envisaged that a receptor with length spanning only around 15 Å is already in the nanosize regime and it may thus be used to give access to architectures of several nanometres by assembly in just a couple of steps. This is important for positioning components at nanoscale distances in order to control long-range energy and electron transfer processes.

Cyclodextrins are ideal molecular receptors for building supramolecular functional systems. They are natural, water-soluble cyclic oligosaccharides[4] with rigid, bucket shaped hydrophobic cavities for inclusion of small molecules. They are commercially available (obtained by the degradation of starch) which makes them attractive "ready-made" molecular receptors in contrast with others that require multi-step synthetic procedures. As a consequence, their host properties have been well studied[5] and they have stimulated a wealth of analytical applications,[6] some of which have been commercialised. The most common cyclodextrins consist of six, seven or eight α-1,4 linked glucose units, named α-, β-, γ-cyclodextrin (CD) respectively (Scheme 1). The glucose arrangement leads to a bucket shaped molecule with the primary hydroxyl groups arranged on the narrow side of the cup while the secondary ones are hydrogen-bonded in the wider rim (Scheme 2). The difference in hydroxyl group reactivity allows selective functionalisation of the primary or secondary rims based on carbohydrate methodology. A clear benefit to cyclodextrin chemistry has been the advances in high-field NMR methods in the last couple of decades that have made possible detailed identification of the glucose substitution sites in cyclodextrin derivatives.

The interaction of metal ions or complexes with cyclodextrins has been of extensive interest in order to bring *diverse* properties to the "sugar" receptor, from the design of catalysts and enzyme mimics to sensors and molecular wires. This review focuses on the designs and features of cyclodextrin-based systems which exhibit a photoactive function *induced* or *introduced* by the metal ion or unit; hence the definition of *metallocyclodextrins*.



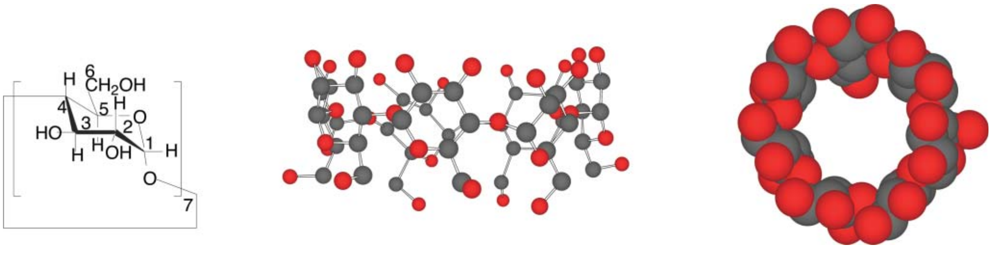
Scheme 1 Cyclodextrin buckets of different sizes, depicting the approximate size of the inner and outer cavities.

The employment of metallo-units in photochemical devices is attractive due to the inherent redox and photochemical properties of metal centres. The excited states of certain metal ions or complexes are sufficiently long-lived in solution to either release their energy as luminescence or to participate in energy and electron transfer processes as a donor or acceptor species. The most favourable energy or electron pathway will be determined by the energy difference of the excited states or the difference of redox potentials between the donor–acceptor pair. In a supramolecular system a photoinduced energy (eqn. 1) or electron transfer process (eqn. 2) between donor–acceptor is described as an intercomponent process[7] to distinguish it from intermolecular or intramolecular processes.

$$\mathrm{D{\cdot}A} \xrightarrow{h\upsilon} \mathrm{D^{*}{\cdot}A} \xrightarrow[\text{transfer}]{\text{energy}} \mathrm{D{\cdot}A^{*}} \qquad (1)$$

$$\mathrm{D{\cdot}A} \xrightarrow{h\upsilon} \mathrm{D^{*}{\cdot}A} \xrightarrow[\text{transfer}]{\text{electron}} \mathrm{D^{+}{\cdot}A^{-}} \qquad (2)$$

From the different available molecular receptors, cyclodextrins are particularly attractive for construction of supramolecular architectures with a photochemical function for several reasons. Firstly, in respect to photochemical activity, cyclodextrins are optically transparent with no light absorption in the ultraviolet and visible part of the spectrum where most of the aromatic and inorganic complexes absorb; consequently there is no interference of the light signal. Secondly, the cyclodextrin cavities fit common organic guest molecules with relatively high binding constants since they are well defined and relatively rigid. These properties are important both for sensing of small molecules and for high-yield construction of supramolecular arrays. Moreover, the size of the cavity varies according to the number of glucose units (α, β, γ) allowing a selection factor in their recognition properties. Thirdly, CDs are water soluble, non-toxic and "environmentally friendly", since they consist of sugars, and can be used in applications from food industry to waste water treatment. The construction of supramolecular assemblies in aqueous solution is a challenge in order to address mechanisms of processes encountered in natural systems. Fourthly, the assembly of nanoscale functional objects is feasible using cyclodextrins since the cyclodextrin receptor spans a couple of nanometres



Scheme 2 β-CD: chemical structure, side and top view. Hydrogen atoms are omitted for clarity.

and has a nanosized cavity. Finally, cyclodextrins have intrinsic chirality with potential preferential binding of stereoisomers, an important advantage for delivery or detection of active target drugs or amino acids. Metallocyclodextrins combine these attractive cyclodextrin features with the electro- and photoactive properties of the metals in a single molecule and this makes metallocyclodextrins unique building blocks for the development of sophisticated supramolecular devices.

2. Cyclodextrins as supramolecular mediators for the sensing of ions

Fluorescence-based methods are popular for analyte detection due to their high sensitivity, facile sample handling and recovery. Metal ion detection has been of wide interest in industrial applications such as waste disposal and recovery as well as for probing the roles of metal ions in natural systems. In the approaches discussed below, cyclodextrins have been employed as mediating units for structural organisation of photoactive moieties, forming supramolecular systems involving metal ions either as analytes or as indirect indicators of a sensing event.

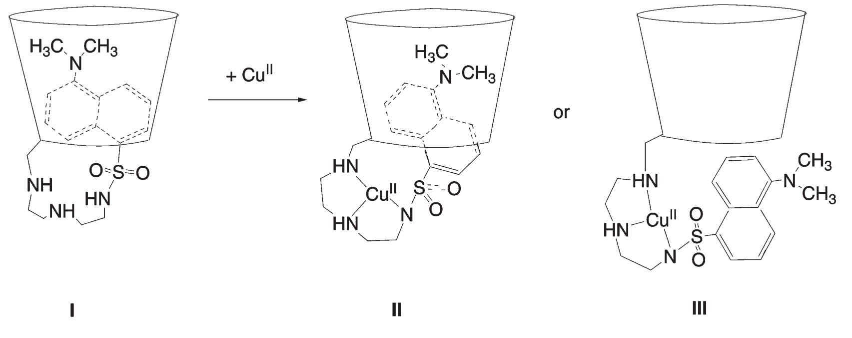
The strategy involves modulation of the properties of an organic fluorophore by its inclusion in the cyclodextrin cavity. The fluorescence signal of an organic fluorophore is most commonly increased by its inclusion in the cyclodextrin cavity due to restriction of its rotational freedom, and hence limitation of deactivation pathways, or due to the change in the medium polarity between bulk water and a hydrophobic cavity. This fluorescence change by insertion into the cavity was used in the examples below as a sensing mechanism. Another related sensing approach has involved the ability of molecules with extended aromatic systems to form excimer species (excited state complexes) in the hydrophobic environment of cyclodextrin cavities.

