Fully reversible guest exchange in tetraphosphonate cavitand complexes probed by fluorescence spectroscopy†

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Received (in Cambridge, UK) 30th January 2008, Accepted 20th February 2008
First published as an Advance Article on the web 5th March 2008
DOI: 10.1039/b801729h

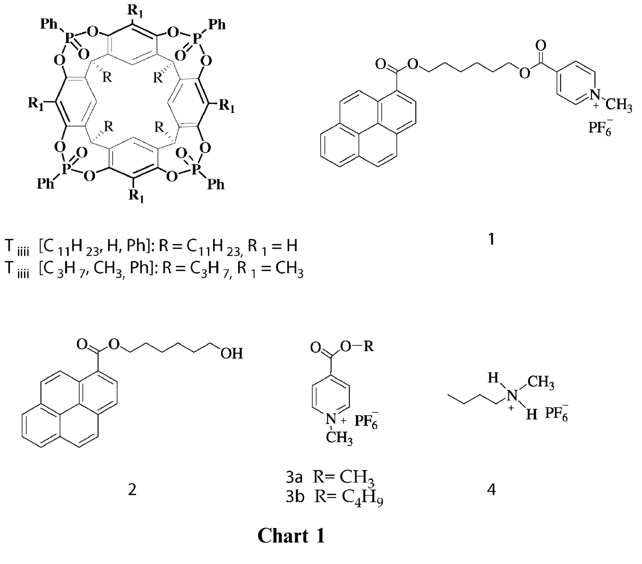
We report here the monitoring of reversible guest inclusion in phosphonate cavitands through a large increase in luminescence intensity caused by the modulation of the exoergonicity of an electron-transfer reaction.

Photoluminescence is one of the most versatile and sensitive techniques for the detection of chemical species in solution, and for this reason standard UV–VIS–NIR spectrofluorimeters, easy to use and low-cost instruments, are largely employed in research and analytical laboratories. In particular, luminescence spectroscopy has been finding applications in fields of great impact from a social and economic point of view, such as medical diagnostics and imaging, environmental sciences, and molecular electronics. In this context, luminescence spectroscopy has proved to be a very powerful technique when it is necessary to monitor molecular recognition events in cells or on surfaces, because of its submicron visualisation and submillisecond temporal resolution. Furthermore, one can take great advantage of the variety of possible ways of modulating the photophysical properties of a chromophore. Typical examples are the introduction of proton-, energy- and electron-transfer processes, the presence of heavy-atom effects, changes of electronic density, and the destabilisation of a nonemissive nπ* excited state. Knowledge of the rules governing these processes is of great importance in obtaining an efficient signal transduction mechanism.[1,2]

Self-assembly is the most promising approach to build organic nanostructures on surfaces, leading to hybrid organic–inorganic materials.[3] Among the different kinds of surfaces, most of the activity in the past has been concentrated on gold, due to the easy access to SAMs (self-assembled monolayers), but attention is shifting more and more towards silicon, because most electronic devices are Si-based. One of the obstacles hindering the development of Si-based hybrid materials is related to their characterization, and it was only very recently that we proposed the use in this context of luminescence spectroscopy, which helped to demonstrate the formation and distribution of coordination cages on Si(100), using a pyrene moiety as a fluorescent label.[4] The same approach could be used to monitor molecular recognition phenomena on silicon surfaces, another important feature to be implemented in Si-based hybrid materials.

As a first step forward in this direction, we report a suitable protocol for the reversible complexation of methylammonium and methylpyridinium salts by the phosphonate cavitand **T$_{iiii}$[C$_{11}$H$_{23}$, H, Ph]**[5] and its monitoring *via* fluorescence spectroscopy (Chart 1).

