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Recognition of quaternary ammonium cations by calix[4]arene derivatives supported on gold nanoparticles†

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Calix[4]arene derivatives supported on monolayer protected gold clusters show a remarkable enhanced binding efficiency towards quaternary ammonium salts in homogeneous solution of apolar solvents with respect to the corresponding unsupported hosts.

The development of the reliable synthetic procedures for monolayer protected clusters (MPC) devised by Brust and Schiffrin,[1] had a high impact in the fields of nanoscience and nanotechnology. Nowadays it is in fact possible to prepare stable gold nanoparticles of controllable size and reduced dispersity. Recently, the introduction of recognition elements onto MPC surfaces has enabled the manufacturing of nanoscale devices with potential applications as sensors, switches and new materials having tunable properties.[2] In this context, a very attractive topological property of MPCs is the possibility of anchoring on their surface a discrete number of suitable receptors in a radial three-dimensional arrangement.[3] In addition the recognition properties of the cluster of receptors thus obtained can be studied in solution.[2] In spite of the remarkable results obtained so far on the use of these systems as receptors for ion pairs and neutral molecules recognition, attempts to compare their binding abilities with those of the monomeric model host have been carried out only very recently.[4,5] It however appeared to us that a possible approach to the rational design of MPC supported hosts should be based on the understanding of the several factors introduced by the clustering of receptors.

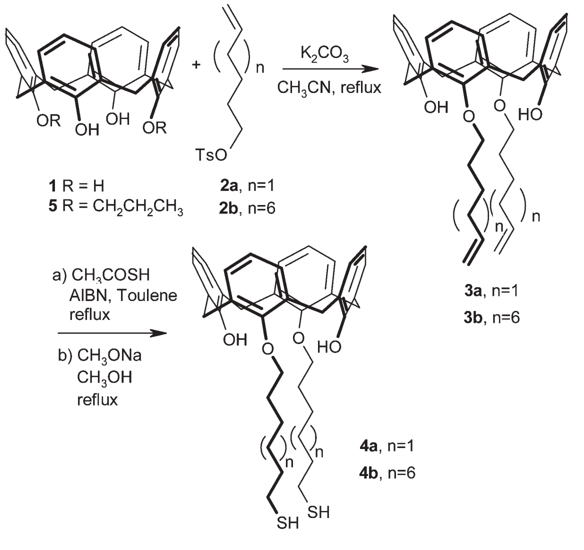
Furthermore the rational study of the binding properties of MPC supported hosts is strictly related to that of synthetic multihosts.[6] These studies generally show, with a multivalent cluster of hosts, reduced binding toward monovalent ionic species, but enhanced binding to multivalent ionic compounds, relative to the strength of the parent monovalent systems.[6b,c] Here we report the synthesis of calix[4]arene derivatives self-assembled in a radial monolayer on gold nanoparticles.[7] The recognition properties of these MPCs toward quaternary ammonium salts in apolar solvents have been studied and compared with those of similar receptors in homogeneous solution.

The hosts chosen for this study were 1,3-dialkoxycalix[4]arenes, which are known to form *endo* cavity inclusion complexes with quaternary ammonium cations.[8,9] To disclose a possible effect of the calixarene cavities distance from the gold core on the recognition efficiency, calix[4]arenes bearing two alkanethiol chains of six (**4a**) or eleven carbon (**4b**) atoms were prepared according to Scheme 1.

The anchoring of these hosts onto gold nanoparticles was performed by partial or total exchange reaction starting from dodecanethiol MPC prepared according to the Brust–Schiffrin method, to obtain gold MPCs having a core diameter of about 2 nm.‡

In particular, two sets of nanoparticles, each loaded with three different percentages of the calix[4]arene host **4a** (**N1**, **N2** and **N3**) and **4b** (**N4**, **N5** and **N6**) were prepared, respectively (see Fig. 1 and Table 1).§ According to Murray and co-workers, these MPCs have a core constituted by *circa* 200–300 gold atoms and a surface of about 20 nm^2 covered with 70–90 alkanethiolate chains.[10] The complete substitution of the alkanethiol chains with calix[4]arenes **4a,b** could thus lead to MPCs having 35–45 calix[4]arene recognition units.¶

The binding abilities of the different gold nanoparticles **N1–6** toward *N*-methylpyridinium tosylate were evaluated by ^{1}H NMR titrations in $CDCl_3$. All NMR spectra showed time-averaged signals for the free and complexed species.[11] The "average binding constant", K_{av}, could be thus measured. K_{av} was introduced by Stoddart and co-workers as "a measure of the strength of the noncovalent binding interaction between a single host moiety and a single guest".[6b,c] The binding constants were calculated,|| having



Scheme 1

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† Electronic supplementary information (ESI) available: synthetic procedures for the preparation of calix[4]arene derivatives **4a,b** and MPCs **N1–6**. ^{1}H NMR spectra of nanoparticles **N3** and **N6** in $CDCl_3$. Binding isotherm for the titrations of tetramethylammonium tosylate with nanoparticles **N6** in $CDCl_3$, and Job's plot for the titration of *N*-methylpyridinium tosylate with nanoparticle **N3**. See http://www.rsc.org/suppdata/cc/b4/b411883a/

