CHAPTER 3

3.1 Introduction to calix[n]arenes

Calix[n]arenes are a well know class of macrocyclic compounds, having four, six or eight phenol units in the annulus, obtained in very high yield through a one-step condensation of formaldehyde with p-*tert*-butyl phenol in basic conditions.[1]

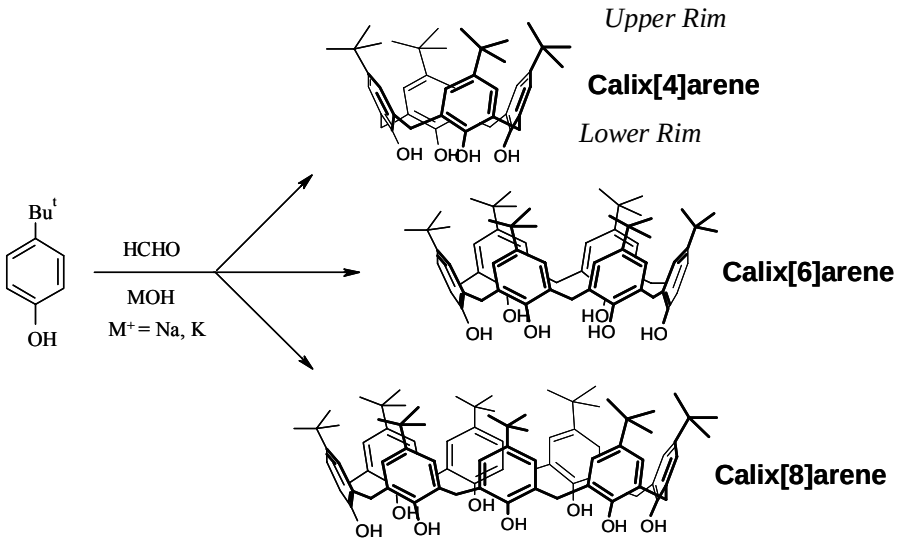

Figure 3.1. Synthesis of p-*tert*-butyl-calix[n]arene compounds (n= 4, 6 and 8).

1. a) C. D. Gutsche, *Calixarenes, Monographs in Supramolecular Chemistry*, Ed.: J. F. Stoddart, Royal Society of Chemistry: Cambridge, U.K., **1989**; b) C. D. Gutsche, *Calixarenes Revisited, Monographs in Supramolecular Chemistry*, Ed.: J. F. Stoddart, Royal Society of Chemistry: Cambridge, U.K., **1998**; c) *Calixarenes in Action*, Eds.: L. Mandolini, R. Ungaro, Imperial College Press: London, **2000**; d) *Calixarenes 2001*, Eds.: Z. Asfari, V. Böhmer, J. Harrowfield, J. Vicens, Kluwer Academic: Dordrecht, **2001**.

Among the several classes of synthetic macrocyclic compounds currently used as receptors (hosts) in supramolecular chemistry, calix[n]arenes have assumed a key role due to their synthetic accessibility and versatility. Indeed, the insertion of new functional groups onto both the "rims" (*upper* and *lower* see Figure 3.1) of the macrocycles can be easily accomplished using common reactions typical of the organic chemistry. Such functionalization reactions allow, as an example, either the insertions of ancillary binding sites or the extension of the hosts aromatic cavity. For this reason calix[n]arenes can be considered as useful building block for the synthesis of new advanced receptors.

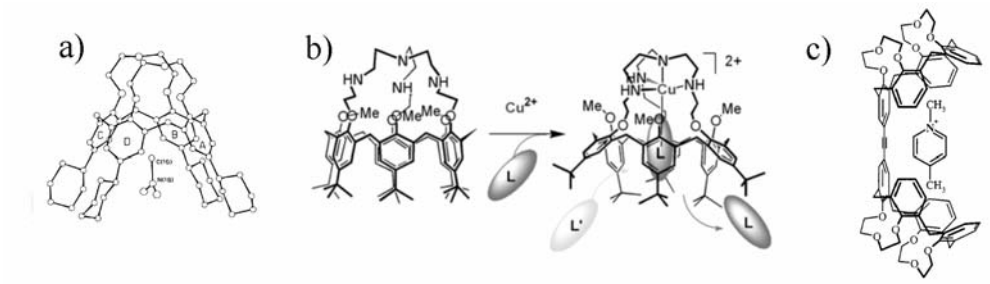

Figure 3.2. Examples of guest inclusion complexes of calix[n]arene derivatives with a) neutral molecules, b) metal cations and c) organic cations.

As far as the recognition properties of these macrocyclic compounds are concerned, those experienced by calix[4]arene derivatives blocked in the *cone* conformation, that is with the four aromatic rings oriented in the same direction, have been the most extensively studied. From the literature it is known that the calix[4]arene cavity may work as binding

site for *i.e.* organic cations such as quaternary ammonium salts[2] (QUATS) (Figure 1c), metal ions[3] (Figure 1b) and neutral molecules containing relatively acidic C-H moieties such as toluene, acetonitrile and nitrometane[4] (Figure 1a).

The driven force of all these recognition processes is found in weak electrostatic intermolecular interactions such as cation/π[5] or CH/π interactions.[6] These interactions are established between the π-rich aromatic cavity of the host with positively charged or acidic neutral guest molecules, respectively. Because of their weak nature, the establishment of these interactions require a very high host preorganisation in order to diminish the entropy loss upon complexation. As matter of fact, a systematic investigation of the parameters that affect the recognition efficiency in low polar media of this type of hosts was pursued by our research group. These studies have shown that both the extension[7] and especially preorganisation[4,8] of the calixarene cavity strongly influence the binding of charged and neutral guests.

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2. A. Arduini, A. Secchi, A. Pochini, *Eur. J. Org.* **2000**, 2325.
3. G. Izzet, B. Douziech, T. Prangé, A. Tomas, I. Jabin, Y. Le Mest, O. Reinaud, *PNAS* **2005**, *102*, 6831.
4. A. Arduini, W. M. McGregor, D. Paganuzzi, A. Pochini, A. Secchi, F. Ugozzoli, R. Ungaro, *J. Chem. Soc. Perkin Trans. 2* , **1996**, 839.
5. See *e.g.*: N. Zacarias, D. A. Dougherty, *Trends Pharmacol Sci* **2002**, *23*, 281 and references therein.
6. See *e.g.*: H. Takahashi, S. Tsuboyama, Y. Umezawa, K. Honda, M. Nishio, *Tetrahedron* **2000**, *56*, 6185 and references therein.
7. A. Arduini, G. Giorgi, A. Pochini, A. Secchi, F. Ugozzoli, *J. Org. Chem.* **2001**, *66*, 8302.
8. A. Arduini, E. Brindani, G. Giorgi, A. Pochini, A. Secchi, *J. Org. Chem.* **2002**, *67*, 6188.

3.2 Ligand "sulphur denticity" as size control element in the Au MPCs synthesis

It is easily foreseen that the combination of the recognition properties of the synthetic macrocyclic receptors such as calix[n]arenes with the attributes typical of the monolayer protected clusters (MPCs) could potentially enable the manufacturing of nanoscale devices with potential applications as sensors, switches and new materials having tunable properties. As seen in chapter 2, a very attractive topological property of MPCs is the possibility to anchor on their surface a discrete number of suitable receptors in a radial tri-dimensional arrangement. In addition the recognition properties of the cluster of receptors thus obtained can be studied in solution.[9] In the latter context, we have recently shown that Au MPCs stabilized with alkylthiolated calix[4]arene derivatives can be successfully employed as multivalent hosts for the recognition of organic salts both in organic[10] and aqueous media.[11] However, it appeared us that a possible approach to the rational design of MPCs supported hosts should be based on the understanding of the several factors introduced by the clustering of receptors. The introduction of the receptors onto the surface of the metal clusters could in fact affect both the recognition properties of the hosts and the size and dispersity of the MPCs thus

9. Several studies are present in the literature where this strategy has been successfully adopted. For a review see: A. B. Descalzo, R. Martínez-Máñez, R. Sancenón, K. Hoffmann, K. Rurack, *Angew. Chem. Int. Ed.* **2006**, *45*, 5924.
10. a) A. Arduini, D. Demuru, A. Pochini, A. Secchi, *Chem. Commun.* **2005**, 645-647; b) D. Demuru, PhD thesis, Università degli Studi di Parma, **2004**.
11. T. R. Tshikhudo, D. Demuru, Z. Wang, M. Brust, A. Secchi, A. Arduini, A. Pochini,. *Angew. Chem. Int. Ed.* **2005**, *44*, 2913.

obtained. On these premises in the following paragraphs, some results aimed at disclosing the role played by the receptor "sulphur denticity" on the resulting size of the gold core of a series of Au MPCs stabilized with calix[n]arene (n= 4 and 6) derivatives will be presented. The whole discussion will be subdivided in different paragraphs here summarized: a) synthesis and structural characterization of the calix[n]arene derivatives to be employed for the Au MPCs preparation; b) synthesis and structural characterization of the Au MPCs; c) extension of the synthesis of MPCs having a different metallic core (Ag and Pd).

3.2.1 Synthesis of calix[n]arene derivatives as passivating agent for the synthesis of AuMPCs

As seen in the previous chapter, the synthesis of lipophilic Au MPCs is usually obtained through the reduction of aurate salts in the presence of thiolated ligands. The formation of the protected clusters could be considered as the result of two processes: growth of the metallic core and gold surface passivation due to the presence in solution of the thiols. The two processes are competitive and Tsukuda has proposed that the isolated MPCs correspond to kinetically trapped intermediates of the growing gold core.[12] Murray has indirectly supported such hypothesis since he shown that the core size of n-alkylthiol-stabilized Au MPCs is strongly affected by the concentration of the reactants, temperature and reductant

12. Y. Negishi, Y. Takasugi, S. Sato, H. Yao, K. Kimura,T. Tsukuda, *J. Phys. Chem. B* **2006**, *110*, 12218.

rate addition.[13] In contrast, the effect of the capping agent, and in particular of the ligand "denticity", has not been systematically investigated yet. In the latter context, a perusal of the data present in the literature evidences that multidentate thiolated ligands could promote the preparation of Au MPCs having improved stability.[14] Moving from these interesting findings, we have formulated the hypothesis that multidentate ligands could also exert a relevant kinetic effect on the gold core growth. Indeed, in the literature are not reported reliable synthetic protocols that allow the preparation of monodispersed lipophilic Au MPCs with very small diameter (<1 nm).[15,16] This aspect could be of great importance considering that sub-nanometer MPCs are particularly enticing owing to their possible quantum size effects.[17]

To evaluate the effect of multidentate ligands on the gold core growth we decided to use a series of thiolated calix[n]arene derivatives bearing a variable number of convergent undecanthiol chains onto their lower rim. In principle such functionalities could be located on both rims

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13. M. J. Hostetler, J. E. Wingate, C.-J. Zhong, J. E. Harris, R. W. Vachet, M. R. Clark, J. D. Londono, S. J. Green, J. J. Stokes, G. D. Wignall, G. L. Glish, M. D. Porter, N. D. Evans, R. W. Murray, *Langmuir*, **1998**, *14*, 17.

14. a) K. Wojczykowski, D. Meißner, P. Jutzi, I. Ennen, A. Hütten, M. Fricke, D. Volkmer, *Chem. Commun*. **2006**, 3693; b) Z. Wang, B. Tan, I. Hussain, N. Schaeffer, M. F. Wyatt, M. Brust, A. I. Cooper, *Langmuir* **2007**, *23*, 885.