2.1. Sensing of transition metals

β-Cyclodextrins modified with dansyl fluorescent groups (**I**) were used for detection of Cu(II) in solution.[8] The dansyl group was linked to the primary side of β-cyclodextrin *via* an ethylene diamine linker which allowed flexibility for the dansyl group to be inserted in the cyclodextrin cavity. It was shown by circular dichroism experiments that in aqueous solutions the hydrophobic dansyl group was self-included in the cyclodextrin cavity in an equatorial orientation (**I**). The length of the linker proved to be important for the orientation of the dansyl group in the cavity. Rigid linkers were shown to favor an axial orientation. This self-inclusion was disturbed upon addition of Cu(II) which resulted in a drastic decrease of the dansyl fluorescence signal. Copper(II) coordinated to the amine donor atoms and the deprotonated sulfonamide forming a rigid linking moiety so that the dansyl group was forced to either change orientation in the cavity (**II**) or to exit the cavity (**III**) (Scheme 3). The process was monitored by circular dichroism spectroscopy. The change in the dansyl group environment affected the fluorescence signal which provided a sensing mechanism for Cu(II) detection. It is well established that the fluorescence intensity of the dansyl is decreased when the group is out of the cyclodextrin cavity or in a conformation of increased rotational freedom. The fluorescence quenching effect was stronger in presence of **I** than for a plain dansyl sulfonamide derivative without the cyclodextrin receptor. Copper(II) led to a more pronounced signal quenching than other transition metals such as Ni(II), Zn(II), Fe(II) and Co(II), suggesting that **I** could be used for selective Cu(II) detection.

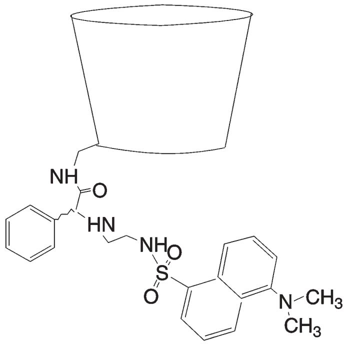
2.2. Amino acid sensing

The same copper dansyl–cyclodextrin system was also used in a fluorescence back-titration for the sensing of amino acids. Addition of copper-binding amino acids such as D-or L-alanine, D-or L-tryptophan or D-or L-thyroxine to a solution of copper dansyl–cyclodextrin **II** led to recovery of the dansyl fluorescence signal. The system was further developed for enantioselective sensing of amino acids by introduction of a chiral linker between the cyclodextrin and the dansyl group (**IV**).[9] The addition of amino acids to the Cu(II) complex of **IV** was monitored by fluorescence, electrospray mass spectrometry and circular dichroism. The increased fluorescence signal displayed depended on the amino acid used and in some cases on the absolute configuration. The best enantiomeric recognition was displayed between the Cu(II) complex of the (*S*)-isomer of **IV** with D-proline. The mechanism of the "switching on" of the chemosensor effect was attributed to a competition between a binary complex formation between the copper and the amino acid, and a ternary complex between the amino acid, copper and dansyl–cyclodextrin. The binary complex formation should lead to a fluorescent complex as copper is removed from the dansyl–cyclodextrin complex and



Scheme 3 Sensing mechanism for Cu(II) detection by change of environment around the dansyl group.

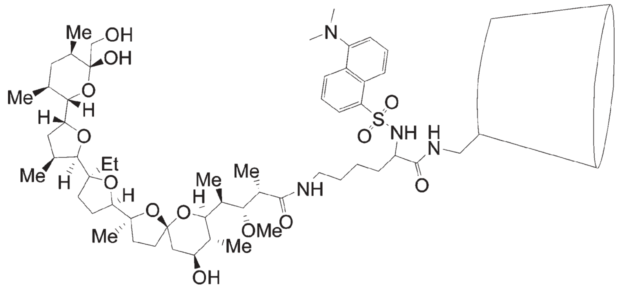
the dansyl group is restored inside the cyclodextrin cavity whereas the ternary complex formation should lead to a weakly fluorescent complex.



IV

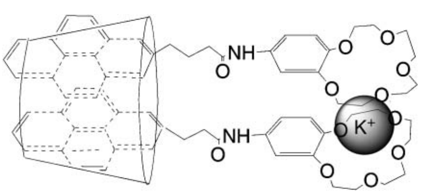
2.3. Alkali metal ion sensing

One approach for sensing an alkali metal ion involved a cyclodextrin modified with an *N*-dansyl–L-lysine chain attached to a monesin unit (**V**).[10] Monesin was chosen as an antibacterial compound with a binding cavity that fits Na^+ selectively over other alkali metal ions. The cyclodextrin derivative **V** was used for sensing steroids in the cyclodextrin cavity by monitoring the dansyl group fluorescence. Addition of a steroid was found to decrease the dansyl signal, which was removed by its self-inclusion position inside the cavity by the steroid binding event. Binding of Na^+ to **V** led to larger fluorescence changes upon steroid binding. This behaviour was more prominent for Na^+ than K^+, Li^+ and Cs^+ in agreement with the binding strengths of those cations to monesin. The fluorescence sensing event was attributed to the formation of a rigid, hydrophobic Na^+–monesin cap on the cyclodextrin site that increased the binding strength of the steroid guests.



V

In another indirect approach the fluorescence of the pyrene excimer was used as a probe for detection of alkali metal ions.[11] Pyrene molecules were functionalised with crown ethers as binding sites for alkali metal ions. The size of the crown ether was chosen so that an alkali metal ion such as K^+ formed a sandwich complex between the two crown ether units, bringing the pyrene moieties in close proximity in aqueous solution (**VI**). In the presence of γ-cyclodextrin the pyrene dimers were included in the cyclodextrin cavity, and a strong excimer signal was observed. The alkali ion selectivity detection was regulated by the choice of the crown ether size.



VI

2.4. Sensing of anionic guests

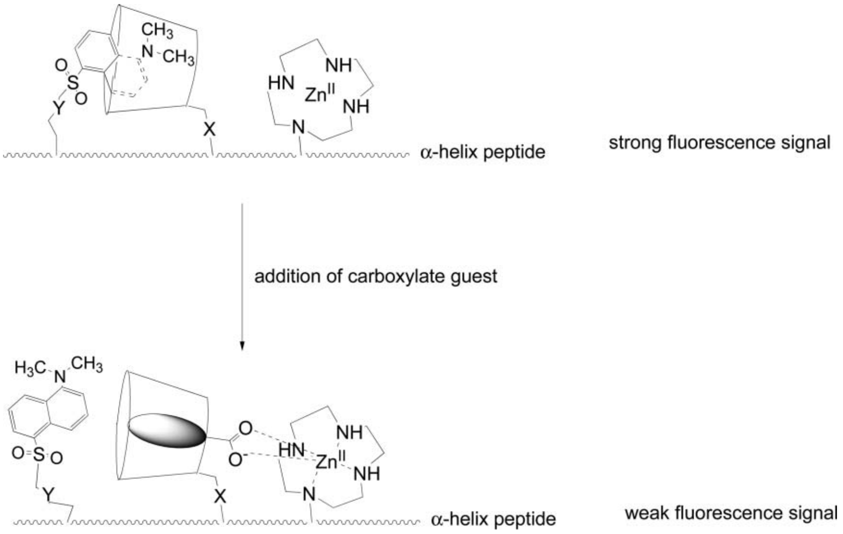
The fluorescence properties of the dansyl group upon inclusion in the cyclodextrin cavity were employed together with the affinity of Zn(II)–cyclam for carboxylate anions.[12] A peptide was used as a scaffold to connect a dansyl group, a β-cyclodextrin and a Zn–cyclam complex (Scheme 4). The helical content of the functionalised peptide was studied by circular dichroism spectroscopy. The positioning of the components was selected such that the dansyl group is included in the cyclodextrin cavity. Control experiments also confirmed no involvement of Glu and Arg in coordination with the zinc cyclam site. Upon addition of ursodeoxycholic acid or 1-adamantyl carboxylic acid, the dansyl signal was quenched. This was attributed to the competitive binding in the cyclodextrin cavity by the added carboxylate guest (Scheme 4). Control experiments demonstrated the importance of the Zn–cyclam unit to the sensitive detection of these anionic guests.