T$_{iiii}$ cavitands present remarkable molecular recognition properties toward charged *N*-methyl derivatives in the solid state,[6] in solution[7] and in the gas phase.[8] The large K_{ass} values measured for the **T$_{iiii}$** *N*-methyl complexes, which exceed 10^7 M^{-1} in dichloromethane, can be attributed to three synergistic interaction modes: (i) $N^+\cdots O{=}P$ cation–dipole interactions; (ii) CH_3–π interactions of the acidic ^+N–CH_3 group with the π basic cavity; (iii) two simultaneous hydrogen bonds between two adjacent P═O bridges and the two nitrogen protons,[8] in the case of protonated secondary amines like **4**. A $K_{ass} = 7.8 \times 10^6$ M^{-1} has been determined for the **T$_{iiii}$[C$_3$H$_7$, CH$_3$, Ph]·3b** complex in dichloromethane by ITC titrations (Table 1). Interestingly, the complexation is not only enthalpy but also entropy driven, indicating that solvation plays a pivotal role in the process. The corresponding K_{ass} for the **T$_{iiii}$[C$_3$H$_7$, CH$_3$, Ph]·4** complex could not be evaluated by ITC since its value in dichloromethane is above the ITC reliable measurement range ($10^2 < K_{ass} < 10^7$ M^{-1}).[9]



T$_{iiii}$ [C$_{11}$H$_{23}$, H, Ph]: R = C$_{11}$H$_{23}$, R$_1$ = H
T$_{iiii}$ [C$_3$H$_7$, CH$_3$, Ph]: R = C$_3$H$_7$, R$_1$ = CH$_3$

1

2

3a R= CH$_3$
3b R= C$_4$H$_9$

4

Chart 1

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† Electronic supplementary information (ESI) available: Synthetic procedures and characterization data. See DOI: 10.1039/b801729h

Table 1 Results of ITC titration of **T_{iiii}[C_3H_7, CH_3, Ph]** with **3b** and fluorescence titration of **T_{iiii}[$C_{11}H_{23}$, H, Ph]** with **1** in dichloromethane at 298 K. The ITC value is the average of three independent measurements

Host	Guest	n^a	ΔH/kJ mol^{-1}	$T\Delta S$/kJ mol^{-1}	ΔG/kJ mol^{-1}	K_{ass}(ITC)/M^{-1}	K_{ass}(Fluorescence)/M^{-1}
T_{iiii}[C_3H_7, CH_3, Ph]	**3b**	0.95 ± 0.01 (1/1)	-24.1 ± 0.4	15.1 ± 1	-39.2 ± 0.2	$(7.8 \pm 0.5) \times 10^6$	—
T_{iiii}[$C_{11}H_{23}$, H, Ph]	**1**	—	—	—	-39.3 ± 0.2	—	$(8.0 \pm 0.6) \times 10^6$

[a] n: Molar ratio of both components in the complex. The value in parentheses is the theoretical value for all binding sites occupied.

As a guest, we synthesized compound **1** (see ESI†), which has a methylpyridinium unit as recognition moiety connected to a pyrene probe *via* a diester tether. In particular, pyrene was chosen as a fluorescent unit for several reasons, in particular (i) its high emission efficiency, (ii) its ability to signal the presence of other pyrenes in the vicinity, (iii) the possibility of observing its fluorescence close to a silicon surface, and (iv) the possibility of giving rise to electron-transfer processes with pyridinium units.

The absorption spectrum of **1** (Fig. S1†) is largely dominated by the transitions centred on the pyrene units, with a small additive contribution from the methylpyridinium moiety at around 300 nm. The fluorescence spectrum of **1** in dichloromethane solution (Fig. 1a) showed the typical monomeric band of pyrene, but with a thirty-fold lower intensity compared to that of the reference compound **2**;‡ the excited state lifetime of **1** was correspondingly shorter (5.8 and 0.2 ns for **2** and **1**, respectively).