15. Monodispersed alkylthiol-stabilized undecagold (Au11) clusters can be obtained through ligand exchange reactions starting from the corresponding rather unstable phosphine-stabilized clusters. See e. g.: a) G. H. Woehrle, M. G. Warner, J. E. Hutchinson, *J. Phys. Chem. B* **2002**, *106*, 9979; b) G. H. Woehrle, J. E. Hutchinson, *Inorg. Chem.* **2005**, *44*, 6149; c) M. F. Bertino, Z.-M. Sun, R. Zhang, L.-S. Wang, *J. Phys. Chem. B.* **2006**, *110*, 21416.

16. Special ligands such as glutathione also promote the formation of very small Au MPCs, see : Y. Negishi, K. Nobusada, T. Tsukuda, *J. Am. Chem. Soc.* **2005**, *127*, 5261.

17. See e. g.: a) Y. Volokitin, J. Sinzig, L. J. de Jongh, G. Schmid, M. N. Vargaftik, I. I. Moiseev, *Nature* **1996**, *384*, 621; b) S. Chen, R. S. Ingram, M. J. Hostetler, J. J. Pietron, R. W. Murray, T. G. Schaaf, J. T. Khoury, M. M. Alvarez, R. L. Whetten, *Science* **1998**, *280*, 2098.

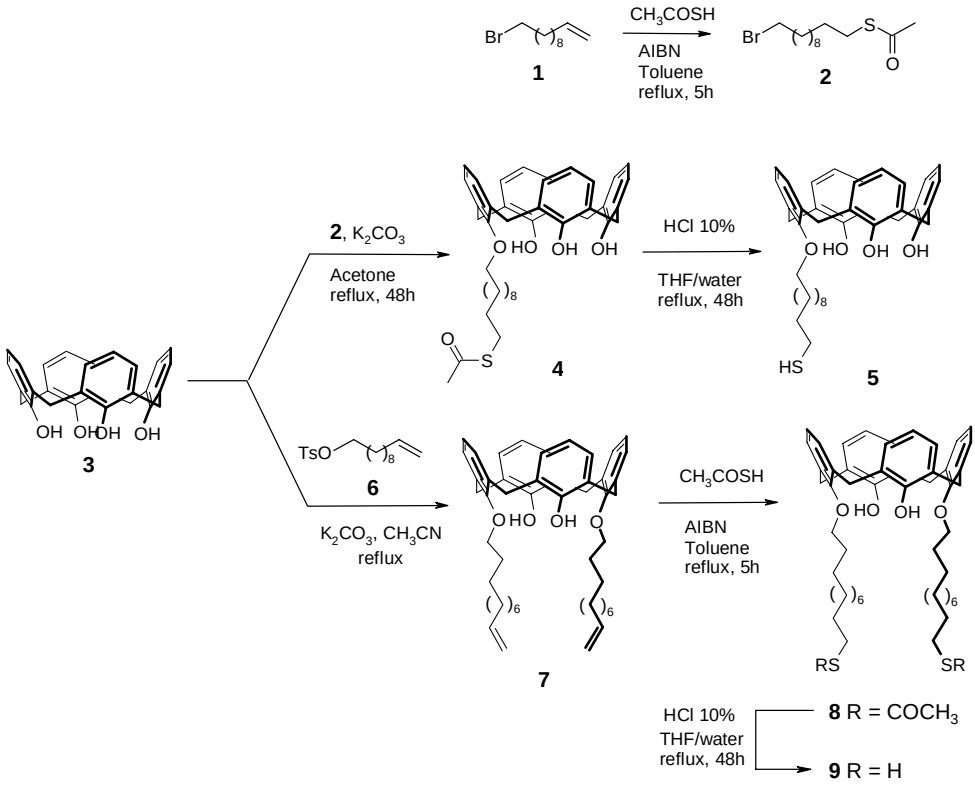
of the macrocycle. Wei et al. have shown that resorc[4]arenes having SH groups onto their upper rim can be used for the stabilization of Au MPCs.[18] This strategy presents, doubtless, the big disadvantage of clusters in which the recognition unit of the hosts are exposed toward the metal surface and not toward the bulk. In contrast, the lower rim functionalization offers several advantages. First of all, the thiol groups can be positioned far from the calixarene cavity by using, as spacers, alkyl chains of variable length. In this way the recognition units are always exposed to the bulk and thus they can exploit their functionalities. Second, the different acidity of the calix[n]arene phenolic OHs allows the regiochemical insertion of a variable number (1 to 4) of thiolated alkyl chains. This is accomplished by varying the nature of the base employed during the alkylation process, and b) by choosing the appropriate molar ratio between the calix[4]arene and the alkylating agent, as well as the solvent and the temperature.

For the anchoring of the host units onto the gold surface were initially designed calix[4]arene derivatives characterized by the presence of one and two long thiolated alkyl chains (C_{11}) onto the macrocycle lower rim.[19] In the dilakylated compound the two chains were inserted in the 1,3 "distal" position to satisfy the requirements of host rigidity and preorganization discussed in the previous paragraph. The use of the thiol group (SH), as the macrocycle anchoring point onto the metallic surface,

18. a) Balasubramanian, R.; Kim, B.; Tripp, S. L.; Wang, X. J.; Lieberman, M.; Wei, A. *Langmuir* **2002**, *18*, 3676-3681; b) A. Wie, *Chem. Commun.* **2006**, 1581.

19. It is known from the literature that lower rim mono- and di-alkylated calix[4]arenes show good recognition properties toward neutral and charged guests, whereas tetra-alkylkated derivatives experience residual mobility in solution that very poor any complexation efficiency, see *e. g* : S. Smirnov, V. Sidorov, E. Pinkhassik, J. Havlicek, I. Stibor, *Supramol Chem.* **1997**, *8*, 187.

was dictated by previous observations that such function yields RS-Au bonds energetically more stable than those formed i.e. by thioether functions (R_2S-Au).[20]



Scheme 3.1. Synthesis of thiolated calix[4]arenes **5** and **9**

Because of regiochemical problems the insertion of the thiolated alkyl chains on the calix[4]arene macrocycle cannot be, however, performed using direct methods. The 25-(11-mercapto-undecanoxy)-calix[4]arene (**5**) and the 25,27-bis(11-mercapto-undecanoxy)-

20. X. M. Li, R. M. de Jong, K. Inoue, S. Shinkai, J. Huskens, D. N. Reinhoudt, *J. Mater. Chem.* **2001**, *11*, 1919.

calix[4]arene (**9**) were thus synthesized in reasonable yield using the synthetic pathway depicted in Scheme 3.1.[21]

For the synthesis of the "monodentate" **5**, the anchoring group (S) was inserted onto the alkyl chain before the alkylation of the macrocycle lower rim. In particular, it was introduced as thioacetyl ($SOCH_3$) group through a radical anti-Markovnikov addition of thioacetic acid, mediated by the radical initiator AIBN, on the 11-bromoundec-1-ene 1 (**1**). The resulting *S*-11-bromoundecyl ethanethioate (**2**) was then used as alkylating agent for the reaction with the calix[4]arene **3**. Such reaction is not regioselective, but acting on both the stoichiometry (defect of alkylating agent) and nature of the base employed, it was possible to synthesize the 25-[11-(acetylthio)-undecanoxy]calix[4]arene (**4**) in good yield (80%). The acetyl protecting group was then removed by acid hydrolysis (HCl) almost quantitatively to afford the target 25-(11-mercapto-undecanoxy)-calix[4]arene (**5**). All compounds were characterized using NMR and mass spectroscopy (see experimental). If calix[4]arene derivatives symmetrically alkylated at their lower rim usually yield quite simple ^{1}H-NMR spectra (see infra), monoalkylated ones give a very complicated pattern of signals due to the lack of symmetry elements. The ^{1}H NMR spectrum of **5**, taken in $CDCl_3$, has been depicted in figure 3.3. It shows two singlets at δ = 9.74 and 9.43 ppm in 1:2 ratio that are diagnostic for the three unsubstituted OH groups. The complicated pattern of the aromatic signals reflects the presence in the compound of three type of aromatic rings, in ratio 1:2:1, having different magnetic environment. The protons of the bridging

21. Synthesis of **9** was partially published, see ref. 10a.

methylene groups give rise to a typical pattern of signals for a monosubstituted calix[4]arene derivative.[22] The four "axial" and the four "equatorial" protons resonate as two couple of doublets (with geminal coupling, J = 14 Hz) at δ = 4.37, 4.28, 3.47 and 3.46 ppm. The undecanyl chain yields several multiplet in the upfield region (2.2 – 0.8 ppm), though both the OCH_2 and CH_2SH methylene protons resonates as characteristic signals. The former is a triplet at δ = 4.15 ppm, while the latter is a *dt* (double-triplet) centered at δ = 2.55 ppm. The multiplicity of the latter signal reflects the coupling of the CH_2 protons with the proton of the SH group. The signal of the SH proton (δ ≈ 1.5 ppm) is completely hidden under the pattern of signals of the aliphatic chain and its presence was confirmed exclusively through 2D COSY experiments.

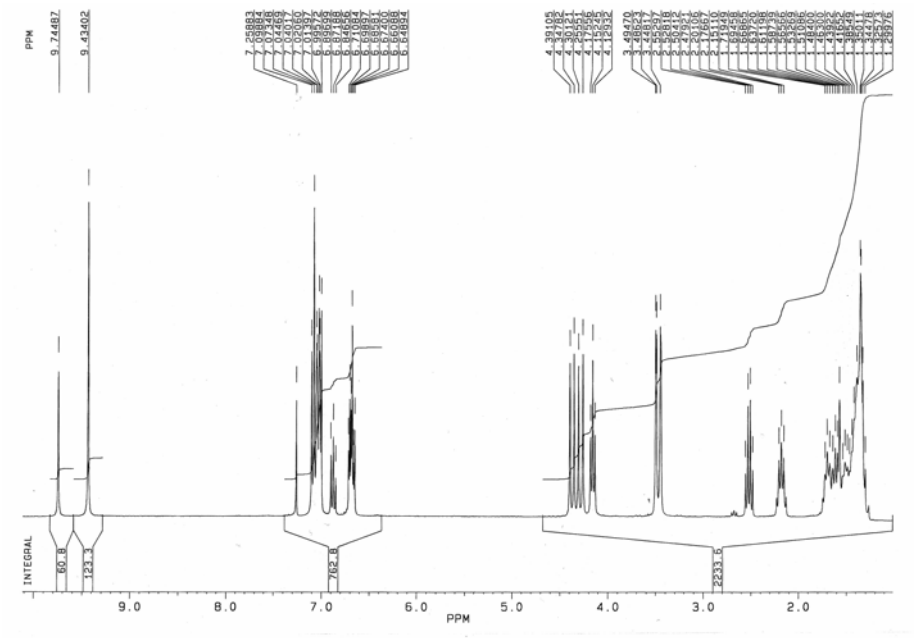


Figure 3.3. ^{1}H NMR spectrum of **5** in $CDCl_3$ (300 MHz).