3. Small molecule sensing by metallocyclodextrins

The most common strategy that involves cyclodextrin receptors in photoactive sensing schemes for small molecules involves the cavity as the recognition unit for detection of small molecules, analytes, in solution. The cyclodextrin rim is functionalised with a ligating site bearing a photoactive metal centre that must be responsive to the presence of a guest in the cavity. The sensing response is based on a *turn-on* or a *turn-off* signal of metal luminescence upon recognition of the analyte by the cavity. The design of a luminescence responsive supramolecular system based on cyclodextrin receptor involves several selection parameters that need to be taken into account: (a) the photophysical properties of the metal such as long-lived luminescence lifetimes for electronic communication, (b) the photophysical mechanism for triggering the signal *on* or *off*, (c) the distance of the photoactive metal from the cavity and (d) the binding constant of the guest/analyte to be detected in the cyclodextrin cavity. Lanthanide and ruthenium photoactive centres have been attached to cyclodextrins for the sensing of aromatic hydrocarbons, quinones and steroids.

3.1. Lanthanide-modified cyclodextrin sensors

Lanthanide ions such as Eu(III) and Tb(III) are ideal luminescent probes for participating in sensing schemes as they have long lifetimes and visible emission, red and green respectively. The detection of environmental toxins such as aromatic hydrocarbons in water was tackled by bringing together different recognition components in a supramolecular system. Cyclodextrins were derivatised with a neutral crown

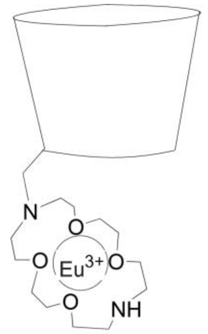


Scheme 4 Sensing mechanism for anionic guests.

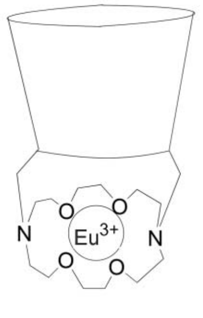
ether moiety[13] (**VII**, **VIII**) or a tribasic aminocarboxylate binding unit[14] (**IX**) and these attached metal binding sites were used to complex luminescent lanthanide(III) ions such as Eu(III) and Tb(III). The lanthanide binding units were attached either in a mono- or a bi-capped fashion on the cyclodextrin rim. The bi-capping of the lanthanide site (**VIII**, **IX**) to the receptor was recognised to be a better arrangement rather than a swing conformation (**VII**) since it would fix the lanthanide sensor unit at a specific distance from the receptor site. Distance is an important factor in energy transfer mechanism and hence influences the sensor design. However, the proximity of the *charged* lanthanide unit to the cyclodextrin in **VIII** was shown to alter the receptor properties of the cyclodextrin unit, limiting this complex to the detection of polar guests. The design of the tribasic site for lanthanides in **IX** gave a neutral complex unit and surmounted both of these limitations.

The sensing mechanism was based on an absorption-energy transfer-emission (AETE) process (detailed below) between the aromatic guest and the appended lanthanide lumophore *via* non-covalent bonds (Scheme 5). The lanthanide cyclodextrin showed weak or no luminescence signal in aqueous solution due to the lack of any sensitiser groups. Upon addition of an aromatic hydrocarbon such as benzene, toluene or biphenylene a strong, characteristic red or green (for Eu^{III} and Tb^{III} respectively) sharp lanthanide luminescence signal was observed. This was attributed to inclusion of the hydrocarbon in the cavity, which sensitised the lanthanide luminescence. The sensitisation effect was optimised for the Tb(III) complex of **IX**, which was used to detect ppm concentrations of biphenylene in aqueous solutions with a signal "turning-on" by a factor of 40. The sensitisation process involving excitation of the light harvesting guest, energy transfer to the lanthanide excited state and subsequent luminescence of the lanthanide was described as an AETE process (Scheme 5). The mechanism of the energy transfer was elucidated by time-resolved luminescence spectroscopy and transient absorption techniques.[15] This approach to luminescence sensing is ideal for applications, since it is based on a "*switching-on*" event of a signal against a dark background.

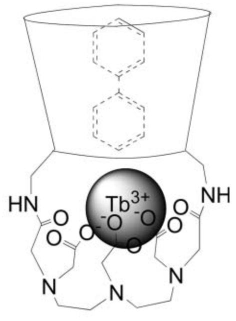
A successful application of this supramolecular approach was realised by fabrication of a microfluidic device based on complex **IX**.[16] Microfluidic devices provide a miniaturization route for analytical and bioanalytical detection of fluid samples on a chip. The secondary site of the cyclodextrin in **IX** was derivatised with a vinyl acrylate moiety, which provided a reactive site for polymerisation without disturbing the structural arrangement of the cyclodextrin receptor and the lanthanide sensor site. Thin films of the acryloyl polymers of **IX** were immobilised by sol-gel techniques on quartz surfaces



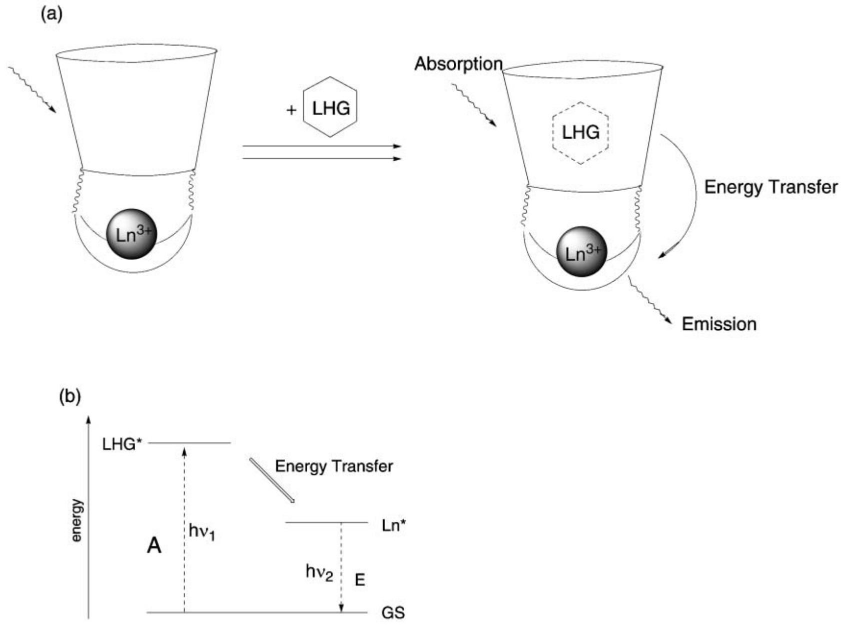
VII



VIII



IX

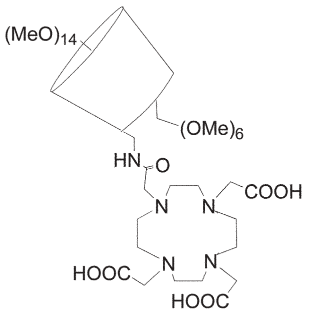


Scheme 5 (a) Sensing mechanism of aromatic light harvesting guests (LHG) by lanthanide derivatised cyclodextrins based on absorption-energy transfer-emission processes within the supramolecular system. (b) A simplified energy diagram illustrating the AETE process.