Apart from the lack of any other thermodynamically accessible quenching mechanism, the occurrence of an electron-transfer process was in this case also supported by electrochemical data. In fact the energy of the singlet excited state centred on the pyrene unit ($E^{\circ\circ}$ = 3.17 eV) is more than sufficient to transfer an electron from the pyrene ($E°(\mathbf{2}^+/\mathbf{2})$ = +1.53 V, irreversible process) to the pyridinium moiety ($E°(\mathbf{3a}/\mathbf{3a}^{\bullet-})$ = −0.68 V, irreversible process). The addition of **T_{iiii}[$C_{11}H_{23}$, H, Ph]** to a dichloromethane solution of **1** did not cause appreciable changes in the absorption spectrum in the 320–450 nm region, while the absorbance at lower wavelengths increased as expected because of the contribution of the added species. On the contrary, the addition of **T_{iiii}[$C_{11}H_{23}$, H, Ph]** caused very evident changes in the fluorescence spectrum, since the intensity of the pyrene band underwent a six-fold increase (Fig. 1a). It is also noteworthy that the fluorescence revival is accompanied by a proportional increase of the excited state lifetime to 1.2 ns. No changes either in absorption or in the fluorescence spectrum were instead observed upon addition to a solution of **T_{iiii}[$C_{11}H_{23}$, H, Ph]** of the reference pyrene compound **2**. These results cannot be explained in terms of a direct interaction between **T_{iiii}[$C_{11}H_{23}$, H, Ph]** and the pyrene moiety, since the lack of any change in the absorption spectrum in the transitions typical of pyrene leads to the conclusion that there is no electronic interaction between this latter unit and **T_{iiii}[$C_{11}H_{23}$, H, Ph]**, also after the formation of the complex depicted in Fig. 2. Rather, the observed increase of the luminescence can be ascribed to the decrease of the exoergonicity of the electron-transfer process that, in turn, leads to the decrease of the rate constant of the process. In fact, the inclusion inside the electron-rich cavity of the electron-poor methylpyridinium moiety is expected to make its reduction process more energy demanding. Although it is very difficult to make a quantitative analysis from chemically irreversible processes, this is supported by a *ca.* 40 mV shift towards more negative values of the reduction potential of the methylpyridinium unit in **1** upon addition of two equivalents of **T_{iiii}[$C_{11}H_{23}$, H, Ph]**. From the changes observed in the fluorescence intensity during the association process between **T_{iiii}[$C_{11}H_{23}$, H, Ph]** and **1**, it has been possible to measure a K_{ass} = 8.0×10^6 M^{-1}, in perfect agreement with the value obtained by ITC titration with reference compounds (Table 1).

To prove the reversibility of the association process, we added an increasing amount of the methylammonium salt **4** to a solution containing the **T_{iiii}[$C_{11}H_{23}$, H, Ph]·1** complex. As inferred by ITC, **4** has a much higher affinity than **3b** towards **T_{iiii}** cavitands. As can be observed from Figs. 1b and 2, such addition is accompanied by a gradual decrease of the fluorescence until the intensity reaches the value typical of **1** alone when one equivalent is added, clearly demonstrating that **1** is ejected away from the cavity by the more competitive **4**. The dissociation of the **T_{iiii}[$C_{11}H_{23}$, H, Ph]·4** complex was obtained

