

Sensing and Fixation of NO₂/N₂O₄ by Calix[4]Arenes

Grigory V. Zyryanov, Yanlong Kang, and Dmitry M. Rudkevich*

Contribution from the Department of Chemistry & Biochemistry, University of Texas at Arlington, Arlington, Texas 76019

Received October 31, 2002; E-mail: rudkevich@uta.edu

Abstract: An approach toward visual detection and chemical utilization of NO₂/N₂O₄ is proposed, which employs simple calix[4]arenes. Exposure of tetra-*O*-alkylated calix[4]arenes **1** and **2**, possessing either a *cone* or a 1,3-*alternate* conformation, to NO₂/N₂O₄, both in chloroform solution and in the solid state, results in deeply colored calixarene–nitrosonium (NO⁺) complexes. In the presence of a Lewis acid, such as SnCl₄, stable calixarene–NO⁺ complexes **7** and **8** were isolated in a quantitative yield and characterized by UV–vis, FTIR, high-resolution ¹H NMR spectroscopy and elemental analysis. NO⁺ is found encapsulated within the calixarene cavity, and stable charge-transfer complexes result with *K*_{ass} > 10⁶ M^{−1} (CDCl₃). The NO⁺ encapsulation was also demonstrated in titration experiments with calixarenes **1**, **2**, and **5** and commercially available NO⁺SbF₆[−] salt in chloroform. The complexation process is reversible, and the complexes dissociate upon addition of water and alcohol, recovering the parent calixarenes. Attachment of functionalized calix[4]arenes to silica gel was demonstrated, which afforded a solid material **15** capable of visual detection and entrapment of NO₂/N₂O₄. Calixarene–NO⁺ complexes can be utilized for the NO⁺ transfer processes and nitrosation reactions. The NO⁺ guest transfer between two calixarene containers **2** and **5** was achieved and studied by UV–vis and ¹H NMR spectroscopy. Chemical fixation of NO₂/N₂O₄ was demonstrated through their quantitative transformation into the calixarene–NO⁺ complex and its use as a nitrosonium transfer agent in the synthesis of *N*-nitrosoamides. These results may lead toward novel nitrogen oxides storing materials.

Introduction

Nitrogen dioxide (NO₂) is a major component of so-called NO_x gases.^{1,2} NO_x is the term used to describe the sum of nitric oxide (NO), NO₂ and other oxides of nitrogen. These are toxic atmospheric pollutants derived from fossil fuel combustion, power plants, and large-scale industrial processes. NO_x's are involved in the formation of ground-level ozone, participate in global warming, and also form toxic chemicals, nitrate particles and acid rain/aerosols. NO_x's are aggressively involved in various nitrosation processes in biological tissues. Free radical NO rapidly reacts with oxygen, producing N₂O₃ (e.g., NO•NO₂) and NO₂/N₂O₄. These are powerful nitrosating agents, both in the gas phase and in solution. The pathophysiological significance of NO_x derives from their ability to generate mutagenic nitrosopeptides and further diazoepitopes, to produce carcinogenic nitrosoamines, and to nitrosate and further deaminate DNA nucleobases. According to The United States Environmental Protection Agency,¹ national emissions of NO_x have increased over the past 20 years by 4%. Tolerable levels of NO_x are ≤ 5 ppm. Extensive NO₂ circulation in the atmosphere requires not only its systematic monitoring but also necessitates the development of improved methods of the NO₂ fixation and utilization. Here, we describe host–guest complexes, formed upon inter-

action between NO₂ and simple calix[4]arenes (Figure 1).³ We found that (a) calixarenes react with NO₂ to form stable nitrosonium (NO⁺) complexes, (b) these calixarene–NO⁺ complexes are deeply colored and can dissociate/bleach upon addition of water, and (c) these complexes can be utilized for the NO⁺ transfer processes and nitrosation reactions. Accordingly, our results offer a novel process of NO₂ visual sensing and chemical utilization and may also lead toward novel, supramolecular NO₂-storing materials.