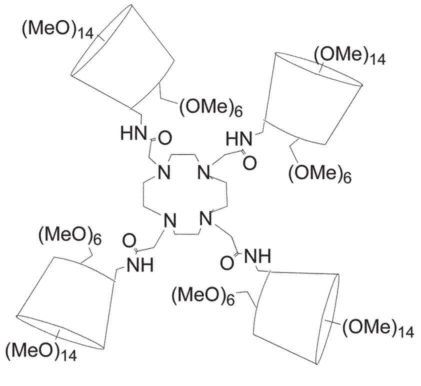
patterned by photolithographic methods. Addition of a biphenyl guest to the immobilised supramolecular receptor showed enhancement of the luminescence signal, which was dependent on the analyte concentration, as expected for a direct detection response. The results demonstrated that the supramolecular sensor preserved its solution sensing luminescence properties for biphenyl in microfluidic conditions.

Other lanthanide-modified cyclodextrins have also been prepared. A macrocyclic unit based on 1,4,7,10-tetraazacyclododecane was used as the lanthanide binding site and was attached to one or four methylated cyclodextrin receptors (**X**, **XI**).[17] The sensitisation of the Tb(III) complex of **X** by naphthoate guests and methyl-*p*-*tert*-butyl benzoate was studied. The Eu(III) complex of the non-methylated cyclodextrin derivative of **X** was prepared for NMR studies of selective binding between (*R*)- and (*S*)-enantiomers of histidinate guests.[18] A bis-cyclodextrin system linked by an EDTA bridge (**XII**) was reported to bind Eu(III) and Tb(III) ions on the EDTA bridge. The complexes acted as sensors for butylbenzoate guests.[19] The lanthanide complexes of **XII** were investigated for bifunctional recognition of bis-adamantyl functionalised biphenyl derivatives. Recognition of both the adamantyl ends of the biphenyl guest took place by both the cyclodextrin cavities leading to emission enhancement of the order of 300-fold.

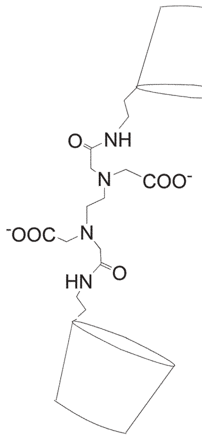
Polypyridine derivatised cyclodextrins have also been reported to coordinate to lanthanides leading to luminescent lanthanide receptors. In one approach a hepta-bipyridine substituted β-cyclodextrin (**XIII**) was shown to bind Eu(III) and Tb (III) ions in the "barrel" at the primary side of the cyclodextrin cavity formed by urea and bipyridyl hard and soft binding sites.[20] We used a nine-coordinate Eu(III) ion to assemble three terpyridyl functionalised β-cyclodextrins (**XIV**) around its coordination sphere leading to luminescent trimer cyclodextrin receptors.[21]



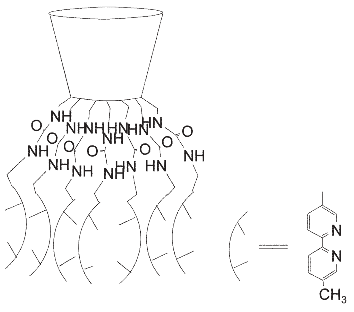
X



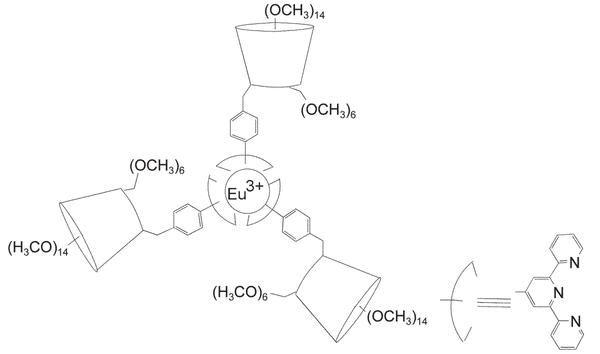
XI



XII



XIII

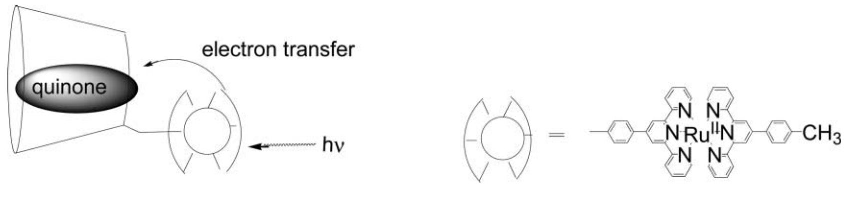


XIV

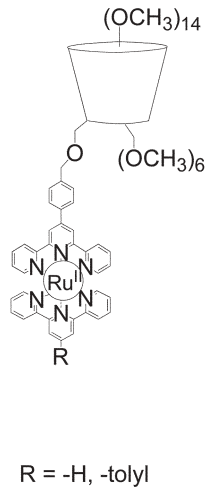
3.2. Transition metal modified cyclodextrin sensors

Luminescent transition metal complexes are also appealing components in the design of sensing systems due to their photophysical and redox properties that enable them to take part in photoinduced energy and electron transfer processes. Rhenium(I) tricarbonyl[22] and ruthenium(II) photoactive centres[23] were attached to cyclodextrins *via* 6-substituted bipyridyl coordinating sites. Although no inclusion properties of the cyclodextrins were investigated, it was reported that the Ru(II) complex showed lower quantum yield and lifetime values than the parent units without cyclodextrins, which was attributed to the steric influence of the 6-substituted bipyridyl on the transition metal complex formation. Further development of a bipyridine β-cyclodextrin substituted with a Re(I) tricarbonyl photoactive unit showed quenching of the Re(I) centre upon binding of an aromatic amine, attributed to electron transfer from the amine to the Re(I) centre.[24] We developed ruthenium cyclodextrin systems based on terpyridyl functionalised β-cyclodextrin (**XV**) for sensing quinone guests.[25] In our approach we used a methodology for permethylating all the hydroxyl cyclodextrin functionalities apart from one which was available for derivatisation with the metal ligating site. The permethylated cyclodextrin derivatives were soluble in organic solvents, readily allowing purification, whilst retaining their aqueous solubility and removing the possibility of hydroxyl interference with metal coordination. Upon excitation of the ruthenium terpyridyl unit intramolecular electron transfer took place from the ruthenium appended unit to the quinone guest included in the cavity (Scheme 6). The system was used for sensing quinone molecules by monitoring the quenching of ruthenium luminescence upon addition of different redox active quinones such as benzoquinone and anthraquinone derivatives.[26] The advantage of the ruthenium terpyridine unit was that there was no contribution to the quenching by bimolecular electron transfer. Quenching of ruthenium luminescence of up to 40% was observed for an anthraquinone guest. The extent of quenching was shown to be dependent not only of the accepting properties of the guest, namely the redox potential, but also the amount of the bound guest to the receptor and the guest's proximity to the metal centres. When benzoquinone was used as a guest, quenching of Ru(II) luminescence of only around 25% was observed (although it is a better electron acceptor than the anthraquinone derivative) due to its weak binding and consequent distance from the metal centre. Stepwise addition of terpyridine[26] or bipyridine modified cyclodextrins[27] to ruthenium led to complexes with two (**XVI**) or three (**XVII**) cyclodextrin recognition sites. The quantum yield of the ruthenium core unit was not affected by the presence of the cyclodextrin cavities. These ruthenium complexes showed higher sensitivity for detection of quinone guests at lower concentrations due to the stronger binding of the multiple receptor sites. Ruthenium and osmium podate cyclodextrins[27] with dual function recognition sites for luminescent sensing were prepared based on an hepta-pyridyl cyclodextrin system (**XIII**). The luminescence sensing of quinone binding to the cyclodextrin cavity and phosphates binding to the urea sites was examined by the quenching of the ruthenium luminescence. A cyclodextrin bicapped with a ruthenium bipyridine unit was also reported for detection of benzoquinone guest.[28] A rather low quenching of Ru(II) luminescence of only 10% was observed, possibly due to the weak binding of benzoquinone, due to the close proximity of the charged metal unit to the cyclodextrin cavity.