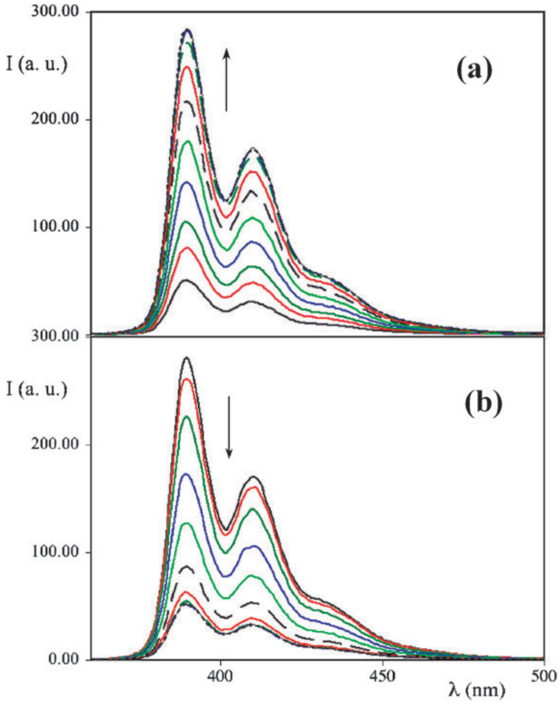

Fig. 1 Fluorescence spectra (λ_{exc} = 345 nm) of (a) a CH_2Cl_2 solution of **1** (1×10^{-5} M) and upon addition of an increasing (0–1.2 equiv.) amount of the cavitand **T_{iiii}[$C_{11}H_{23}$, H, Ph]**; (b) an equimolar CH_2Cl_2 solution of **T_{iiii}[$C_{11}H_{23}$, H, Ph]** and **1** (1×10^{-5} M) and upon addition of an increasing (0–1.3 equiv.) amount of the ammonium ion **4**.

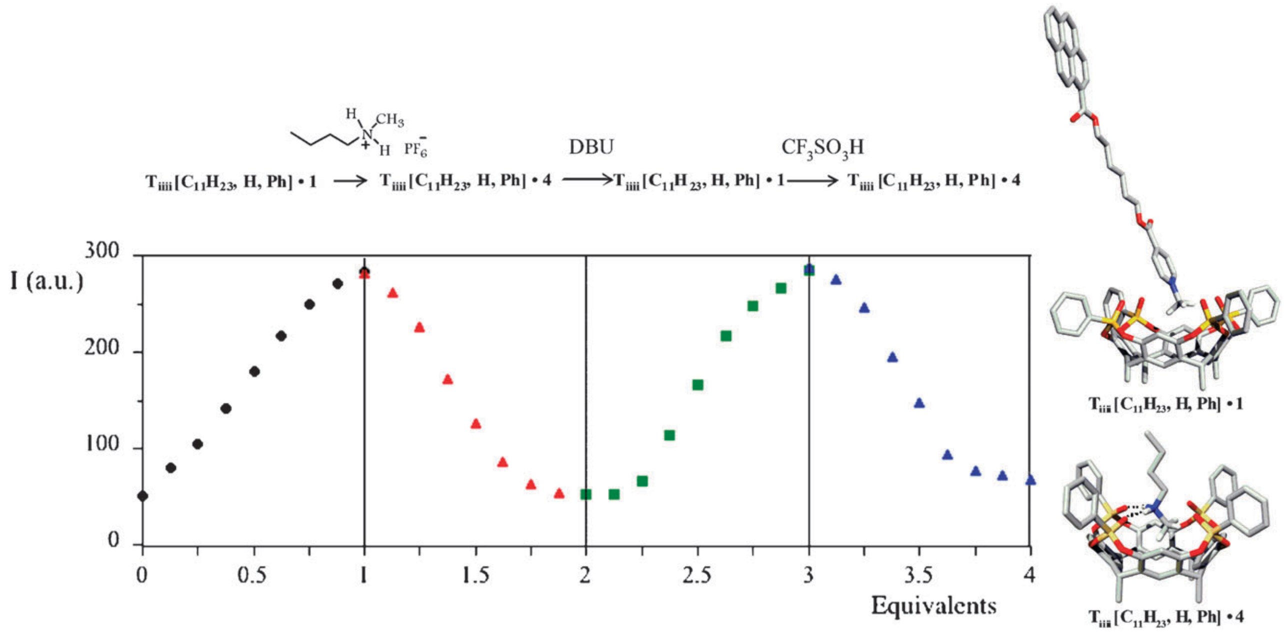

Fig. 2 Fluorescence intensity (λ_{exc} = 345 nm, λ_{em} = 390 nm) of a 1×10^{-5} M CH_2Cl_2 solution of **1** upon a subsequent addition of one equivalent of cavitand **T$_{iiii}$[C$_{11}$H$_{23}$, H, Ph]** (from 0–1 in the figure), one equivalent of ammonium ion **4** (from 1 to 2), one equivalent of DBU (from 2 to 3), and one equivalent of triflic acid (from 3 to 4). In the structures of the complexes the alkyl feet and the counterions are omitted for clarity.

by the addition of a hindered base (such as 1,8-diazabicyclo[5.4.0]undec-7-ene, DBU), that, by deprotonating the ammonium ion **4**, makes it unfit for interacting with the cavity, while the addition of triflic acid shifted the system towards the **T$_{iiii}$[C$_{11}$H$_{23}$, H, Ph]·4** complex again. As can be seen from Fig. 2, all these processes, which are completely reversible, were clearly monitored by looking at the fluorescence of the pyrene unit.