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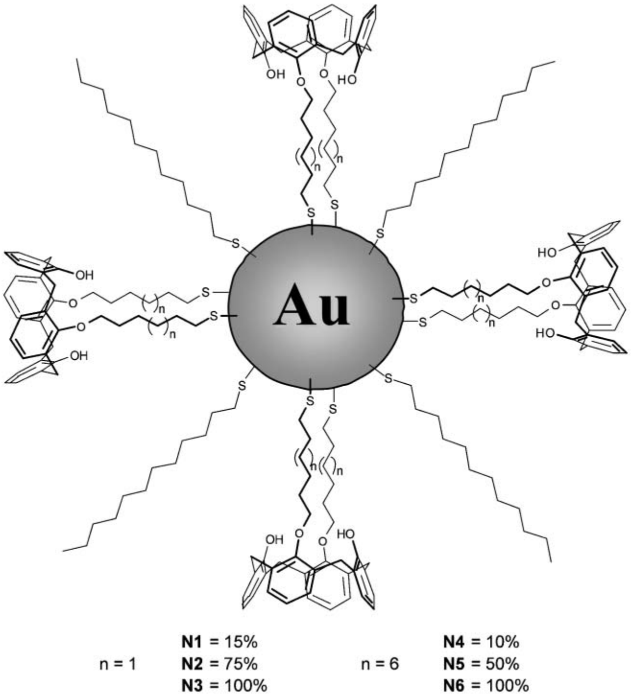

Fig. 1 Schematic representation of gold MPCs functionalised with calix[4]arenes **4a** ($n = 1$) and **4b** ($n = 6$). The percentage represents the ratio in moles between the receptor and dodecanethiol chains in each MPC.

verified a 1 : 1 stoichiometry through continuous variation methods, as previously described[9a] and summarised in Table 1. The binding constant K for 1,3-dipropoxy calix[4]arene **5** was also calculated as representative for an homogeneous system.[12]

Analysis of the results clearly shows that the introduction of calix[4]arene recognition elements with a C6 linker onto the MPC surface increases the extent of binding of *N*-methylpyridinium tosylate with respect to host **5** (see entries 1 and 2, Table 1). The efficiency of binding is further enhanced as the number of calixarene units present on the gold nanoparticle increases (see entries 2–4, Table 1). The length of the two alkyl chains that act as spacers between the host cavity and the nanoparticle surface, largely affects the extent of binding. In particular, the nanoparticles derived from **4b** show a further enhancement in the binding efficiency. For instance, the binding constant calculated for **N6**, where the dodecanethiol chains are completely substituted, is three orders of magnitude higher than that experienced by **5**. This trend was also confirmed, although to a lesser extent, using tetramethylammonium salts (see Table 2).

Table 1 Association constants (K) for host **5** and average binding constant (K_{av}) for MPCs **N1–6** with *N*-methylpyridinium tosylate in $CDCl_3$

Entry	Host	Host/$C_{12}H_{25}SH$ (%)[a]	K, K_{av} ($\times 10^3$)[b]
1	**5**	—	0.25
2	**N1**	15	1.4
3	**N2**	75	2.3
4	**N3**	100	4.5
5	**N4**	10	2.9
6	**N5**	50	10.1
7	**N6**	100	100

[a] In moles (%), calculated by integration of dodecanethiol methyl and calixarene methylene groups signals. [b] Errors 20%.

Table 2 Association constants (K) for host **5** and average binding constant (K_{av}) for **N6** with tetramethylammonium (TMA) acetate (Ac) and tosylate (Ts) salts in $CDCl_3$[a]

Host	TMAAc	TMATs
5	20	41
N6	540	1030

[a] Errors 20%.

These data clearly show that in apolar media clusters of calixarene hosts supported on a nanoparticle are very efficient receptors for the recognition of ion-pairs. This could be due to the presence, on the monolayer, of alternating complexed cations and counteranions, which could reduce the interactions between the ions present in the ion pair. This should thus increase the binding efficiency of these systems as verified for example in the dual host strategy.[9b]

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Notes and references

‡ Dodecanethiol stabilised MPCs were synthesised at room temperature using the following molar ratio of starting reagents: $HAuCl_4 \cdot 3H_2O$: n-$C_{12}H_{25}SH$: $(n\text{-}C_8H_{17})_4N^+Br^-$: $NaBH_4$ = 1 : 3 : 3 : 20, closely following the method developed by Brust *et al.* (see Ref. 1).

§ MPCs **N1–6** were prepared as follows: 50 mg of dodecanethiol stabilised MPCs were mixed in toluene at room temperature with different percentages of the appropriate receptor (**4a** or **4b**) for 5 days. The resulting mixture was purified by column chromatography (silica gel, *n*-hexane : ethyl acetate = 4 : 1), followed by ultra centrifugation of the eluate.

¶ From the elemental analyses of **N3** and **N6** (see Supp. Info.), the presence of 60 calixarene units per nanoparticle could be estimated.

|| ^1H NMR titrations were performed using a weighted amount of 1,1,2,2-tetrachloroethane as internal standard to determine the calixarene receptor units present in solution. The validity of this method was checked performing a titration of host **5** with *N*-methylpyridinium tosylate using the same internal standard.

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