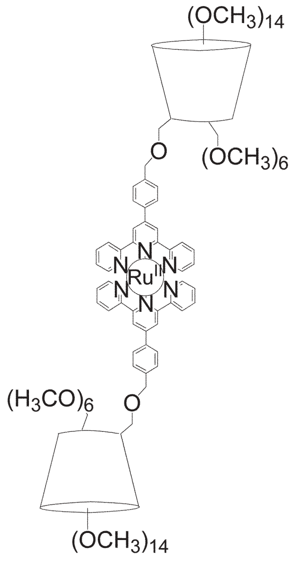
A luminescent system with "*switch-on*" behavior for detection of steroids was designed using a ruthenium tris-bipyridine complex with six attached β-cyclodextrin cavities.[29] A 2,2′-bipyridine was functionalised at the 4- and 4′-positions with two cyclodextrins (**XVIII**) attached by their secondary site. Coordination of ruthenium led to a luminescent complex with six cyclodextrin sites around the metal. The positions of the bipyridine functionalisation and the spacer used to connect



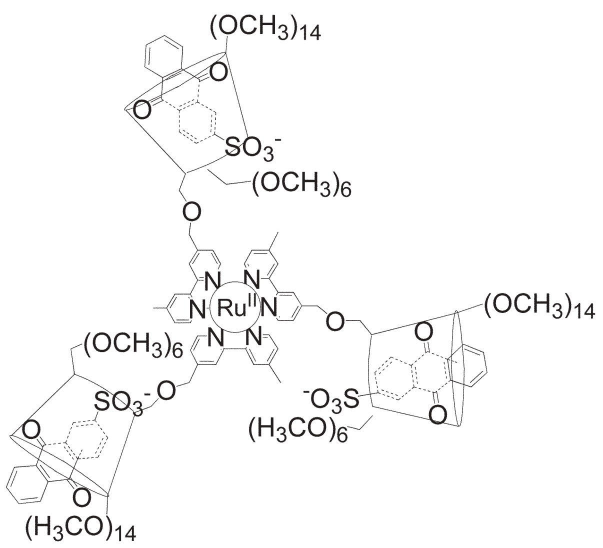
Scheme 6 Representation of the sensing scheme based on photoinduced electron transfer between Ru(II) terpyridyl units and a quinone guest.



XV

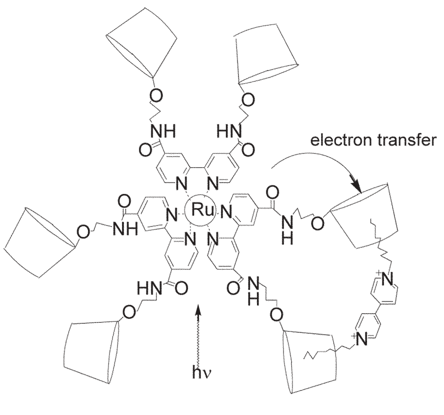


XVI



XVII

the bipyridine to the cyclodextrin receptor were chosen to avoid steric hindrance to the metal complex formation by the bulky receptors around the bipyridine unit. Addition of *N*,*N*′-dinonyl-4,4′-bipyridinium bromide led to luminescence quenching of the ruthenium centre based on intramolecular electron transfer from the bipyridinium electron donor to Ru(II).[30] Addition of ursodeoxycholic acid, lithocholic acid or cholesterol restored the ruthenium luminescence signal. This "switch-on" behaviour was based on competitive binding of the steroid guest to the cyclodextrin cavity, replacing the bipyridinium moiety and hence shutting off the intramolecular electron transfer process, which quenches the ruthenium luminescence.

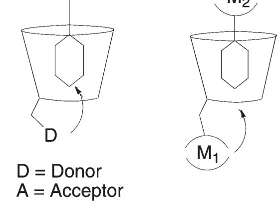


(XVIII)

4. Metallocyclodextrins for the construction of molecular wires

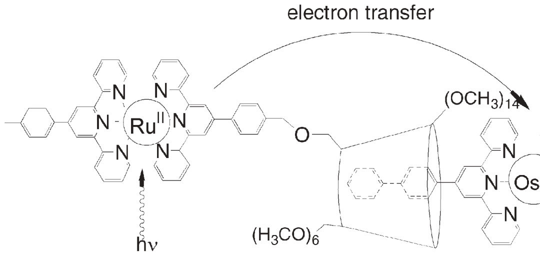
Nature provides many intelligent systems that are capable of inducing directional motion of electrons and excitation energy *via* non-covalent bonds leading to efficient charge separation. It is challenging to design synthetic systems in which there is similar control of energetic and structural directionality. Such systems may introduce new applications in energy storage (*via* efficient charge separation) or in new materials based on molecular electronics. Metal–metal communication *via* photo-induced energy or electron transfer has been studied extensively for development of molecular wires.[31] In these systems the metal centres are linked *via covalent bonds* by rigid bridges in a "rod-type" arrangement. Metallocyclodextrins represent a versatile receptor system that can bring together donor and acceptor units in one supramolecular structure *via non-covalent* bonds (Scheme 7). This is achieved by functionalising the cyclodextrin rim with one donor or acceptor unit and bringing the other acceptor or donor into the cyclodextrin cavity as a guest. In such a design the guest properties can be tuned by simply swapping the guest, without the requirement to completely reconstruct the macromolecular system. As described above, ruthenium cyclodextrins were employed in electron transfer schemes that showed communication from a metal appended on the cyclodextrin rim to a guest inside the cavity. These electron transfer examples from ruthenium centres to quinones or viologens are important templates for studying charge separation or wire function *via non-covalent* bonds.

We established metal–metal communication through non-covalent bonds between ruthenium centres appended to cyclodextrins and osmium or iridium metalloguests. The



Scheme 7 Design of the assembly of metal units *via* non-covalent bonds by a cyclodextrin receptor.

binding interaction of metal complexes as guests in cyclodextrins has been studied by different spectroscopic techniques.[32] In our approach the metalloguests were designed based on metal ligating sites with an appended hydrophobic tail to recognise the cyclodextrin cavity.[26] The assembly of a ruthenium terpyridyl functionalised cyclodextrin and the osmium metalloguest (**IXX**) was performed in water and monitored by spectroscopic techniques. The Os(III) complex was chosen as an ideal electron acceptor for the Ru(II) centre. The ruthenium luminescence lifetime showed a short component of 100 ps, which was around 80% of the signal and a long component of 1.9 ns corresponding to the ruthenium centre's lifetime without the guest. The short component was attributed to quenching by photoinduced electron transfer from the appended Ru(II) to the Os(III) acceptor. The rate for this intercomponent transfer in the supramolecular system was estimated to be $9.5 \times 10^9\ s^{-1}$. Independent binding studies of the metalloguest with cyclodextrin indicated that at the conditions of the experiment 80% of the cyclodextrin cups were occupied by the metalloguest. A control experiment with the photoactive metal units, Ru(II) and Os(III) in solution without the cyclodextrin showed no short component in the Ru(II) lifetime, confirming the intramolecular process. A high efficiency of this fast photoinduced process *via* non-covalent bonds was postulated.