It is important to note at this point that, as desired because of the intrinsic higher offered sensitivity, the **T$_{iiii}$[C$_{11}$H$_{23}$, H, Ph]·1** complex formation is accompanied by a large increase in the luminescence signal, the final value of the fluorescence quantum yield being remarkably high (Φ = 0.08). This is not a trivial result, since quenching between a pyrene chromophore and a resorcinarene receptor was previously observed.[10] Furthermore, while PET processes have been often used with success to modulate the fluorescence intensity of a dye in a variety of sensors through the involvement of a nitrogen atom as electron donor,[2,11] this is in our opinion a rather elegant signal transduction mechanism since it makes the process orthogonal to the presence of protons or metal ions. A different design of the molecular thread would not have led easily to similar results. For example, a hypothetical linear molecule with a pyrene and an amine group covalently linked to it could have the luminescence of the dye quenched if the two groups were not too far apart, and the protonation of the amine would lead to both insertion in the cavity, if present, and to an increase of the fluorescence signal. However this latter effect would be observed independently of the presence of the cavitand and, as a consequence, of the association process. The extension of these studies on surfaces is in progress in our laboratories.

This work has been financially supported by MIUR through FIRB 2003-2004 LATEMAR, PRIN 2005 "Supramolecular approaches to oriented SMM at surfaces" and Fondazione Cassa di Risparmio in Bologna. We thank Prof. J. de Mendoza and his team at ICIQ for the use of the ITC instrument and Dr Damiano Genovese for performing the electrochemical measurements.

Notes and references

‡ It is worth emphasizing that in aerated solution **2** has a higher quantum yield but shorter lifetime than pyrene, and for this reason is also much less sensitive to the concentration of molecular oxygen.

1 M. Montalti, A. Credi, L. Prodi and M. T. Gandolfi, *Handbook of Photochemistry*, CRC Taylor & Francis, Boca Raton, 3rd edn, 2006.
2 L. Prodi, *New J. Chem.*, 2005, **29**, 20.
3 A. B. Descalzo, R. Martinez-Manez, F. Sancenon, K. Hoffmann and K. Rurack, *Angew. Chem., Int. Ed.*, 2006, **45**, 5924.
4 M. Busi, M. Laurenti, G. G. Condorelli, A. Motta, M. Favazza, I. L. Fragalà, M. Montalti, L. Prodi and E. Dalcanale, *Chem.–Eur. J.*, 2007, **13**, 6891.
5 For the nomenclature used to define tetraphosphonate cavitands see: R. Pinalli, M. Suman and E. Dalcanale, *Eur. J. Org. Chem.*, 2004, 451.
6 R. De Zorzi, B. Dubessy, J.-C. Mulatier, S. Geremia, L. Randaccio and J.-P. Dutasta, *J. Org. Chem.*, 2007, **72**, 4528.
7 J.-P. Dutasta, *Top. Curr. Chem.*, 2004, **232**, 55.
8 E. Kalenius, D. Moiani, E. Dalcanale and P. Vainiotalo, *Chem. Commun.*, 2007, 3865.
9 J. L. Sessler, D. E. Gross, W.-S. Cho, V. M. Lynch, F. P. Schmidtchen, G. W. Bates, M. E. Light and P. A. Gale, *J. Am. Chem. Soc.*, 2006, **128**, 12281.
10 M. Inhouye, K. Hashimoto and K. Isagawa, *J. Am. Chem. Soc.*, 1994, **116**, 5517.
11 L. Prodi, F. Bolletta, M. Montalti and N. Zaccheroni, *Coord. Chem. Rev.*, 2000, **205**, 59.