22. For a detailed discussion on NMR spectra of calix[n]arene compounds see ref. 1a.

For the synthesis of the "bidentate" calix[4]arene **9**, the anchoring group (S) was inserted onto the alkyl chains after the alkylation of the macrocycle lower rim because this synthetic approach offered the highest yields. In particular, calix[4]arene **3** was initially regioselectively alkylated in 1,3 positions with undec-10-enyl tosylate (**6**) in acetonitrile using K_2CO_3 as base. The resulting dialkylated derivative **7**, whose identity was confirmed by the presence of the vinyl signals in its ^1H NMR spectrum (see experimental), was then converted in the 25,27-bis-[11-(acetylthio)-undecanoxy]calix[4]arene (**8**) using the same experimental conditions employed in the synthesis of **2**. The hydrolysis of the thioacetyl groups of **8** was accomplished as usual in acid conditions (HCl 10% in THF/water) to yield the "bidentate" thiolated calix[4]arene **9** in high yield.

The identity of **9** was confirmed both through NMR and mass spectroscopy (see experimental). Its ^1H NMR spectrum, taken in $CDCl_3$ (see Figure 3.4), is simpler than that of **5**. Indeed, the structure of **9** presents a C_{2v} symmetry that generates only a singlet for the two OH groups at δ = 8.29 ppm, two doublets and two triplets, respectively, for the two different *meta* and *para* protons of the aromatic nuclei. An unique AX system of two doublets (δ = 4.40 and 3.45 ppm) for the axial and equatorial protons of the methylene bridging units. As for **5**, the protons of the methylene group in α to the SH resonates as multiplet centered at δ = 2.59 ppm.

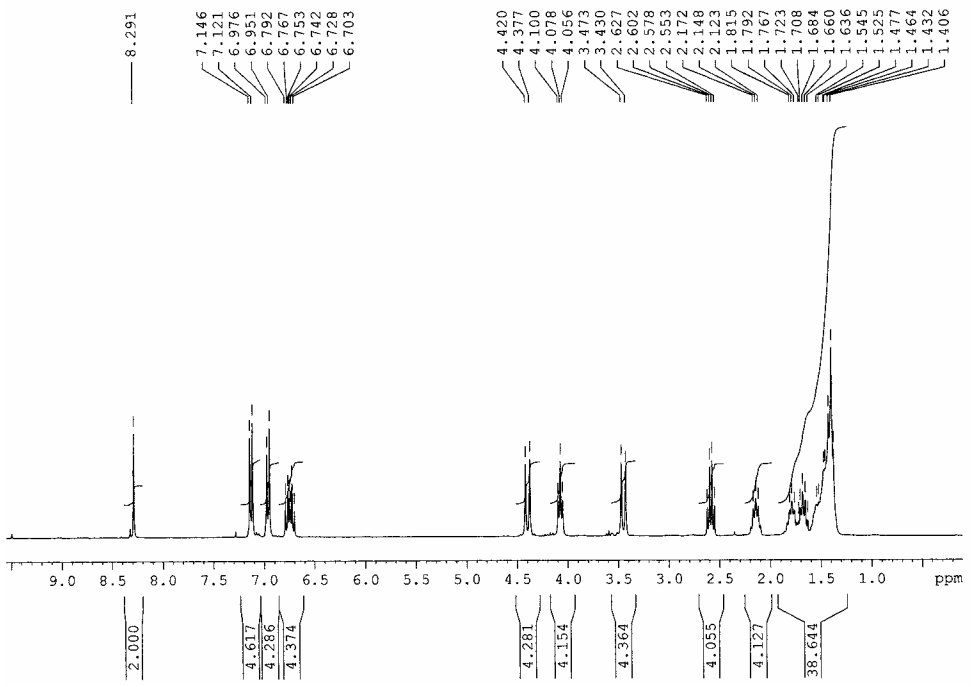


Figure 3.4. ^{1}H NMR spectrum of **9** in $CDCl_3$ (300 MHz)

3.2.2 Synthesis and characterization of the calix[n]arene-coated Au MPCs

A systematic study aimed at the development of reliable protocols for the synthesis of Au MPCs coated with calix[4]arene-based hosts has been undertaken in a previous PhD thesis.[10b] The clusters were successfully prepared using the "ligand-place exchange reactions" introduced by Murray.[23] According to this method, Au clusters loaded in the organic shell with different percentages of calix[4]arenes (from 10 to 100%) were obtained equilibrating in toluene *n*-dodecanthiol-coated Au

23. M. J. Hostetler, A. C. Templeton, R. W Murray, *Langmuir* **1999**, *15*, 3782.

MPCs (∅ ≈ 2 nm) with increasing amounts of thiolated calix[4]arene derivatives (see Figure 3.5). Such method has, however, an important limitation: the core size of the exchanged Au MPCs is derived by the core size of the *n*-dodecanthiol-coated Au MPCs used as starting material.[24]

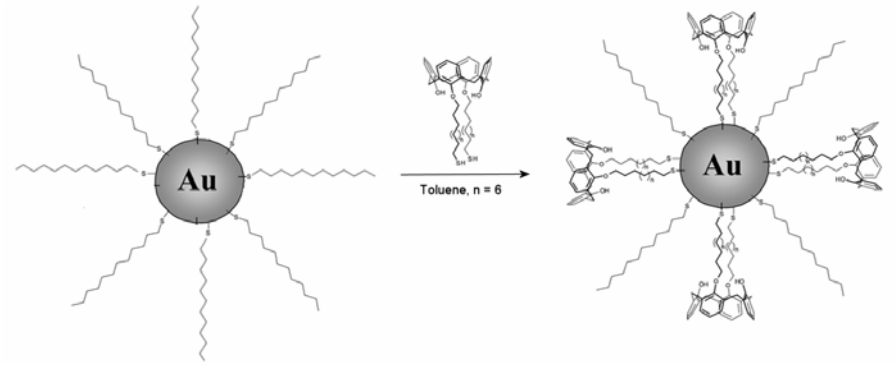


Figure 3.5. Schematic representation of the "ligand-place exchange" reaction for the synthesis of Au MMPCs stabilized with calix[4]arene **9**

Taking advantage of the synthetic procedure reported by Murray,[13] calixarene-protected clusters were thus prepared using direct methods by adding the reducing agent ($NaBH_4$) to a toluene solution containing the calix[4]arenes **5** or **9** and the aurate salt in the following molar ratios: calix$(SH)_n/AuCl_4^-$ = 3/n, 0.33/n and 0.16/n. Thus, for the monodentate **5** (n = 1) we used **5**$(SH)/AuCl_4^-$ = 3, 0.33 and 0.16, whereas for the bidentate **9** (n = 2) we used **9**$(SH)_2/AuCl_4^-$ = 1.5, 0.17 and 0.08. For sake

24. According to the Brust-Schiffrin method, the diameter lower limit for the synthesis of *n*-dodecanthiol-coated Au MPCs is of ca. 1.5 nm. See e. g.: a) M. Brust, M. Walker, D. Bethell, D. J. Schiffrin, R. Whyman, R., *J. Chem. Soc., Chem. Commun.* **1994**, 801; b) M. Brust, J. Fink, D. Bethell, D. J. Schiffrin, C. Kiely, *J. Chem. Soc., Chem. Commun.* **1995**, 1655.

of comprehension, the clusters synthesized with the different molar ratios were labelled as reported in Table **3.1**.

Table 3.1. Composition and core diameter of Au MPCs stabilized with the calix[n]arene derivatives **5**, **9**, **13** and *n*-dodecanthiole.

Designation	Thiol	Molar ratio[a]	D (nm)[b]	Organic fraction (%)[e]
5-MPCs(1)	**5**	3	1.5±0.4	52
(2)	*n*-$C_{12}H_{25}SH$	3[c]	1.6[c]	47
9-MPCs(3)	**9**	3(1.5)	0.9±0.2	70
13-MPCs(4)	**13**	3(1)	0.9±0.2	82
5-MPCs(5)	**5**	0.33	2.5±0.5	36
(6)	*n*-$C_{12}H_{25}SH$	0.33[d]	2.8[d]	17
9-MPCs(7)	**9**	0.33(0.17)	1.6±0.4	38
13-MPCs(8)	**13**	0.33(0.11)	2.1±0.3	47
5-MPCs(9)	**5**	0.16	3±1	21
(10)	*n*-$C_{12}H_{25}SH$	0.16[d]	4.4[d]	9
9-MPCs(11)	**9**	0.16(0.08)	2.5±0.7	31
13-MPCs(12)	**13**	0.16(0.05)	2.8±0.6	31

[a]thiol : $AuCl_4^-$ mole ratio used during clusters synthesis (in parenthesis the same ratio expressed in terms of equivalents of ligand); [b]determined by TEM measurements (mean ± std dev); [c]see Ref. [25]; [d]see ref. 13; [e,f]inferred by TGA or elemental analysis.

The composition of the calix[4]arene protected clusters was initially inferred by TGA measurements and elemental analysis. In all cases the determined organic fractions were larger than those reported for the corresponding alkylthiol stabilized clusters synthesized using the same mole ratios (see table 3.1). These results were somewhat expected because the calix[4]arene skeleton yields a contribution of organic matter that is higher than a dodecanthiol chain. However, the results obtained for the MPCs loaded with the bidentate ligand **9** were, after normalization, in all instances unexpectedly high. In particular the 70% of organic fraction experienced by the clusters **9**-MPCs(3) [S/Au = 3]

25. W. P. Wuelfing, A. C. Templeton, J. F. Hicks, R. W. Murray, *Anal. Chem.* **1999**, *71*, 4069.

suggested that very small particles, approximately composed by a gold core of about 20 atoms and of 8-10 calix[4]arene units were obtained.[26] For **9**-MPCs(7) [S/Au = 0.33] and **9**-MPCs(11) [S/Au = 0.16], the percentage of organic fraction was 38 and 31, respectively. These organic fractions approximately indicate in the former case the formation of Au MPCs having a core of 120-140 Au atoms (see Figure 3.6) and surrounded by about 20-30 calix[4]arene units of **9**, while in the latter case the formation of Au MPCs having a core with 2800-3000 Au atoms surrounded by about 200-250 calix[4]arene units of **9**.