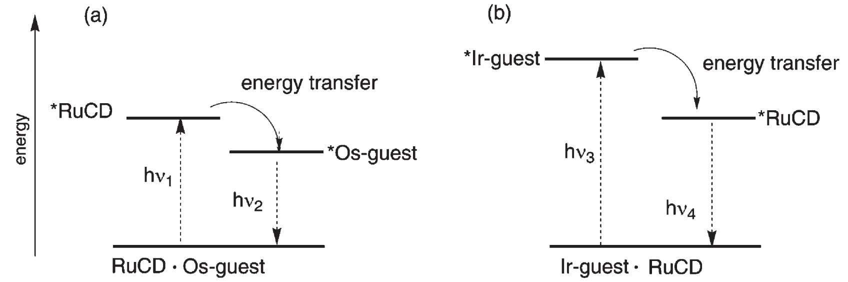
IXX

Vectorial control of energy transfer between the metalloguest and metal core centre was demonstrated when a ruthenium tris-bipyridyl unit was used as the photoactive core centre.[33] The donor–acceptor properties of the ruthenium tris-bipyridyl core are more versatile than the bis-terpyridyl system due to its longer luminescence lifetime. The Ru(II) core could act as an energy acceptor or donor depending on the choice of the metal properties of the guest (Scheme 8).

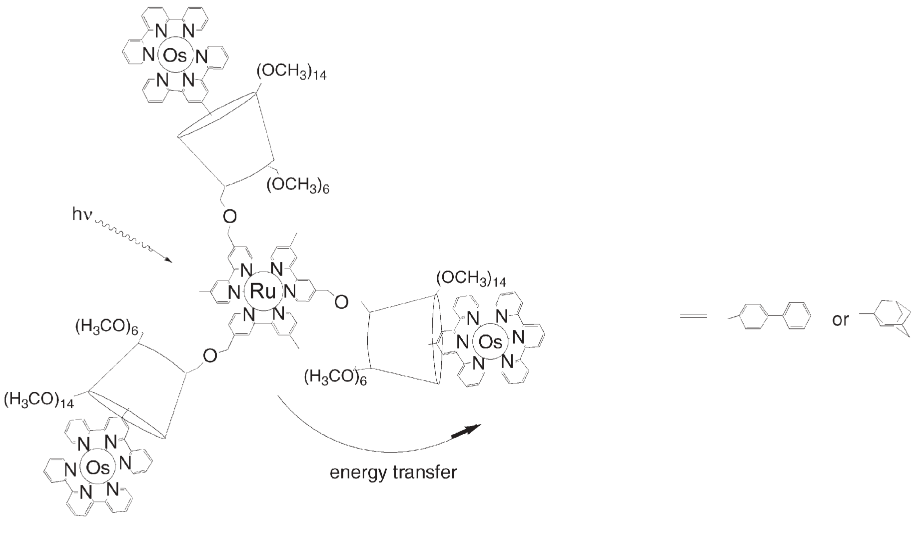
Light excitation of the assembly created by mixing an Os(II) guest and the Ru(II) cyclodextrin (**XX**) led to energy transfer from the Ru(II) inner core to the outer Os(II) centre.[33] A signature of the energy transfer process was the observed rise time of the Os(II) luminescence which agreed with the short component of the ruthenium luminescence. When an Ir(III) metalloguest was used (**XXI**), the direction of energy transfer was reversed. The ruthenium centre now acted as an acceptor in this case where Ir(III) with a higher energy excited state was introduced as a donor (Scheme 8). Energy transfer from the Ir(III) to Ru(II) was observed by monitoring the luminescence lifetime of the Ir(III) complex.

A rather surprising result was obtained when the tail of the metalloguest was changed from biphenyl to adamantyl; the energy transfer slowed down. In the Ru–Os system with biphenyl the rate was $8.3 \times 10^{10}\ s^{-1}$ while with adamantyl it was $6.4 \times 10^8\ s^{-1}$. A similar effect was observed for the Ru–Ir case. The adamantyl metalloguest was expected to bring the metal centres closer in space than the biphenyl one based on the inclusion properties and size of the tail. Hence an argument based on the distance between the two metal centres should have worked in favour of the adamantyl guest. The effect thus showed the importance of the conjugation of the tail in the communication between the two metal centres *via* non-covalent interactions. Although a dipole mechanism was expected, based on the rather long distances between the donor and acceptor units estimated around 16 Å, the results suggested that an electron exchange mechanism in the energy transfer rate was also operational.

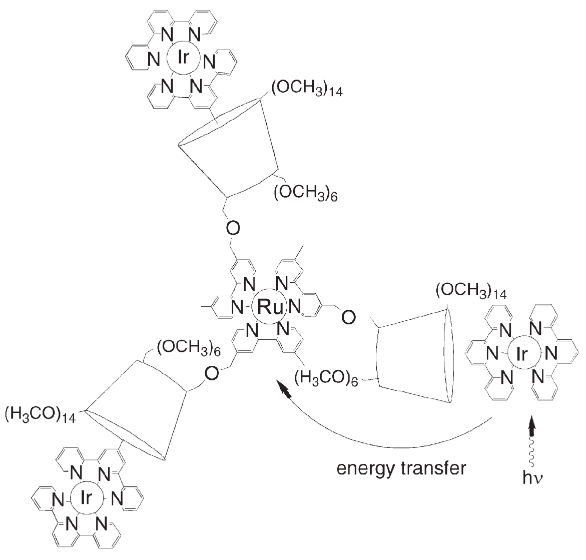
The involvement of manganese metal centres in the catalysis of oxygen to water in green plant photosynthesis led to an interest in attaching manganese centres to cyclodextrins. It was shown that the secondary site of β-CD provided an oxygen donor network for coordination of two Mn(III) centres at the wider rim of the cyclodextrin cup.[34] The system was further developed to include a sensitiser for photoinduced electron transfer.[35] A ruthenium bis-bipyridyl unit was attached to a phenanthroline derivatised cyclodextrin (**XXII**) and a dinuclear Mn(III) unit was incorporated in the secondary cyclodextrin site. The Ru(II) excited state may act as an electron acceptor in the presence of Mn(III). Excitation at the Ru(II) unit led to electron transfer from



Scheme 8 Simplified Jablonski energy diagrams to illustrate the energy transfer processes in the complexes RuCD·Os-guest (**XX**) and RuCD·Ir-guest (**XXI**).

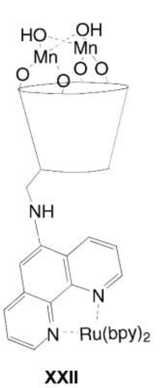


XX



XXI

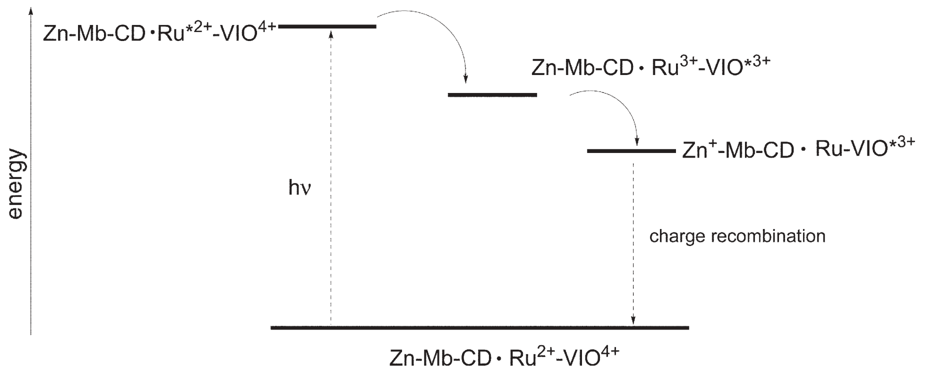
Mn(III) to Ru*. The cyclodextrin acted as a bridge for the donor–acceptor pair.