Results and Discussion

Rationale and Design. Calix[4]arenes are popular building blocks in molecular recognition and they are widely used in the construction of molecular containers — cavitands, (hemi)-carcerands, and capsules.⁴ *Cone*-shaped calix[4]arenes are ~4 Å deep and ~7 Å in diameter at the upper rim. Tetra-*O*-alkylated *cone* calix[4]arenes exist in the pinched C_{2v} symmetrical conformation, with two opposite aromatic rings almost parallel and situated ~5 Å apart, and two others flattened. This conformation is more preferable than the perfect cone C_{4v} conformation. Usually, the interconversion between two C_{2v}

- (1) (a) Lerdau, M. T.; Munger, J. W.; Jacob, D. J. *Science* **2000**, 288, 2291–2293. (b) U. S. Environmental Protection Agency site: <http://www.epa.gov/air/urbanair/nox/index.html>.
(2) Kirsch, M.; Korth, H.-G.; Sustmann, R.; de Groot, H. *Biol. Chem.* **2002**, 383, 389–399.

- (3) Part of this work appeared as a preliminary communication, see: Zyryanov, G. V.; Kang, Y.; Stampp, S. P.; Rudkevich, D. M. *Chem. Commun.* **2002**, 2792–2793.
(4) (a) *Calixarene 2001*; Asfari, Z., Böhrer, V., Harrowfield, J., Vicens, J., Eds.; Kluwer Academic Publishers: Dordrecht, 2001. (b) Gutsche, C. D. *Calixarenes Revisited*; Royal Society of Chemistry: Cambridge, 1998. (c) Rudkevich, D. M. *Bull. Chem. Soc. Jpn.* **2002**, 75, 393–413.

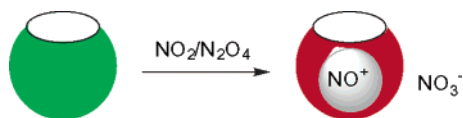


Figure 1. Chemical fixation of $\text{NO}_2/\text{N}_2\text{O}_4$ with calix[4]arenes, a cartoon representation. Formation of encapsulated nitrosonium complexes.

structures is fast on the NMR time scale.⁵ Calix[4]arenes in a 1,3-*alternate* conformation are much more rigid and possess a cylindrical inner tunnel, defined by two cofacial pairs of aromatic rings oriented orthogonal along the cavity axis. According to the number of X-ray studies, this tunnel is $\sim 5\text{--}6$ Å in diameter.⁶

Complexes of calix[4]arenes with neutral molecules are weak. The cavities are obviously too small and they also lack additional binding sites. In most of the crystal structures of the inclusion complexes of calixarenes, the guest molecule is positioned not inside but roughly above the plane defined by the upper carbon atoms of the cyclic polyaromatic skeleton. On the other hand, cations are known to more strongly interact with the calixarene π -surface. Ammonium ions and metal cations were found complexed within the cone-shaped cavities.⁷ 1,3-*Alternates*, functionalized with appropriate binding sites on the phenol oxygens, bind metal cations— Na^+ , K^+ , and Ag^+ —both with “hard” oxygens and “soft” π -basic aromatic rings.⁸ Recently, Kochi, Rathore and co-workers described very stable complexes between calix[4]arenes and nitrosonium (NO^+) cation, both in solution and in the solid state.⁹ The NO^+ cation was found *encapsulated* within the calixarene cavity (X-ray analysis), and strong charge-transfer interactions with the π -surface of calixarene positioned the guest between the cofacial aromatic rings at a distance 2.4 Å, which is much shorter than the typical van der Waals contact (3.2 Å).

NO_2 is a paramagnetic gas since it has an unpaired electron on the nitrogen. It has an intense brown-orange color. Reacting with itself, it forms the colorless dimer, dinitrogen tetroxide (N_2O_4).¹⁰ The N—N bond in N_2O_4 is quite weak, and as the temperature is raised it rapidly dissociates back to NO_2 . The position of the equilibrium between the two compounds and the color of the system vary with temperature. Below -21°C , only pure, solid N_2O_4 is present. Above 140°C the system is 100% NO_2 . The *dynamic* interconversion between NO_2 and N_2O_4 makes it impossible to study either of these species alone.