Figure 3.6. Schematic representation of the gold core of clusters **9**-MPCs(7)**.**

The organic fractions determined for the clusters prepared using the "monodentate" **5** reflected, on the contrary, the formations of particles whose composition was similar, after normalization, to that found in the Murray's clusters prepared in the same experimental conditions. These findings could thus support the hypothesis that the particular "bidentate" structure of **9** sensibly affects the growth of the gold core reducing its final size. To verify this hypothesis the MPCs obtained using **5** and **9** were submitted to further investigations. Initially the samples were submitted to NMR analysis. However, according with previous findings

26 G. H. Woehrle, J. E. Hutchinson, J. E. *Inorg. Chem.* **2005**, *44*, 6149–6158.

reported in the literature, the ^{1}H NMR spectra are quite broad due to the different positions of the calix[4]arene derivatives around the Au core.[13]

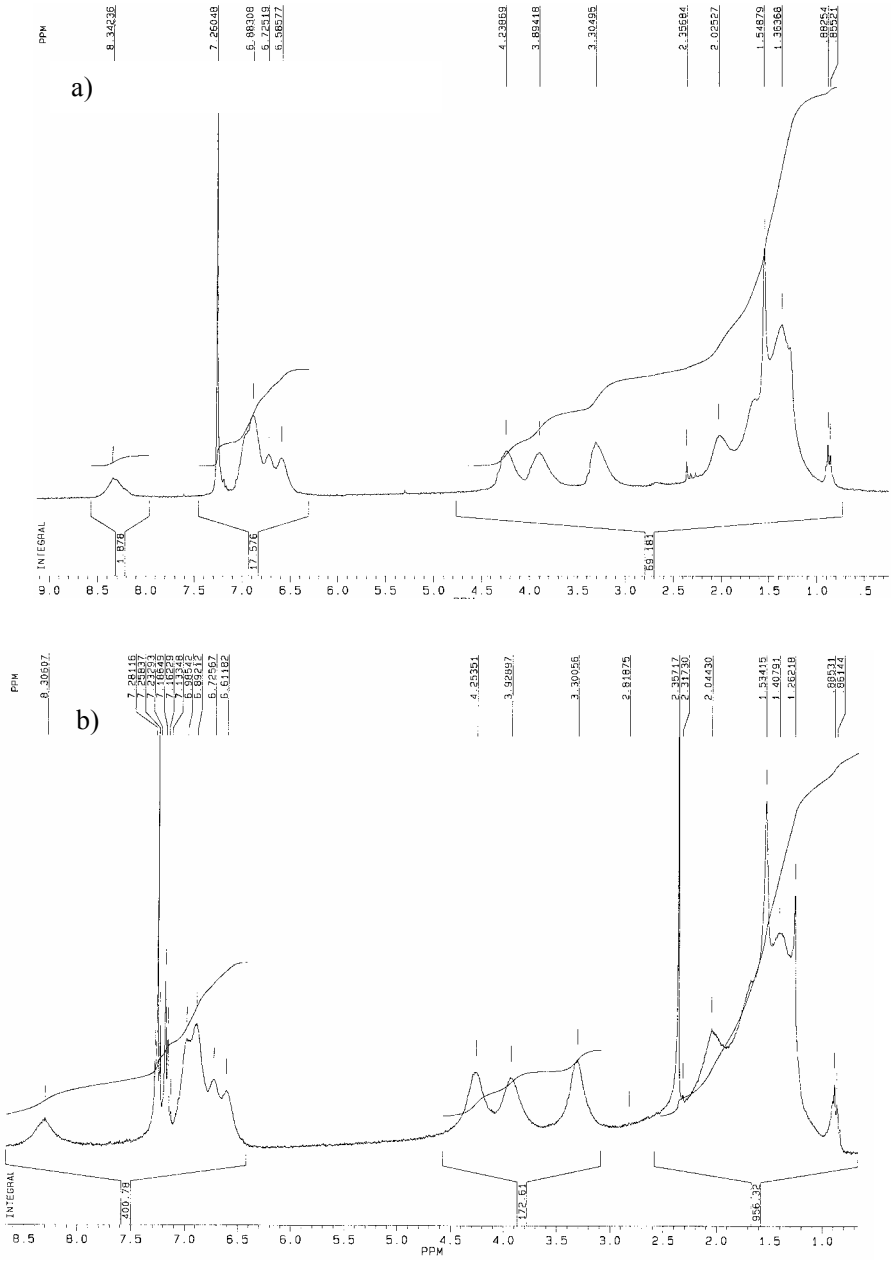


Figure 3.7. ^{1}H NMR in $CDCl_3$ (300 MHz) of clusters a) **9**-MPCs(7) and b) **9**-MPCs(11).

In figure 3.7 have been reported the ^{1}H NMR spectra, taken in $CDCl_3$, of clusters **9**-MPCs(7) and **9**-MPCs(11), obtained using S/Au = 0.33 and 0.16 molar ratios, respectively.[27] In both spectra it is possible to recognize several broad regions that can be ascribed to the calix[4]arene units. The signal corresponding to the methylene group in α position respect with the sulphur atoms is not visible at all. In **5** and **9** such signal is usual visible as a multiplet at δ ~ 2.6 ppm, but it is known from the literature that it tends to disappear for clusters having core diameter larger than 1.2 nm.[13]

The ^{1}H NMR spectrum of clusters **9**-MPCs(3) [S/Au = 3] (see figure 3.8), although less resolved, is very similar to that of the original ligand **9** (see figure 3.4). The most striking feature of the spectrum of these clusters is the change of multiplicity of the signal resonating at δ ≈ 2.6 ppm. In the ligand **9** such signal was a multiplet ascribed to the methylene protons in α to the sulphur atom (-CH_2SH) that were coupled with the SH proton. In the clusters, the signal becomes a broad triplet and it is slightly downfield shifted with respect its original position. Both observations support the close proximity of the CH_2 group with the metallic surface and the formation of the S-Au bond. The higher resolution of the NMR spectrum of clusters **9**-MPCs(3) with respect the spectra recorded for clusters **9**-MPCs(7) and **9**-MPCs(11) is also an indication that the large excess of ligand promotes the formation of very small clusters, as was indirectly derived from the determination of the organic fraction.

27. Spectra with a similar pattern of signals were also recorded for the corresponding clusters obtained starting from **5**.

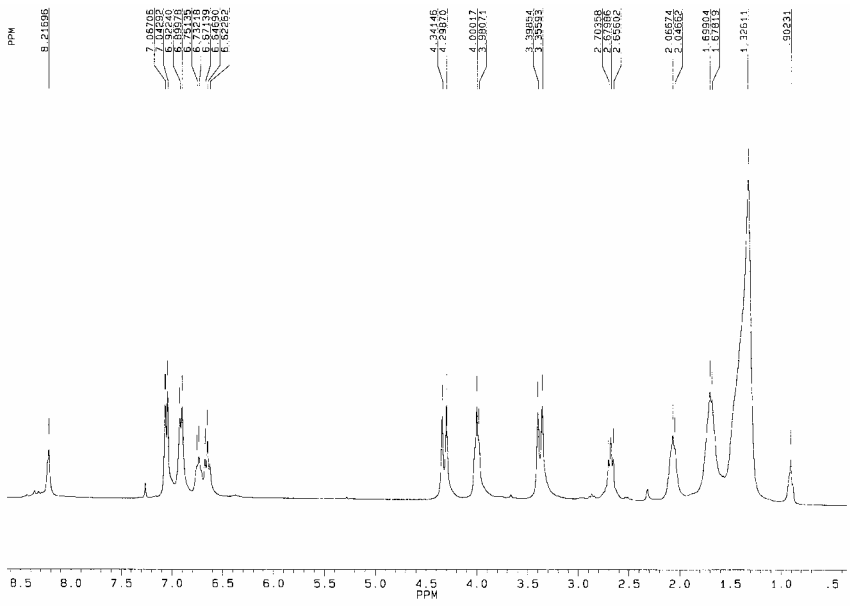


Figure 3.8. ^{1}H NMR in $CDCl_3$ (300 MHz) of clusters **9**-MPCs(3).

To confirm these findings, all the clusters synthesised using calix[4]arene **5** and **9** as passivating agents were submitted to TEM analysis to determine the core size distribution (see Figure 3.9 and 3.10). The analysis of the core size distribution revealed that, as expected, for both ligands the mean diameter D (nm) of the clusters becomes as smaller as the S/Au molar ratio employed during the synthesis is increased (see Table 3.1). However, the clusters obtained from the monodentate **5** were rather polydispersed (see Figure 3.9a) and their mean diameter D was comparable to that reported for the *n*-dodecanthiol clusters prepared with identical ligand/aurate ratios (see Table 3.1).[13,25] In contrast, the mean diameter of all MPCs loaded with **9** was significantly lower (see Table 3.1). Within the latter series, the clusters obtained with

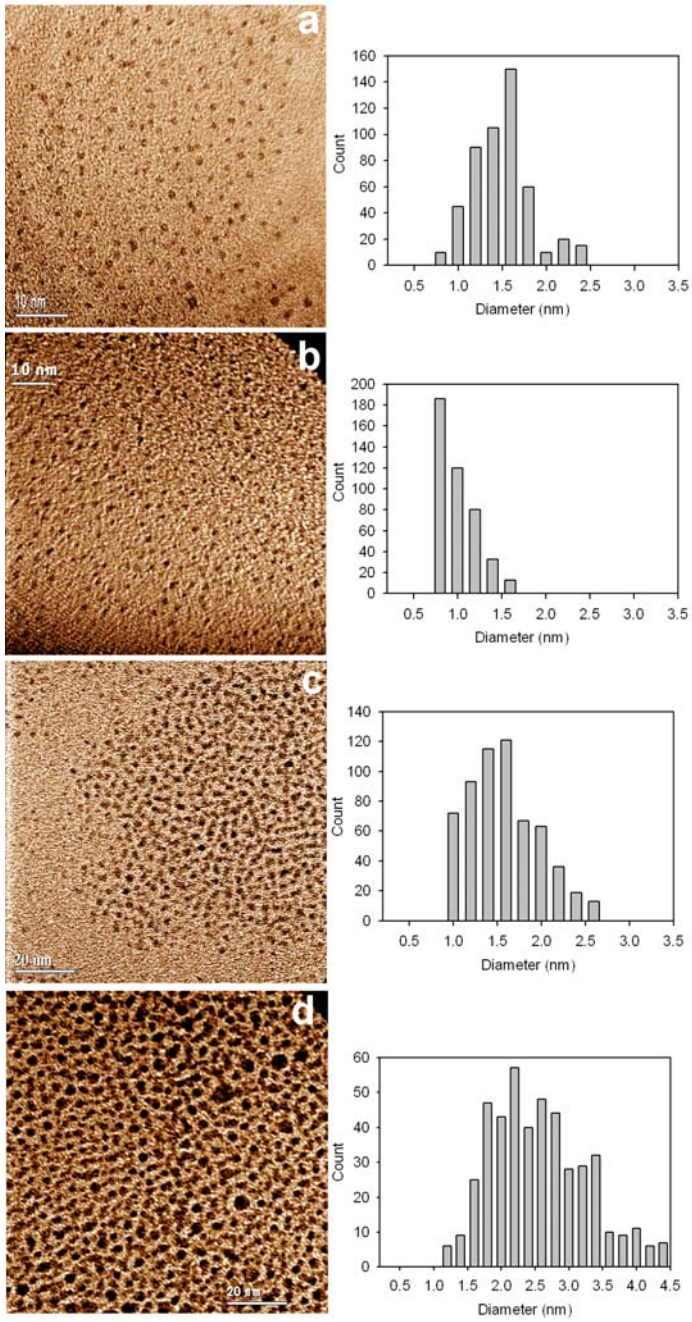


Figure 3.9. TEM image and core size distribution diagrams of the calix[n]arene-coated Au MPCs: a) **5**-MPCs(1), b) **9**-MPCs(3), c) **9**-MPCs(7) and d) **9**-MPCs(11). See Table 3.1 for ligand/aurate molar ratio employed during the synthesis.

an excess of **9** [**9**-MPCs(3); S/Au = 3] have mostly a subnanometric core size (see Figure 3.9b).