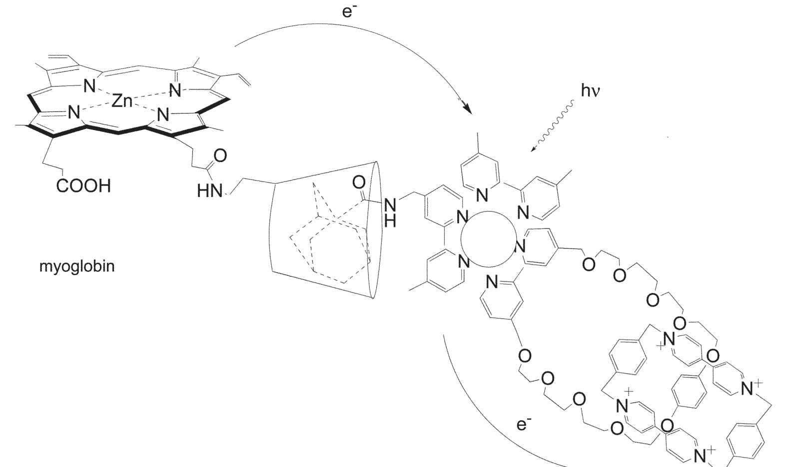
XXII

Cyclodextrins derivatised with photoactive metalloporphyrin units have also attracted considerable interest. A donor–sensitizer–acceptor triad attached to a protein matrix was developed.[36] A cyclodextrin derivatised with a Zn^{II} porphyrin unit was used for reconstitution of a myoglobin leading to a cyclodextrin-appended Zn^{II} myoglobin, Zn–Mb–CD (**XXIII**). A Ru^{II} guest, Ru–VIO^{4+}, was designed with an adamantyl unit attached to one bipyridine and a bis-viologen cyclophane on the other bipyridine unit. The adamantyl unit was chosen for inclusion in the cyclodextrin cavity so that the ruthenium guest could bring together in space the viologen unit and the Zn(II) site *via* non-covalent interactions. The bis-viologen moiety was pre-assembled with the ethylene–oxo macrocyle to form the Ru(II) cyclophane by π– π and electrostatic interactions. The ruthenium–bipyridine core acted as a sensitizer where the Zn^{II} porphyrin was the electron donor and the bis-viologen site the electron acceptor. Excitation of the Ru(II) led to electron transfer from the ruthenium to the viologen and subsequently electron transfer from the Zn–myoglobin to the ruthenium centre (Scheme 9). This led to a charge separated state Zn^{+}–Ru^{2+}–MV^{-}, which could be detected *via* transient absorption spectroscopy. The lifetime of the charge separated state, Zn^{+}–Mb–CD·Ru^{2+}–VIO^{3+} was reported to be 640 ns (a rate of 1.56×10^{6} s^{-1} for the charge recombination was estimated by transient absorption spectroscopy). The system presented a triad of donor–sensitizer–acceptor assembled *via* non-covalent interactions.

Heteroporphyrins were assembled in a supramolecular structure by attachment of one porphyrin unit to a cyclodextrin and inclusion of another one in the cyclodextrin cavity (**XXIV**).[37] The inclusion of the guest porphyrin took place through the phenyl group in the *meso* position of the porphyrin. A parent compound with one cyclodextrin attached to the porphyrin was also prepared. Addition of the guest Zn^{II} porphyrin to the host cyclodextrin modified porphyrin resulted in a 3-fold fluorescence enhancement of the host porphyrin, indicating energy transfer from the Zn^{II} guest to the core porphyrin. This enhancement was in agreement with quenching of the Zn^{II} porphyrin fluorescence. When the parent host compound was used with the Zn^{II} guest under the same



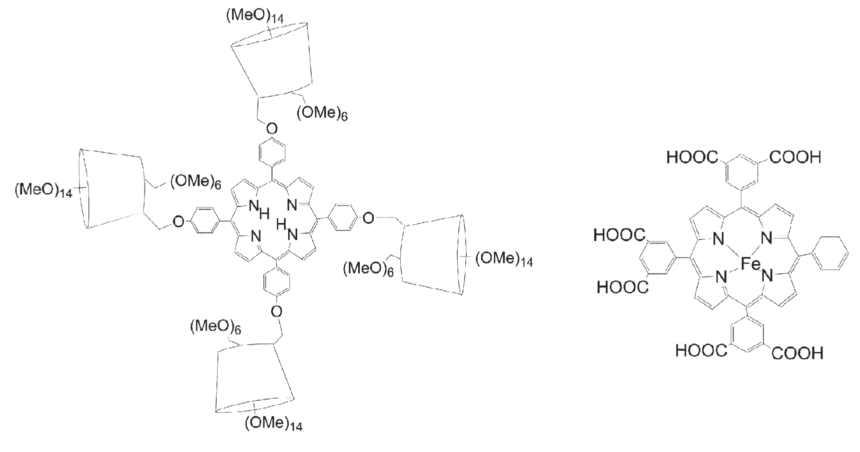
Scheme 9 Schematic energy diagram that illustrates the photoinduced electron transfer process in Zn–Mb–CD·Ru^{2+}–VIO^{4+} complex **XXIII**.



XXIII

experimental conditions the changes in fluorescence intensity were less pronounced.

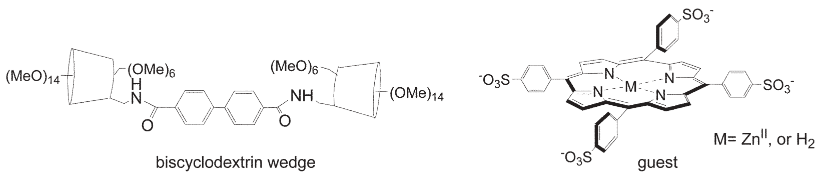
In another approach, the inclusion properties of a porphyrin in cyclodextrin were adopted for the self-assembly of an architecture with two different porphyrin units (Scheme 10).[38] A bis-cyclodextrin system where the two cyclodextrins were linked by together with a biphenyl unit served as a wedge to bring together two different porphyrins (**XXV**). The formation of the 2 : 2 host–guest system was monitored by absorption spectroscopy and electrospray mass spectrometry. Fluorescence monitoring of the assembled architecture showed evidence of energy transfer between two different guest porphyrins (Scheme 10). The 2 : 2 formation of the assembly with two different porphyrins is only one



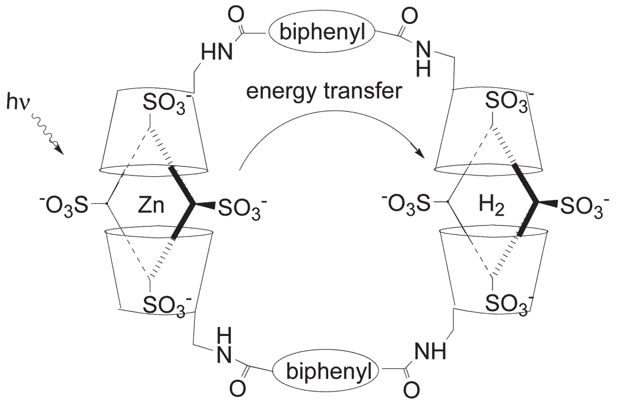
host compoud

guest

XXIV



XXV



Scheme 10 Representation of one of the possible structures for the 2 : 2 formation of the wedge assembly that allows communication of the two porphyrin guests.

possible arrangement of the statistical mixture. The estimated distance between the two porphyrins in such an architecture is 27 Å.