Of particular importance for us, N_2O_4 may disproportionate to ionic NO^+NO_3^- upon reacting with aromatic compounds.^{10,11}

Combining these features of $\text{NO}_2/\text{N}_2\text{O}_4$ with unique complexing abilities of calix[4]arenes, we expected that interactions between them might lead to calixarene-nitrosonium complexes. Below, we describe the sequence of experiments, elaborating this idea, and also the chemical consequences, that follow.

Synthesis. Calix[4]arenes **1**¹² and **2**, possessing a *cone* and a 1,3-*alternate* conformation, respectively, were synthesized through O-alkylation of the corresponding parent calix[4]arenes with *n*-hexylbromide (Scheme 1). In the synthesis of **1**, NaH was employed as a base in hot DMF. Preparation of **2** includes the two-step alkylation of de-*tert*-butylated calix[4]arene with *n*-hexyl bromide, using successively K_2CO_3 and then Cs_2CO_3 in boiling MeCN.¹³

Bromination of **2** with NBS in acetone afforded tetrabromo-calix[4]arene **3** in 53% yield (Scheme 2). Tetrahydroxylated 1,3-*alternate* derivative **4** was obtained through bromo-lithium exchange in **3** (*n*-BuLi, THF, -78°C), followed by treatment with $\text{B}(\text{OMe})_3$ and oxidation with H_2O_2 and aq NaOH (40% yield after three steps). Calixarene **4** was subsequently alkylated with *n*-hexylbromide and NaH in hot DMF to yield octahexyloxy-calix[4]arene **5** in 85%.¹⁴ Mesitylene derived 1,3-*alternate* **6** was obtained for comparison, according to the literature procedure by Pappalardo^{15,16} and subsequent O-alkylation with *n*-hexylbromide (Scheme 3).

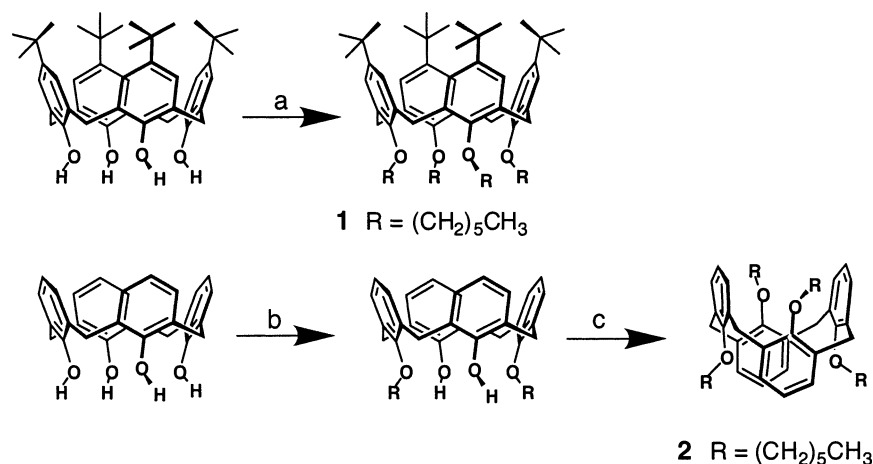
Interaction of Calix[4]arenes with NO_2 . Bubbling NO_2 through the solutions of **1**, **2**, and **5** in CHCl_3 resulted in instant, deep coloration. Solutions of **1** and **5** turned dark blue, and solution of **2** became deep purple. The UV–vis spectra changed accordingly: the broad bands appeared at $\lambda_{\text{max}} = 560, 512$, and 600 nm for NO_2 -exposed solutions of **1**, **2**, and **5**, respectively. This is in a striking contrast to colorless solutions of **1**, **2**, and **5**, and pale yellow solution of NO_2 in CHCl_3 , and implies a charge-transfer mechanism.