These findings support our hypothesis that the clusters core size distribution of the calix[n]arene-coated MPCs is significantly influenced by both the "denticity" of the ligand and by the convergent arrangement of its thiol chains. It is reasonable to assume that bidentate ligand **9** control the kinetic of the core growth during the reduction step favouring, because of an elevated effective molarity, the passivation of the surface of the growing gold core after the formation of the first Au-S bond (see Figure 3.11).[28]

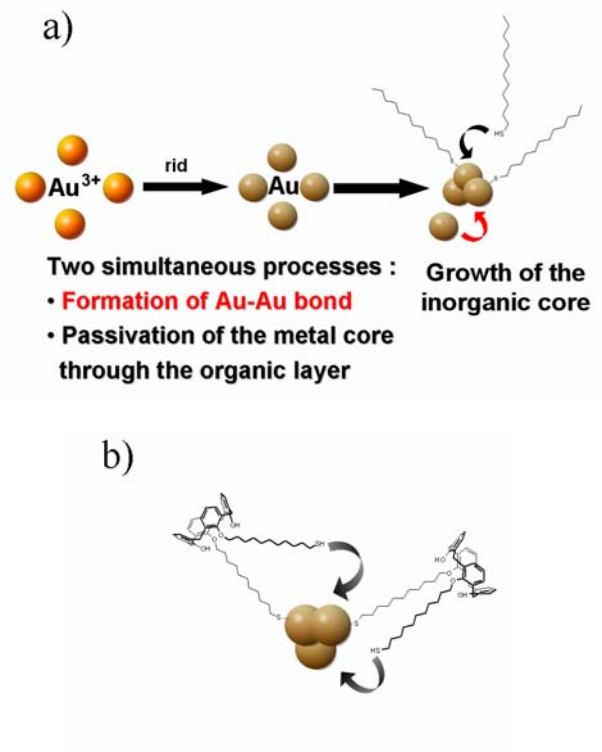
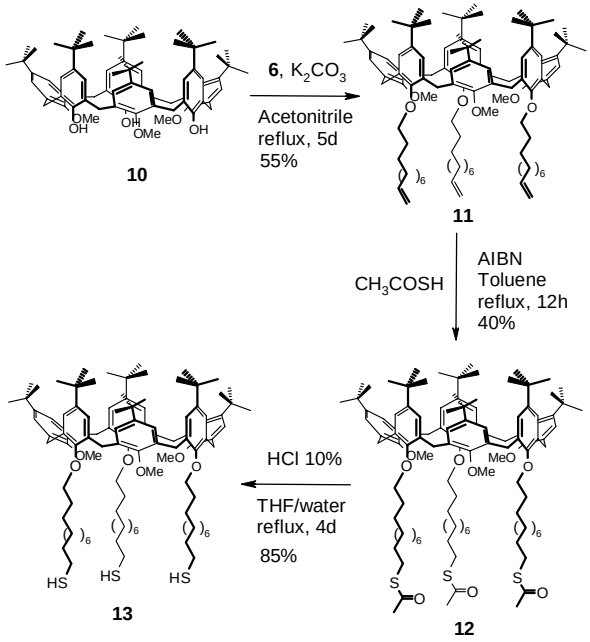


Figure 3.10. Proposed mechanism for the growth of the clusters inorganic core and its passivation with a) simple alkylthiol chains and b) with the bidendate calix[4]arene **9**.

28. E. E. Finney, R. G. Finke, *J. Colloid Interface Sci* **2008**, *317*, 351.

The isolated MPCs correspond to trapped growing clusters whose surface is fully passivated and the better stabilizing ability of the calix[4]arene unit with respect simple alkylthiol chains can be ascribed to a "denticity effect".[29]

A further piece of evidence of the ligand denticity as control element during the gold core growth was obtained employing the 1,3,5-tris(11-mercapto-undecanoxy)-calix[6]arene (**13**) as the gold passivating agent. This ligand is characterized by the presence of three undecanthiol chains on its lower rim, therefore it can be considered as a tridentate thiolated ligand. The ligand **13** has been synthesized using the same synthetic approach employed for the preparation of **9** (see scheme 3.2).



Scheme 3.2. Synthesis of the "tridentate" thiolated calix[6]arene **13**.

29. Similar results were also found in the synthesis of silver nanoparticles in a mono-phase system (DMF solution) using multithiolated β-CDs as stabilizing agents. The reduced size of the resulting nanoparticles was ascribed to a "macrocyclic effect". See: J. Liu, W. Ong, A. E. Kaifer, C. Peinador, C. *Langmuir* **2002**, *18*, 5981.

The experimental details and characterization have been summarized in the experimental part.

Three samples of Au MPCs were prepared starting from **13** using the same experimental conditions and molar ratios employed for the preparation of the Au MPCs coated with **5** and **9** (see Table 3.1). After TEM measurements, these clusters were characterized by a core size distributions similar to those obtained with the bidentate derivative **9** (see Table 3.1). As previously observed with **9**, the clusters synthesized with an excess of **13** with respect the aurate are characterized by subnanometric core size (see Figure 3.12a).

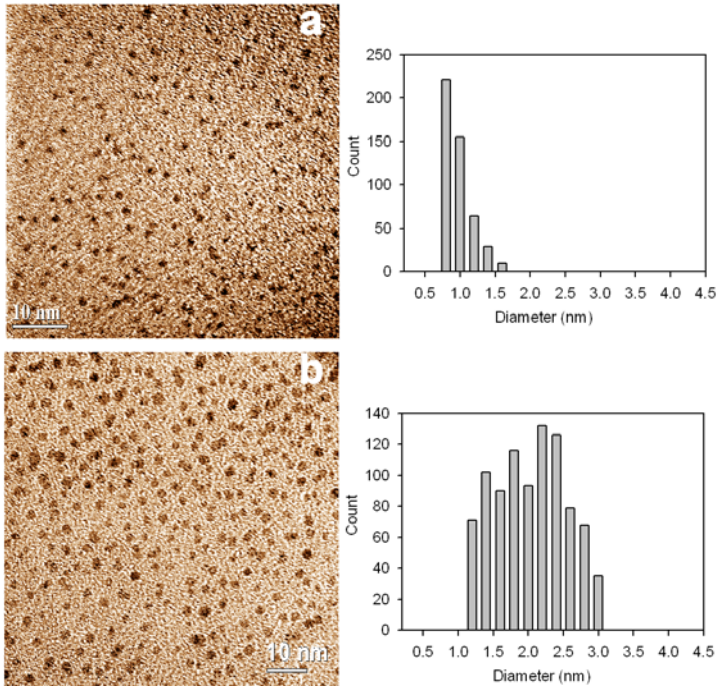


Figure 3.11. TEM image and core size distribution diagrams of the calix[n]arene-coated Au MPCs: a) **13**-MPCs(4) and b) **13**-MPCs(8).

Several attempts were also carried out to obtain stabile Au MPCs using the not thiolated di-alkylated calix[4]arene **14** (see Figure 3.13), but after work-up of the reaction only colloidal gold was separated together with the unreacted calix[4]arene. These results suggest that the host cavity do not play an active role in the stabilization of the gold surface, contrary to what found with i.e. resorcin[4]arene derivatives.[18]

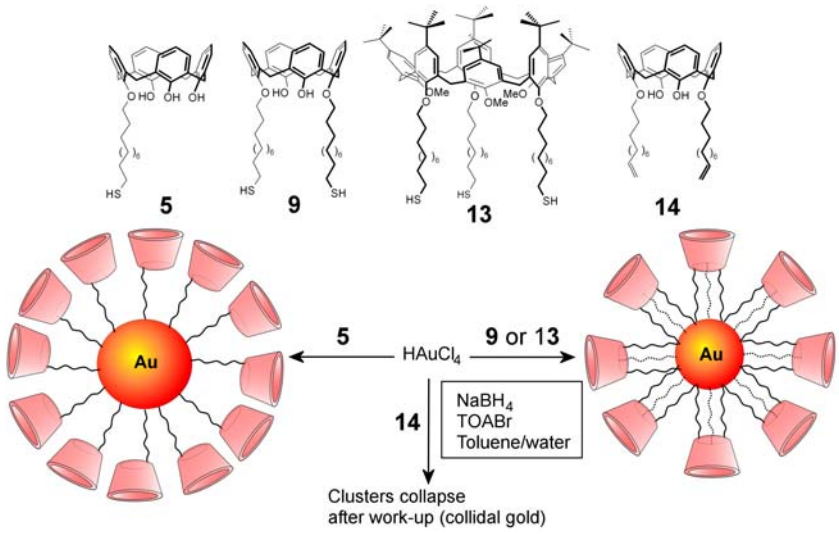


Figure 3. 12. Polyalkylthiols lower rim functionalized calix[n]arene derivatives for the preparation of Au MPCs.

3.2.3 Characterization of the sub-nanometric Au MPCs

Because clusters **9**-MPCs(3) had mostly sub-nanometric core size, the same sample was also submitted to XRD measurement. The corresponding diffraction spectrum has been depicted in Figure 3.13.

It is known from the literature that XRD spectra of large clusters are characterized by well defined and sharp diffraction peaks.[30] In general, the diffraction peaks become as broad as the clusters core size decreases due to the lack of diffraction planes.

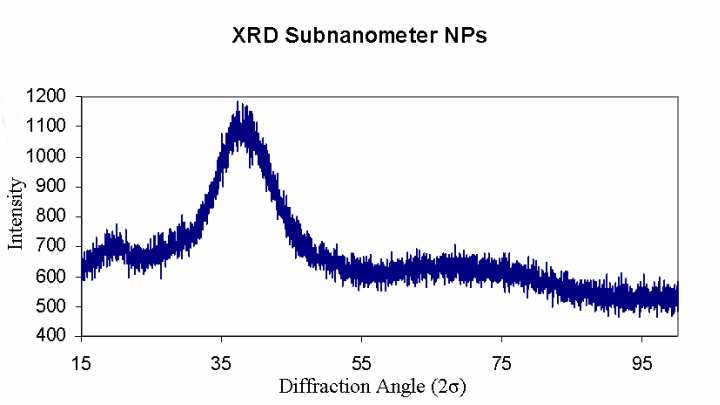


Figure 3.13. XRD spectrum of clusters **9**-MPCs(3).

Application of the Scherrer formula (see Chapter 2) to the data obtained from the XRD spectrum of clusters **9**-MPCs(3) yielded a mean diameter of 8.6 Å taking the reflections of KCl as a reference. This result is in complete agreement with the diameter calculated from the analysis of the corresponding TEM images.

In order to understand the oxidation state of the Au atoms that form the core of the clusters **9**-MPCs(3), some preliminary XPS analysis were carried out. This analysis revealed a peak for Au $4f_{7/2}$ and a peak for S $2p_{3/2}$ at 84.35 and 166.66 eV, respectively. The energy was calculated taking as reference the data corresponding to C 1s (285 eV). The

30. D. V. Leff, P. C. Ohara, J. R. Heath, W. M Gilbert, *J. Phys. Chem. B* **1995**, *99*, 7036.

calculated BE for both peaks are quite different from those reported for Au clusters having large diameters. For instance Brust has reported that XPS analysis for n-dodecanthiol-stabilized Au MPCs having a mean core diameter of ≈ 2.5 nm shows two peaks typical for Au^0 with BE of 83.8 eV (Au $4f_{7/2}$) and 87.5 eV (Au $4f_{5/2}$).[24a] Indeed, the binding energy calculated for the Au $4f_{7/2}$ (84.35 eV) peak in **9**-MPCs(3) is sensibly lower and more similar to the binding energy found in Au^I–thiol complexes (84.9 eV).[31] However, this result is not surprising if it is considered that the core of **9**-MPCs(3) clusters is composed by very few atoms (reasonably ranging from 12 to 20 as determined from elemental analysis).[32] Most of these atom will be on the cluster surface in a oxidized state because in close contact with sulphur atoms of the ligand. On the other hand the energy calculated for the sulfur S $2p_{3/2}$ is similar to that calculated for disulfide species[33]. This unexpected value could be due to the fact that for a small clusters the proximity of the S atoms surrounding the core can give rise to reciprocal interaction like those find in disulfides. More detailed studies are therefore necessary to better rationalize these findings.

31. A. McNeille, D. H. Brown, W. E. Smith, M. Gibson, L. Watson, *J. Chem. Soc., Dalton Trans* **1980**, 767.
32. Phosphine-stabilized clusters of subnanometric core size contains 11-13 gold atoms, see Ref. 15
33. D. G. Castner, *Langmuir* **1996**, *12*, 5083.