5. Conclusions and outlook

In the examples presented, new sensing schemes and functions were demonstrated using the assembly of intriguing cyclodextrin architectures and uniting metal properties and cyclodextrin recognition features. The design principles for systems to act as sensors for metal ions or amino acids employed the cyclodextrin cavity as a mediator for a fluorescence response of an organic probe which interacts with the analyte species in an indirect fashion. A rather more articulate strategy for small molecule detection involved the direct influence of the metal photophysics (by energy or electron transfer) upon guest-analyte inclusion in the cyclodextrin cavity. In this strategy the properties, and hence the choice, of the photoactive metal were important for a pronounced *turn-on* or *turn-off* response of the sensing system and the building of a ligating site on the cyclodextrin for the metal is required. The application of one of these compounds in a device for analytical detection demonstrated the potential of these systems for sensitive detection. The issues of cost and selectivity, in particular for analytes of low-binding constants, still need to be addressed. There is no doubt that in the future technological development together with academic design will bring novel sophisticated sensor systems in the scientific spotlight.

In the development of molecular wires a range of self-assembly motifs was obtained involving metallocyclodextrin systems. The assembled architectures were constructed in aqueous solutions by supramolecular chemistry principles and, together with a judicious selection of photoactive units, led to vectorially-controlled photochemical functions of the systems. These results established the function of such assemblies as molecular wires and introduced a cyclodextrin-based approach as a bottom-up approach for construction of wires with metal centres. The aqueous assembly is a clear advantage of cyclodextrins for applications in materials and for easy handling. More fundamentally the studies of photoinduced processes in non-covalent systems in water may lead to a better understanding of the efficiency of natural systems that achieve long-lived charge separation. Ultimately, this may lead to more efficient energy conversion using synthetic systems. Photoactive nanodevices with control of directionality in energy and electron motion will undoubtedly attract further interest in the coming years. There is currently also much attention on the attachment of cyclodextrins onto surfaces such as gold and platinum; the properties of metallocyclodextrins coupled with surface communication will be an important asset for new device fabrication for wire function.

Acknowledgements

We wish to thank EPSRC, the Leverhulme Trust and the Royal Society for funding.

Johanna M. Haider and Zoe Pikramenou*
School of Chemistry, The University of Birmingham, Edgbaston, UK B15 2TT. E-mail: z.pikramenou@bham.ac.uk

References

1 J. M. Lehn, *Proc. Natl. Acad. Sci. USA*, 2002, **99**, 4763.
2 C. A. Schalley, A. Lutzen and M. Albrecht, *Chem. Eur. J.*, 2004, **10**, 1072.
3 V. Balzani, *Photochem. Photobiol. Sci.*, 2003, **2**, 459.
4 J. Szejtli, *Chem. Rev.*, 1998, **98**, 1743.
5 M. V. Rekharsky and Y. Inoue, *Chem. Rev.*, 1998, **98**, 1875.
6 S. Li and W. C. Purdy, *Chem. Rev.*, 1992, **92**, 1457.
7 V. Balzani and F. Scandola, *Supramolecular Photochemistry*, Ellis Horwood, Chichester, 1991.
8 R. Corradini, A. Dossena, G. Galaverna, R. Marchelli, A. Panagia and G. Sartor, *J. Org. Chem.*, 1997, **62**, 6283.
9 S. Pagliari, R. Corradini, G. Galaverna, S. Sforza, A. Dossena, M. Montalti, L. Prodi, N. Zaccheroni and R. Marchelli, *Chem. Eur. J.*, 2004, **10**, 2749.
10 A. Ueno, A. Ikeda, H. Ikeda, T. Ikeda and F. Toda, *J. Org. Chem.*, 1999, **64**, 382.
11 A. Yamauchi, T. Hayashita, A. Kato and N. Teramae, *Bull. Chem. Soc. Jpn.*, 2002, **75**, 1527.
12 S. Furukawa, H. Mihara and A. Ueno, *Macromol. Rapid Commun.*, 2003, **24**, 203.
13 Z. Pikramenou, J. A. Yu, R. B. Lessard, A. Ponce, P. A. Wong and D. G. Nocera, *Coord. Chem. Rev.*, 1994, **132**, 181.

14 M. A. Mortellaro and D. G. N. Nocera, *J. Am. Chem. Soc.*, 1996, **118**, 7414.
15 C. M. Rudzinski, D. S. Engebretson, W. K. Hartmann and D. G. Nocera, *J. Phys. Chem. A*, 1998, **102**, 7442.
16 C. M. Rudzinski, A. M. Young and D. G. Nocera, *J. Am. Chem. Soc.*, 2002, **124**, 1723.
17 P. J. Skinner, A. Beeby, R. S. Dickins, D. Parker, S. Aime and M. Botta, *J. Chem. Soc., Perkin Trans. 2*, 2000, 1329.
18 S. L. Kean, C. J. Easton, S. F. Lincoln and D. Parker, *Aust. J. Chem.*, 2001, **54**, 535.
19 J. J. Michels, J. Huskens and D. N. Reinhoudt, *J. Am. Chem. Soc.*, 2002, **124**, 2056.
20 R. Heck, F. Dumarcay and A. Marsura, *Chem. Eur. J.*, 2002, **8**, 2438.
21 J. M. Haider and Z. Pikramenou, *Eur. J. Inorg. Chem.*, 2001, 189.
22 R. Deschenaux, M. M. Harding and T. Ruch, *J. Chem. Soc., Perkin Trans. 2*, 1993, 1251.
23 R. Deschenaux, T. Ruch, P. F. Deschenaux, A. Juris and R. Ziessel, *Helv. Chim. Acta*, 1995, **78**, 619.
24 A. Nakamura, T. Imai, S. Okutsu, A. Ueno and F. Toda, *J. Electroanal. Chem.*, 1997, **438**, 159.
25 S. Weidner and Z. Pikramenou, *Chem. Commun.*, 1998, 1473.
26 J. M. Haider, M. Chavarot, S. Weidner, I. Sadler, R. M. Williams, L. De Cola and Z. Pikramenou, *Inorg. Chem.*, 2001, **40**, 3912.
27 M. J. J. Pereira Silva, J. M. Haider, R. Heck, M. Chavarot, A. Marsura and Z. Pikramenou, *Supramol. Chem.*, 2003, **15**, 563.
28 D. Armspach, D. Matt and A. Harriman, *Eur. J. Inorg. Chem.*, 2000, 1147.
29 H. F. M. Nelissen, A. F. J. Schut, F. Venema, M. C. Feiters and R. J. M. Nolte, *Chem. Commun.*, 2000, 577.
30 H. F. M. Nelissen, M. Kercher, L. De Cola, M. C. Feiters and R. J. M. Nolte, *Chem. Eur. J.*, 2002, **8**, 5407.
31 F. Barigelletti and L. Flamigni, *Chem. Soc. Rev.*, 2000, **29**, 1.
32 W. Xu, A. Jain, B. A. Betts, J. N. Demas and B. A. DeGraff, *J. Phys. Chem. A*, 2002, **106**, 251.
33 J. M. Haider, R. M. Williams, L. De Cola and Z. Pikramenou, *Angew. Chem., Int. Ed.*, 2003, **42**, 1830.
34 B. U. Nair and G. C. Dismukes, *J. Am. Chem. Soc.*, 1983, **105**, 124.
35 N. Van Hoof, T. E. Keyes, R. J. Forster, A. McNally and N. R. Russell, *Chem. Commun.*, 2001, 1156.
36 I. Hamachi, H. Takashima, Y.-Z. Hu, S. Shinkai and S. Oishi, *Chem. Commun.*, 2000, 1127.
37 K. Kano, R. Nishiyabu, T. Yamazaki and I. Yamazaki, *J. Am. Chem. Soc.*, 2003, **125**, 10625.
38 K. Sasaki, H. Nakagawa, X. Zhang, S. Sakurai, K. Kano and Y. Kuroda, *Chem. Commun.*, 2004, 408.