In the experiments with noncyclic anisole (e.g., methoxybenzene), only pale coloration was observed upon exposure to NO_2 . Moreover, when mesitylene derived, Pappalardo's calixarene **6**, with the sterically *blocked* and conformationally much more *rigid* cavity, was tested, no coloration was observed either. In **6**, the pair of methyl groups in the ortho-positions to the oxygen forces the methyl groups of the adjacent aromatic rings toward each other, not only blocking an access to the cylindrical inner cavity, but also significantly rigidifying it. The same effect takes place on the other side of the calixarene **6**, which makes its interior completely hindered. These model experiments emphasize the importance of *cavities* in the described transformations and suggest the possibility of the NO^+ coordination inside **1**, **2**, and **5** (Figure 2, Figure 3, Figure 4).

- (5) (a) Arduini, A.; Fabbi, M.; Mirone, L.; Pochini, A.; Secchi, A.; Ungaro, R. *J. Org. Chem.* **1995**, *60*, 1454–1458. (b) Conner, M.; Janout, V.; Regen, S. L. *J. Am. Chem. Soc.* **1991**, *113*, 9670–9671. (c) Scheerder, J.; Vreekamp, R. H.; Engbersen, J. F. J.; Verboom, W.; van Duynhoven, J. P. M.; Reinhoudt, D. N. *J. Org. Chem.* **1996**, *61*, 3476–3481.
- (6) (a) Iwamoto, K.; Shinkai, S. *J. Org. Chem.* **1992**, *57*, 7066–7073. (b) Beer, P. D.; Drew, M. G. B.; Gale, P. A.; Leeson, P. B.; Ogden, M. I. *J. Chem. Soc., Dalton Trans.* **1994**, 3479–3485. (c) Perez-Adelmar, J.-A.; Abraham, H.; Sanchez, C.; Rissanen, K.; Prados, P.; de Mendoza, J. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1009–1011. (d) de Mendoza, J.; Cuevas, F.; Prados, P.; Meadows, E. S.; Gokel, G. W. *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 1534–1537.
- (7) (a) Ikeda, A.; Shinkai, S. *Chem. Rev.* **1997**, *97*, 1713–1734. (b) Lhotak, P.; Shinkai, S. *J. Phys. Org. Chem.* **1997**, *10*, 273–285. (c) Assmus, R.; Böhrer, V.; Harrowfield, J. M.; Ogden, M. I.; Richmond, W. R.; Skelton, B. W.; White, A. H. *J. Chem. Soc., Dalton Trans.* **1993**, 2427–33.
- (8) (a) Ikeda, A.; Shinkai, S. *J. Am. Chem. Soc.* **1994**, *116*, 3102–3110. (b) Ikeda, A.; Tsuzuki, H.; Shinkai, S. *Tetrahedron Lett.* **1994**, *35*, 8417–8420. (c) Ikeda, A.; Shinkai, S. *J. Chem. Soc., Chem. Commun.* **1994**, 2375–2376. (d) Ikeda, A.; Tsudera, T.; Shinkai, S. *J. Org. Chem.* **1997**, *62*, 3568–3574.
- (9) Rathore, R.; Lindeman, S. V.; Rao, K. S. S.; Sun, D.; Kochi, J. K. *Angew. Chem., Int. Ed.* **2000**, *39*, 2123–2127.
- (10) Addison, C. C. *Chem. Rev.* **1980**, *80*, 21–39.