3.3 Ligand "sulphur denticity" as size control element in the synthesis of MPCs of other metals (Pd, Ag)

The promising results obtained in the synthesis of Au MPCs with multidentate calix[n]arene ligands prompted us to verify whether the "sulphur denticity" can be considered a valid control element for the core size of other metal MPCs. We decided to synthesize MPCs of Pd[34] and Ag[35] because the experimental condition adopted for their preparation is very similar to the Brust method (see experimental).

The interest in the synthesis of Pd MPCs arises from the important role played by this metal in catalysis. Indeed, it has been shown that the catalytic activity of this metal is very sensitive to the size and shape of the particles as well as the surrounding media.[36] The growth kinetic of Pd MPCs is very different from their Au counterparts. It was found[37] that Au MPCs: (i) forms rather rapidly, within seconds after the addition of the reducing agent; (ii) their core size increase slightly within the first few minutes after the reduction; and (iii) afterward, they experience modest fluctuation in size distribution in span up to 5 days. In contrast, Pd MPCs seem to be less stable because the black solution of the preformed Pd

34. S. Chen, K. Huang , J. A. Stearns, *Chem. Mater.* **2000**, *12*, 540.
35. B. A. Korgel, D. Fitzmaurice, *Adv. Mater.* **1998**, *10*, 661.
36. a) N. Dhas, A. Gedanken, *J. Mater. Chem.* **1998**, *8*, 445; b) T. Teranishi, M. Miyake, *Chem. Mater.* **1998**, *10*, 594; c) S. Giorgio, C. Chapon, C. R. Henry, *Langmuir* **1997**, *13*, 2279; d) G. Schmid, M. Harms, J.-O. Malm, J.-O. Bovin, J. van Ruitenbeck, H. W. Zandbergen, *J. Am. Chem. Soc.*, **1993**, *115*, 2046; e) M. T. Reetz, S. A. Quaiser, *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 2240; f) M. T. Reetz, W. Helbig, *J. Am. Chem. Soc.*, **1994**, *116*, 7401.
37. S. Chen, A. C. Templeton, R. W. Murray, *Langmuir* **2000**, *16*, 3543.

MPCs slowly change back to orange/red colour (the colour of free ions in solution) if the solution was allowed to stir under ambient conditions for a short period of time (e.g. 90 min).[38] Such discrepancy in stability might, at least in part, be attributed to the variation of the metal-metal and metal-sulfur bonding strengths. In particular, the poor stability of Pd MPCs might be a direct consequence of the much weaker Pd-Pd and Pd-S bonding interactions.[39] In short, it appears that the core growth kinetic of Pd MPCs stabilized with n-dodecanthiol can be summarized in three stages : i) a few seconds after the addition of the reducing agent, a rapid nucleation with formation of large particles is observed for the first 15 min.; ii) in the following 60 min. the large particles break-up to yield smaller and more stable particles; iii) for longer reaction time (90 min.), particle decomposition could occur.[34]

Table 3.2. Main properties of the Pd MPCs stabilized with calix[4]arene **9**.

Stabilizer	S/Pd ratio	*D* core (nm)
n-dodecanthiol	0.33	3.1 ± 0.7
Calix[4]arene (**9**)	0.33	2.5 ± 0.4

In our preliminary studies we used the procedure reported by Chen[34] for the synthesis of our Pd MPCs using the bidentate calix[4]arene **9** as stabilizer. Pd MPCs are synthesised in a biphasic system (similar to the synthesis of Au MPCs) reducting Pd^{2+} ions ($PdCl_2$) in the presence of thiolated compound using $NaBH_4$. The synthesis was accomplished

38. S. Chen, K. Huang, J. A. Stearns *Chem. Mater.* **2000**, *12*, 540.
39. See *e. g.*: *CRC Handbook of Chemistry and Physics*, 76th ed., CRC Press; Baton Raton, **1995**.

several times using a S/Pd ratio of 0.33. In all cases, no clusters decomposition was observed for a long time after synthesis. TEM analysis revealed that the resulting Pd MPCs are slightly smaller, although more monodispersed, of the corresponding clusters stabilized by dodecanthiol (see Table 3.2 and Figure 3.14).

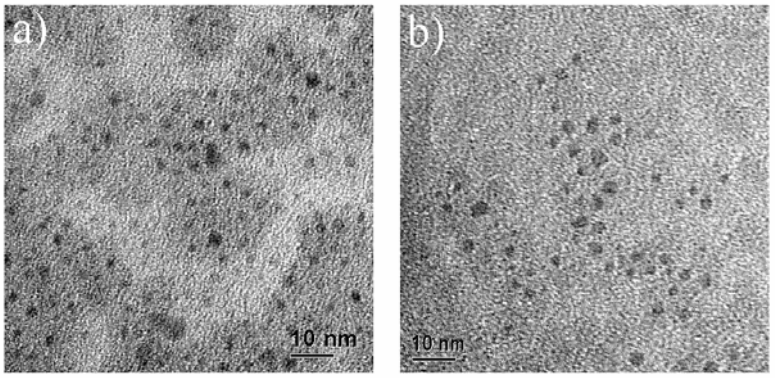


Figure 3.14. TEM images of Pd MPCs stabilized with a) calix[4]arene **9** and b) n-dodecanthiol.

These findings support the hypothesis that the multidentate nature of **9** can substantially contribute to the stabilization of the Pd clusters. However, the denticity of the calix[4]arene derivative does not exert an effective control on the core size of the cluster due to the fast kinetic of nucleation peculiar of these clusters.

Ag MPCs were synthesised using the procedure reported by Fitzmaurice.[35] Ag MPCs are synthesised in a biphasic system (similar to the synthesis of Au MPCs) reducting Ag^+ ions ($AgNO_3$) in the presence of thiolated compound using $NaBH_4$. For comparison, the clusters have been prepared using both n-dodecanthiol and the bidentate calix[4]arene **9** as stabilizing agents. In both cases TEM analysis showed a perfect disposition of the clusters on the Cu grid that revealed an high degree of

monodispersity (see Figure 3.15). Analysis of the core size distribution, however, shows that the Ag MPCs synthesized with **9** are characterized by a mean diameter sensibly lower than those stabilized with n-dodecanthiol (see Table 3.3).

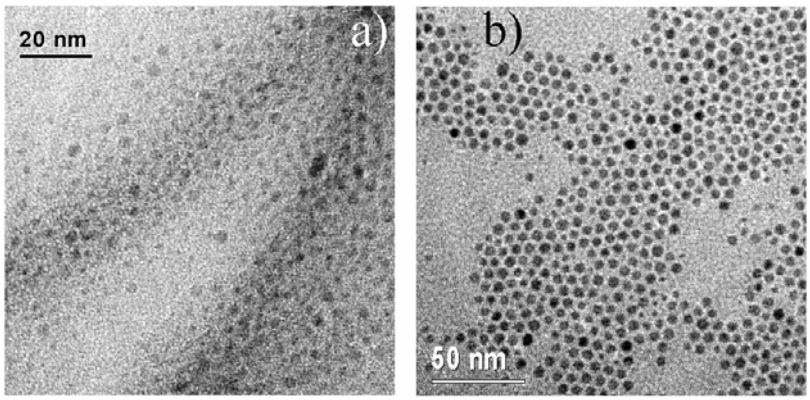


Figure 3.15. TEM images of Ag MPCs stabilized with a) calix[4]arene **9** and b) n-dodecanthiol.

Table 3.3. Main properties of the Ag MPCs stabilized with calix[4]arene **9**.

Stabilizer	S/Ag ratio	*D* core (nm)
n-dodecanthiol	1	5.1 ± 0.6
Calix[4]arene (**9**)	1	2.8 ± 0.5

TEM images also revealed that Ag MPCs stabilized with calix[4]arene **9** self-assembled in circles on the Cu grid (see Figure 3.16). Such behaviour is actually under investigation.

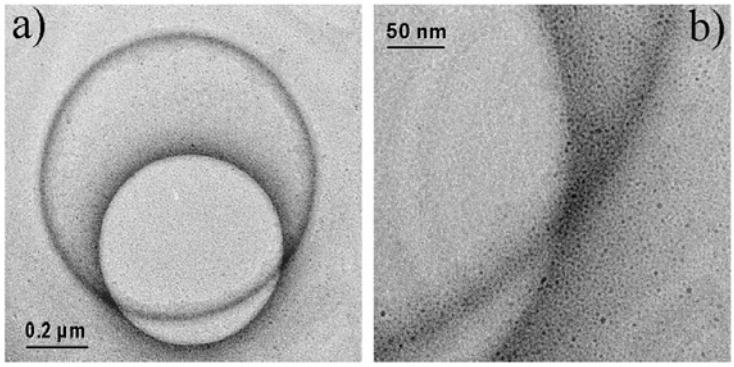


Figure 3.16. (a) and (b) TEM images of Ag MPCs stabilized with **9**.

UV-Vis spectra of both NPs have been registred and the different in the SPB is due to the different of the Ag core dimension. (see Figure 3.17)

Both spectra show a sharp SPB of the Ag MPCs but is looks strange that the SPB of dodecanthiol Ag MPCs appears more sharp than the SPB of calix[4]arene AgMPCs. That can be caused by the strange self-assembly of calix[4]arene AgMPCs seen in TEM images. Such behaviour is obviously under investigation.

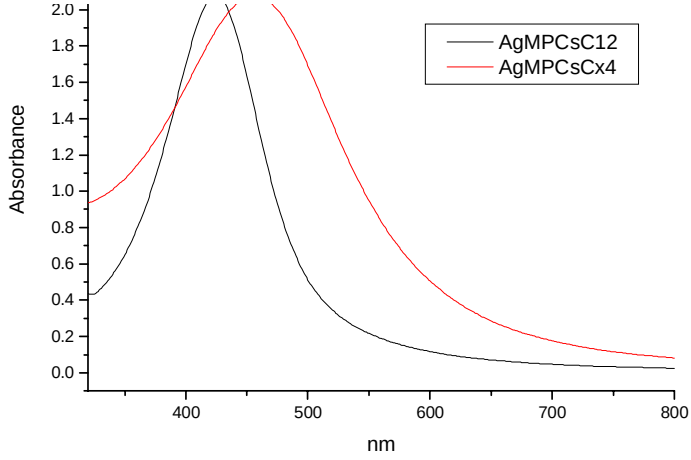


Figure 3.17. UV-Vis spectra of calix[4]arene **9**-Ag MPCs (red line) and dodecanthiol AgNPs (black line)

Experimental Section

General Remarks:

All reactions were carried out under nitrogen, and all solvents were freshly distilled under nitrogen prior to use. All other reagents were reagent grade quality obtained from commercial supplies and used without further purification. Thin-layer chromatography was performed on aluminium sheets coated with silica gel 60F (Merck 5554). Column chromatography was carried out by using silica gel (ICN 4663, 63-200 mesh). ^{1}H NMR spectra were recorded at 300 MHz. ^{13}C NMR spectra were recorded at 75 MHz. Mass spectra were recorded in the ESI mode. Undec-10-enyl 4-methylbenzenesulfonate (**6**),[40] calix[4]arene (**3**),[41] and calix[6]arene (**10**)[42] were prepared according to published procedure. Melting points are uncorrected.

TEM images have been recorded at a Trasmission Electron Microscope JEOL JEM 2010 at C.I.G.S. (Università di Modena e Reggio Emilia).