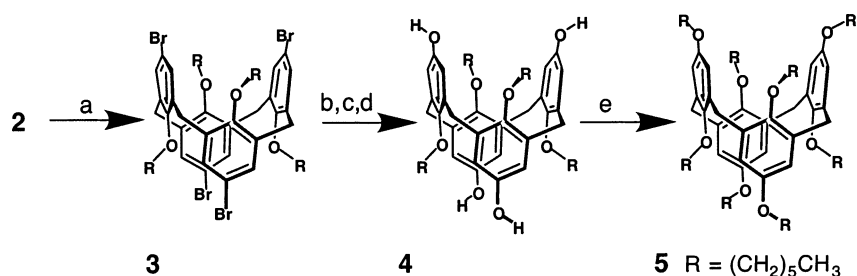
- (11) (a) Bosch, E.; Kochi, J. K. *J. Org. Chem.* **1994**, *59*, 3314–3325 and references therein. (b) Evans, J. C.; Rinn, H. W.; Kuhn, S. J.; Olah, G. *Inorg. Chem.* **1964**, *3*, 857–861.
- (12) Kenis, P. J. A.; Noordman, O. F. J.; Schonherr, H.; Kerver, E. G.; Snellink-Ruel, B. H. M.; van Hummel, G. J.; Harkema, S.; van der Vorst, C. P. J. M.; Hare, J.; Picken, S. J.; Engbersen, J. F. J.; van Hulst, N. F.; Vancso, G. J.; Reinhoudt, D. N. *Chem. Eur. J.* **1998**, *4*, 1225–1234.
- (13) For a typical preparation of calix[4]arene 1,3-*alternates*, see: Casnati, A.; Pochini, A.; Ungaro, R.; Ugozzoli, F.; Arnaud, F.; Fanni, S.; Schwing, M.-J.; Egberink, R. J. M.; de Jong, F.; Reinhoudt, D. N. *J. Am. Chem. Soc.* **1995**, *117*, 2767–2777.
- (14) For a typical procedure, see: Pellet-Rostaing, S.; Chitry, F.; Nicod, L.; Lemaire, M. *J. Chem. Soc., Perkin Trans. 2* **2001**, 1426–1432.
- (15) Pappalardo, S.; Ferguson, G.; Gallagher, J. F. *J. Org. Chem.* **1992**, *57*, 7102–7109.
- (16) Staffilani, M.; Bonvicini, G.; Steed, J. W.; Holman, K. T.; Atwood, J. L.; Elsegood, M. R. *J. Organometallics* **1998**, *17*, 1732–1740.

Scheme 1



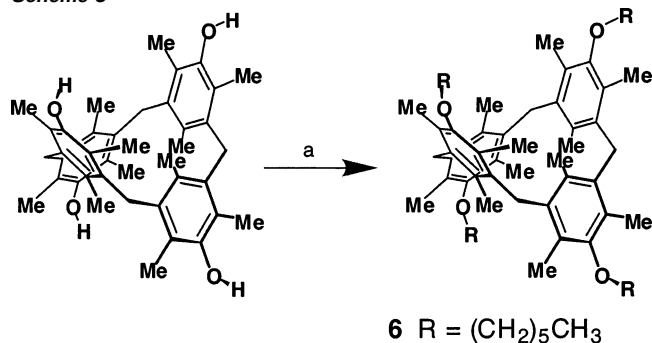
(A) *n*-hexyl Bromide, NaH, DMF, 70 °C, 24 H, 75%. (B) *n*-hexyl Bromide, K_2CO_3 , MeCN, 80 °C, 48 H, 84 %. (C) *n*-hexyl Bromide, Cs_2CO_3 , MeCN, 80 °C, 48 H, 46%.

Scheme 2



(A) NBS, Acetone, Rt, 48 H, 53% Yield. (B) *n*-BuLi (60 eq), THF, -78 °C, 0.5 h. (C) $\text{B}(\text{OMe})_3$, -78 °C to 0 °C. (D) H_2O_2 , Aq NaOH, -78 °C to 25 °C, 40%, Three Steps). (E) *n*-hexyl Bromide, NaH, DMF, 70 °C, 24 H, 85%.

Scheme 3



(A) *n*-hexyl Bromide, NaH, DMF, 70 °C, 72 H, 50%.

According to molecular modeling,¹⁷ one NO^+ cation can fit inside the cavities **1**, **2**, and **5**, and neither bent NO_2 nor bulky NO_3^- can be accommodated. Two parallel aromatic rings of a cone calix[4]arene participate in the NO^+ complexation, and all four rings of a 1,3-alternate calixarene are involved. In mesitylene derived calixarene **6**, no NO^+ encapsulation may occur for steric reasons.