XPS experiments are performed by Prof. Robertino Zanoni (Univerisità "La Sapienza" Roma).

Synthesis of *S*-11-bromoundecyl ethanethioate (2)

To a solution of 11-bromoundec-1-ene (5 g, 2.2 mmol) and thioacetic acid (2.77 g, 36.5 mmol) in dry toluene (250 ml), a tip of spatula of AIBN was added. After refluxing for 5h, the reaction was quenched by

40. R. Métivier; I. Leray; B. Lebea B. Valeur, *J. Mater. Chem.* **2005**, *15*, 2965.
41. C. D. Gutsche, L.-G. Lin, *Tetrahedron*, **1986**, *42*, 1633.
42. R. G. Janssen, W. Verboom, D. N. Reinhoudt, A. Casnati, M. Freriks, A. Pochini, F. Ugozzoli, R. Ungaro, P. Nieto, M. Carramolino, F. Cuevas, P. Prados, J. de Mendoza, *Synthesis* **1993**, 380.

addition of water (250 ml). The separated organic phase was dried over Na_2SO_4. After the removal of the solvent under reduced pressure, the solid residue was purified by column chromatography (eluent: hexane/ethyl acetate = 9/1) to afford the pure **2** as a yellowish oil (95%). ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) 3.37 (t, 2H, *J* = 6.6 Hz), 2.83 (t, 2H, *J* = 7.5 Hz), 2.29 (s, 3H), 1.9-1.7 (m, 2H), 1.6-1.4 (m, 2H), 1.4-1.2 (m, 14H). ^{13}C NMR (75 MHz, $CDCl_3$): δ (ppm) 196.0, 164.4, 34.0, 32.7, 30.6, 29.4, 29.3, 29.1, 29.0, 28.7, 28.6, 28.1. MS-ESI (m/z): 311 (M+2, 100), 309 (M^+, 100). Anal. Calcd for $C_{13}H_{25}BrOS$: C, 50.48; H, 8.15; S, 10.37; Found: C, 51.28, H, 8.14, S, 10.07.

Synthesis of 25-[11-(acetylthio)-undecanoxy]calix[4]arene (4)

A solution of calix[4]arene **3** (0.42 g, 1 mmol), K_2CO_3 (0.11 g, 0.8 mmol), and *S*-11-bromoundecyl ethanethioate **2** (0.25 g, 0.8 mmol) in dry acetone (70 ml) was poured in a small glass autoclave filled with nitrogen. After sealing the autoclave, the reaction mixture was refluxed at 80 °C for 48h. After this period, the mixture was cooled at room temperature and the solvent evaporated to dryness under reduced pressure. The solid residue was taken up with a 10% solution of HCl (100 ml) and CH_2Cl_2 (100 ml). The separated organic phase was washed with water up to neutrality, dried over Na_2SO_4, and evaporated to dryness under reduced pressure. The crude product was purified by column chromatography (eluent: hexane/CH_2Cl_2 = 7/3) to afford the pure **4** as a white solid (80%). ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) 9.75 (s, 1H), 9.44 (s, 2H), 7.1-7.0 (m, 8H), 6.87 (t, 1H, *J* = 7.5 Hz), 6.7-6.6 (m, 3H), 4.37 (d, 2H, *J* = 13 Hz), 4.28 (d, 2H, *J* = 14 Hz), 4.16 (t, 2H, *J* = 7.2 Hz),

3.47 (d, 2H, *J* = 14 Hz), 3.46 (d, 2H, *J* = 13 Hz), 2.86 (t, 2H, *J* = 7.2 Hz), 2.32 (s, 3H), 2.2-2.1 (m, 2H), 1.8-1.6, 1.6-1.5 and 1.5-1.3 (3m, 16H). ^{13}C NMR (75 MHz, $CDCl_3$): δ (ppm) 196.0, 151.4, 150.8, 149.2, 134.2, 129.2, 128.8, 128.7 (2 resonances), 128.3, 126.0, 121.9, 120.8, 77.2, 31.8, 31.4, 30.6, 29.8, 29.4 (2 resonances), 29.1, 28.8, 25.8. m.p. 53.0-54.0 °C. MS-ESI (m/z): 653 (M+1, 100), 675 (M+Na, 50). Anal. Calcd for $C_{41}H_{48}O_5S$: C, 75.43; H, 7.41; S, 4.91; Found: C, 75.03, H, 7.41, S, 4.85.

Synthesis of 25-[11-(mercapto)-undecanoxy]-calix[4]arene (5)

A solution of calix[4]arene **4** (0.6 g, 0.9 mmol) in a mixture of THF (20 ml) and HCl (10% v/v in H_2O, 20 ml) was refluxed for 2 days. After cooling to room temperature, the mixture was extracted with CH_2Cl_2 (30 ml). The resulting organic phase was separated, washed with water up to neutrality, dried over Na_2SO_4 and evaporated to dryness under reduced pressure. The oily residue was purified by column chromatography (eluent: hexane/CH_2Cl_2 = 7/3) to afford the pure **5** as a white solid (90%). ^1H NMR (300 MHz, $CDCl_3$): δ (ppm) 9.75 (s, 1H), 9.43 (s, 2H), 7.1-7.0 (m, 8H), 6.87 (t, 1H, *J* = 7.5 Hz), 6.7-6.6 (m, 3H), 4.37 (d, 2H, *J* = 13 Hz), 4.28 (d, 2H, *J* = 14Hz), 4.15 (t, 2H, *J* = 7.2 Hz), 3.47 (d, 2H, *J* = 14 Hz), 3.46 (d, 2H, *J* = 13 Hz), 2.6-2.5 (m, 2H), 2.2-2.1 (m, 2H), 1.8-1.6, 1.6-1.5 and 1.5-1.3 (3m, 16H). ^{13}C NMR (75 MHz, $CDCl_3$): δ (ppm) 151.4, 150.8, 149.2, 134.2, 129.3, 128.8, 128.7 (2 resonances), 128.4, 126.0, 121.9, 120.9, 77.4, 34.0, 31.9, 31.4, 29.9, 29.5 (2 resonances), 29.4, 29.1, 28.4, 25.9, 24.6. m.p. 87.0-88.0 °C. MS-ESI (m/z): 611 (M+1,

10), 634 (M+Na, 85), 650 (M+K, 60).). Anal. Calcd for $C_{39}H_{46}O_4S$: C, 76.68; H, 7.59; S, 5.25; Found: C, 75.62, H, 7.46, S, 4.81.

Synthesis of 25,27-bis(undec-10-en-1-oxy)-calix[4]arene (7)

A mixture of calix[4]arene **3** (3 g, 7 mmol), K_2CO_3 (2.9 g, 21 mmol), undec-10-enyl 4-methylbenzenesulfonate **6** (7 g, 21 mmol) and KI (catalytic) in CH_3CN (150 ml) was stirred and heated under reflux. After five days, the solvent was evaporated under vacuum and the solid residue taken up with CH_2Cl_2. The organic phase was washed with H_2O up to neutrality and dried over Na_2SO_4. After evaporation of the solvent under reduced pressure, the resulting crude product was purified by column chromatography (silica gel, hexane:ethyl acetate = 9:1) to give **7** as yellowish solid (70%). ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) 8.17 (s, 2H), 7.04 (d, 4H, *J* = 7 Hz), 6.91 (d, 4H, *J* = 7 Hz), 6.73 (t, 2H, *J* = 7 Hz), 6.64 (t, 2H, *J* = 7 Hz), 5.9-5.8 (m, 2H), 5.0-4.9 (m, 4H), 4.32 (d, 4H, *J* = 14 Hz), 3.99 (t, 4H, *J* = 6 Hz), 3.37 (d, 4H, *J* = 14 Hz), 2.1-2.0 (m, 8H), 1.7-1.6 (m, 4H), 1.5-1.3 (m, 20H); ^{13}C NMR ($CDCl_3$, 75 MHz): δ (ppm) 155.2, 150.8, 138.0, 132.3, 127.6, 127.2, 127.0, 124.0, 117.7, 112.9, 76.4, 32.6, 30.2, 28.8, 28.4, 28.3, 27.9, 24.8. m.p. 120-122 °C. MS-ESI (m/z): 729 (MH^+). Elemental analysis: Anal. Calcd for $C_{50}H_{64}O_4$: C, 82.37, H, 8.85; Found: C, 82.45, H, 8.52.

Synthesis of 25,27-bis[11-(acetylthio)-undecanoxy]-calix[4]arene (8):

To a solution of calix[4]arene (**7**) (3 g, 4.2 mmol) and thioacetic acid (1.3 g, 17 mmol) in toluene (100 ml), a catalytic amount of AIBN was added. The resulting homogeneous mixture was refluxed for 3 h, then the

solvent was evaporated to dryness under reduced pressure. The solid residue was taken up with CH_2Cl_2 and the organic phase was washed twice with H_2O and with a saturated solution of $NaHCO_3$. After the removal of the solvent under reduced pressure, the solid residue was purified by column chromatography (silica gel, hexane:ethyl acetate = 8:2) to afford **8** as a yellowish sticky solid (70%). ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) 8.22(s, 2H), 7.07 (d, 4H, *J* = 7 Hz), 6.91 (d, 4H, *J* = 7 Hz), 6.73 (t, 2H, *J* = 7 Hz), 6.66 (t, 2H, *J* = 7 Hz), 4.33 (d, 4H, *J* = 14 Hz), 4.02 (t, 4H, *J* = 6 Hz), 3.39 (d, 4H, *J* = 14 Hz), 2.88 (4H, *J* = 6 Hz), 2.32 (s, 6H), 2.1-2.0 (m, 4H), 1.8-1.7 (4H, m), 1.6-1.4 (2m, 28H); ^{13}C NMR (75 MHz, $CDCl_3$): δ (ppm) 153.3, 1520.0, 133.3, 128.8, 128.3, 128.1, 125.1, 118.9, 76.5, 31.4, 30.5, 29.9, 29.5, 29.4. MS-ESI (m/z): 904 ($M+Na^+$). Elemental analysis: Anal. Calcd for $C_{54}H_{62}O_6S_2$: C, 73.51, H, 8.22, S, 7.27; Found: C, 73.55, H, 8.14, S, 6.98.

Synthesis of 25,27-bis[11-(mercapto)-undecanoxy]-calix[4]arene (9).

A solution of calix[4]arene **8** (1.5 g, 1.7 mmol) in a mixture of THF (50 ml) and HCl (10% v/v in H_2O, 50 ml) was refluxed for 2 days. After cooling to room temperature, the mixture was extracted with CH_2Cl_2 (30 ml). The resulting organic phase was separated, washed with water up to neutrality, dried over Na_2SO_4 and evaporated to dryness under reduced pressure. The oily residue was purified by column chromatography (eluent: hexane/CH_2Cl_2 = 7/3) to afford the pure **9** as a white solid (80%). ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) 8.29 (s, 2H), 7.13 (d, 4H, *J* = 7 Hz), 6.96 (d, 4H, *J* = 7 Hz), 6.8-6.7 (m, 4H), 4.40 (d, 4H, *J* =14 Hz), 4.07(t, 4H, *J* = 6 Hz), 3.45 (d, 4H, *J* =14 Hz), 2.7-2.5 (m, 4H), 2.2-2.1

(m,4H), 1.9-1.8 (m, 4H), 1.8-1.7 (m, 4H), 1.6-1.3 (m, 24H); ^{13}C NMR (75 MHz, $CDCl_3$): δ (ppm) 153.3, 133.4, 128.8, 128.3, 128.1, 125.2, 118.9, 75.6, 31.4, 31.3, 30.1, 29.9, 29.7, 29.5, 29.1, 29.0, 28.5, 26.1, 25.9. m.p. 300-302°C. MS-ESI (m/z): 818($M+Na^+$). Elemental analysis: Anal. Calcd for $C_{50}H_{68}O_4S_2$: C, 75.33, H, 8.60, S, 8.05; Found: C, 75.40, H, 8.32, S, 8.26.

Synthesis of 37,39,41-trimethoxy-38,40,42-tris(undec-10-en-1-oxy)-calix[6]arene (11)

To a stirred solution of calix[6]arene **10** (1 g, 0.98 mmol) and K_2CO_3 (0.4, 3 mmol) in acetonitrile (200 ml), undec-10-enyl 4-methylbenzenesulfonate **6** (0.96 g, 3 mmol) was added. The resulting heterogeneous mixture was refluxed for 5 days. After this period, the solvent was evaporated to dryness under reduced pressure. The solid residue was taken up with a 10% solution of HCl in water (100 ml) and ethyl acetate (200 ml). The organic phase was separated, washed with brine up to neutrality, dried over Na_2SO_4. After the removal of the solvent under reduced pressure, the solid residue was purified by column chromatography (eluent : CH_2Cl_2/n-hexane = 8/2) to afford **11** as a white solid (55%). ^1H NMR (300 MHz, $CDCl_3$): δ (ppm) 7.33 (s, 6H), 6.70 (s, 6H), 6.0-5.8 (m, 3H), 5.1-4.8 (m, 6H), 4.63 (d, 6H, *J* = 14.1 Hz), 3.93 (t, 6H, *J* = 6.4 Hz), 3.44 (d, 6H, *J* = 14.1 Hz), 2.26 (s, 9H), 2.1-2.0 (m, 6H), 2.0-1.8 (m, 6H), 1.6-1.5 (m, 6H), 1.44 (s, 27H), 1.4-1.3 (m, 30H), 0.84 (s, 27H). ^{13}C NMR (75 MHz, $CDCl_3$): δ (ppm) 154.5, 152.1, 145.5, 145.2, 139.2, 133.6, 133.3, 127.9, 123.4, 114.1, 73.0, 60.2, 34.2, 33.9, 33.8,

31.6, 31.3, 31.2, 30.4, 29.7, 29.6, 29.5, 29.1, 28.9, 26.2. m.p. 133-135 °C. MS-ESI (m/z): 1495 (100, $M+Na^+$).

Synthesis of 37,39,41-trimethoxy-38,40,42-tris[11-(acetylthio)-undecanoxy]-calix[6]arene (12)

To a solution of calix[6]arene **11** (1 g, 0.68 mmol) and thioacetic acid (0.16 g, 2 mmol) in dry toluene (100 ml), a tip of spatula of AIBN was added. After refluxing for 12h, the reaction was quenched by addition of water (300 ml). The separated organic phase was dried over Na_2SO_4. After the removal of the solvent under reduced pressure, the solid residue was purified by column chromatography (eluent: hexane/THF = 9/1) to afford the pure **12** as a yellowish solid (40%). ^1H NMR (300 MHz, $CDCl_3$): δ (ppm) 7.29 (s, 6H), 6.66 (s, 6H), 4.59 (d, 6H, *J* = 15.0 Hz), 3.88 (t, 6H, *J* = 6.5 Hz), 3.40 (d, 6H, *J* = 15.2 Hz), 2.87 (t, 6H, *J* = 7.3 Hz), 2.32 (s, 9H), 2.22 (s, 9H), 2.0-1.8 (m, 6H), 1.6-1.4 (m, 6H), 1.42 (s, 27H), 1.4-1.1 (m, 42H), 0.80 (s, 27H). ^{13}C NMR (75 MHz, $CDCl_3$): δ (ppm) 196.0, 164.4, 152.0, 145.6, 145.2, 133.8, 133.6, 133.2, 127.9, 126.8, 125.7, 124.7, 123.6, 123.3, 73.0, 60.1, 59.5, 34.2, 34.0, 33.9, 31.6, 31.4, 31.1, 30.6, 30.4, 29.6, 29.5, 29.4, 29.1, 28.8, 26.3, 26.2, 19.1. m.p. 125-127 °C. MS-ESI (m/z): 1723 ($M+Na^+$)

Synthesis of 37,39,41-trimethoxy-38,40,42-tris-[11-(mercapto)-undecanoxy]-calix[6]arene (13)

A solution of calix[6]arene **12** (0.6 g, 0.34 mmol) in a mixture of THF (20 ml) and HCl (10% v/v in H_2O, 20 ml) was refluxed for 4 days. After cooling to room temperature, ethyl acetate (30 ml) was added to the mixture. The resulting organic phase was separated, washed with water

until neutrality, dried over Na_2SO_4 and evaporated to dryness under reduced pressure. The solid residue was triturated with hot methanol to afford **13** as white solid (85%). ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) 7.29 (s, 6H), 6.64 (s, 6H), 4.59 (d, 6H, *J* = 15.0 Hz), 3.89 (t, 6H, *J* = 6.4 Hz), 3.40 (d, 6H, *J* = 15.0 Hz), 2.51 (q, 6H, *J* = 7.2 Hz), 2.20 (s, 9H), 2.0-1.8 (m, 6H), 1.7-1.2 (m, 81H), 0.79 (s, 27H); ^{13}C NMR (75 MHz, $CDCl_3$) δ (ppm) 154.4, 152.0, 145.6, 145.2, 133.8, 133.6, 133.5, 133.2, 127.9, 123.3, 73.0, 60.1, 34.2, 34.0, 33.9, 31.6, 31.4, 31.3, 31.2, 31.1, 30.6, 30.4, 29.6, 29.53, 29.50, 29.4, 29.0, 28.3, 26.2, 24.6. m.p. 69.5-70.5 °C. MS-ESI (m/z): 1595 ($M+Na^+$)

Calix[n]arene-coated Au MPCs were synthesized according to the procedure published by Murray[13] for n-dodecanthiol-coated Au MPCs here reported:

General procedure for the synthesis of 5-MPCs(1), (2), 9-MPCs(3) and 13-MPCs(4).

To a vigorous stirred solution of 2.5 g of tetraoctylammonium bromide in 100 ml of toluene was added 0.1 g of $HAuCl_4{\cdot}xH_2O$ in 50 ml of deionized water. The yellow $HAuCl_4{\cdot}xH_2O$ aqueous solution quickly became colourless and the toluene phase became orange as the $AuCl_4^-$ was transferred into it. The organic phase was isolated and the precise amount of calix[n]arene was added, and the resulting solution was stirred for 10 min at room temperature. After the solution has become colourless the reaction solution was put into an ice bath,vigorous stirred and than 0.17 g of $NaBH_4$ in 50 ml of deionized water was quickly added (10 sec).

The now very dark organic phase was further stirred at 0°C for 1 h and at room temperature for at least another 3 h. Than 200 ml of a solution of 10% HCl in water was added. The organic phase was collected, dryed on $NaSO_4$ and than the solvent removed on a rotary evaporator. The black product was suspended in 100 ml of ethanol and than precipitated at -18°C. The etherogeneous solution was ultracentrifugated (15000 rpm for 20 minutes) and the solid was collected. This process is repeated until the utilised calix[n]arene is present (TLC = exane/ethylacetate 9/1). In order to remove the tetraoctylammonium bromide the solid was washed few times with methanol. The product was obtained with a yield of ~ 30%.

General procedure for the synthesis of 5-MPCs(5), (6), 9-MPCs(7) and 13-MPCs(8).

To a vigorous stirred solution of 0.8 g of tetraoctylammonium bromide in 70 ml of toluene was added 0.2 g of $HAuCl_4 \cdot xH_2O$ in 50 ml of deionized water. The yellow $HAuCl_4 \cdot xH_2O$ aqueous solution quickly became colourless and the toluene phase became orange as the $AuCl_4^-$ was transferred into it. The organic phase was isolated and the precise amount of calix[n]arene was added, and the resulting solution was stirred for 10 min at room temperature. Than 0.2 g of $NaBH_4$ in 50 ml of deionized water was quickly added (10 sec). The now very dark organic phase was further stirred at room temperature for at least 3 h. Than 200 ml of a solution of 10% HCl in water was added. The organic phase was collected, dryed on $NaSO_4$ and than the solvent removed on a rotary evaporator. The black product was suspended in 100 ml of ethanol and precipitated at -18°C.. The etherogeneous solution was ultracentrifugated

and the solid was collected. This process is repeated until the utilised calix[n]arene is present (TLC = exane/ethylacetate 9/1). In order to remove the tetraoctylammonium bromide the solid was washed few times with methanol. The product was obtained with a yield of ~ 60%.

General procedure for the synthesis of 5-MPCs(9), (10), 9-MPCs(11) and 13-MPCs(12).

To a vigorous stirred solution of 1 g of tetraoctylammonium bromide in 100 ml of toluene was added 0.2 g of $HAuCl_4 \cdot xH_2O$ in 50 ml of deionized water. The yellow $HAuCl_4 \cdot xH_2O$ aqueous solution quickly became colourless and the toluene phase became orange as the $AuCl_4^-$ was transferred into it. The organic phase was isolated and the desired amount of calix[n]arene was added, and the resulting solution was stirred for 10 min at room temperature. Than 0.2 g of $NaBH_4$ in 50 ml of deionized water was slowly added (30 min). The now very dark organic phase was further stirred at at room temperature for at least 3 h. Than 200 ml of a solution of 10% HCl in water was added. The organic phase was collected, dryed on $NaSO_4$ and than the solvent removed on a rotary evaporator. The black product was suspended in 100 ml of ethanol and precipitated at -18°C. The etherogeneous solution was ultracentrifugated and the solid was collected. This process is repeated until the utilised calix[n]arene is present (TLC = exane/ethylacetate 9/1). In order to remove the tetraoctylammonium bromide the solid was washed few times with methanol. The solid was dissolved in toluene and centrifugated at 6000 rpm in order to remove gold in excess. The product was obtained with a yield of ~ 80%.

General procedure for the synthesis of Pd-MPCs.

0.17g (1mmol) of $PdCl_2$ was dissolved in 50 ml of a solution 10% of HCl in water. A total of 80 ml of toluene with 1.1 g of TOABr was then added into yhis solution, where the bright orange/red Pd(II) was transeferred from the aqueous phase to the toluene phase. The aqueous phase was then removed, and a calculated amount of thiolated compound was added into the toluene phase. The solution was stirred for about 20 min, and then 0.39 g of $NaBH_4$ in 20 ml of water was added quickly into the solution. The black solution was under vigorous stirring for 20 min before the toluene part was collected. Solvent was then removed under reduced pressure and the resulting samples were thoroughly rinsed with ethanol to remove excessive thiols and other reaction byproducts.

General procedure for the synthesis of Ag-MPCs.

In a typical experiment, silver ions (0.15 g $AgNO_3$ in 30 ml of pure water) are transferred into chloroform using the phase-transfer catalyst TOABr (2.23g in 29.4 ml of chloroform). After collecting the organic phase, the silver ions are reduced with $NaBH_4$ (0.39g in 24 ml of pure water) in the presence of the precise amount of thiolated compound. After 3 hours solvent was then removed under reduced pressure and the resulting samples were thoroughly rinsed with ethanol to remove excessive thiols and other reaction byproducts.