While the instant coloration implied charge-transfer between the prereactive nitrosating/nitrating species and **1**, **2**, and **5**, this was difficult to monitor. Interaction of NO_2 with **1**, **2**, and **5** is very dynamic, and the initial ^1H NMR analysis of the solutions gave rather complex, quickly changing pictures. The $\text{NO}_2/\text{N}_2\text{O}_4$ mixture is known as an effective nitrosating/nitrating agent.^{2,10,11}

(17) MacroModel 7.1; MM2 and Amber* Force Field. See: Mohamadi, F.; Richards, N. G.; Guida, W. C.; Liskamp, R.; Lipton, M.; Caufield, C.; Chang, G.; Hendrickson, T.; Still, W. C. *J. Comput. Chem.* **1990**, *11*, 440–467.

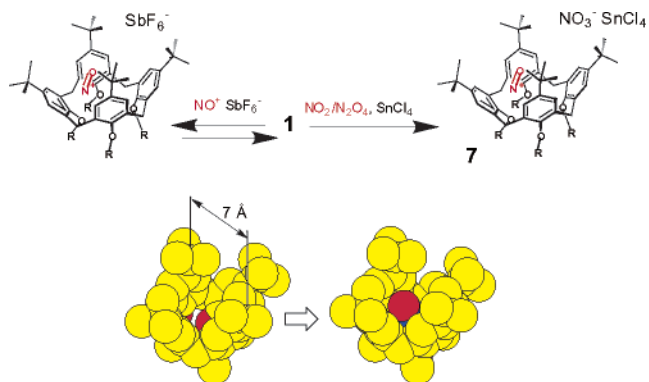


Figure 2. Nitrosonium complexes of calix[4]arene **1**; two methods of preparation. Left: addition of $\text{NO}^+\text{SbF}_6^-$ to **1** in chloroform. Right: reaction of $\text{NO}_2/\text{N}_2\text{O}_4$ with **1** in the presence of SnCl_4 in chloroform. Below: MacroModel representation of the NO^+ encapsulation process. The CH hydrogen and long alkyl chains are omitted for viewing clarity.

Not surprisingly, the NO_2 -containing CHCl_3 solutions of **1** and **2** bleached within 1–2 h, yielding mixtures of known *p*-nitrated calixarenes¹⁸ (preparative TLC, ^1H NMR). Calixarene **5**, much more activated for the electrophilic aromatic substitution, reacts with NO_2 even faster—within few minutes, producing a very complex mixture of dealkylated and oxidized products.¹⁹

At the same time, when treated with SnCl_4 , solutions of **1**, **2** and 2–3 equivs of NO_2 did not yield the nitration products. It

(18) Kelderman, E.; Derhaeg, L.; Heesink, G. J. T.; Verboom, W.; Engbersen, J. F. J.; van Hulst, N. F.; Persoons, A.; Reinhoudt, D. N. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 1075–1077.

(19) Dealkylation and oxidation of phenol ethers upon nitrosation/nitration, see: Rathore, R.; Bosch, E.; Kochi, J. K. *Tetrahedron* **1994**, *50*, 6727–6758 and references therein.

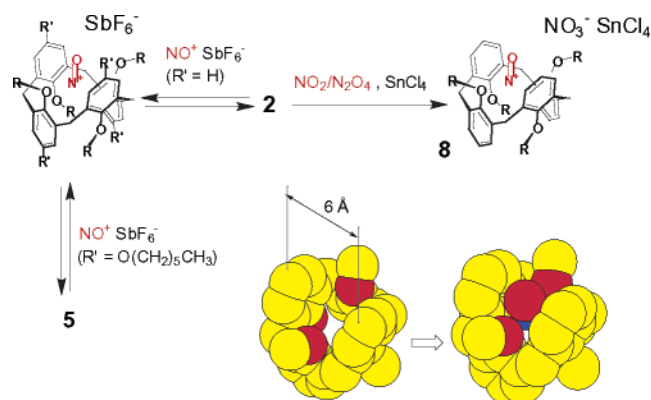


Figure 3. Nitrosonium complexes of calix[4]arene **2**; two methods of synthesis. Below: MacroModel representation of the NO^+ encapsulation process. The CH hydrogen and long alkyl chains are omitted for viewing clarity.

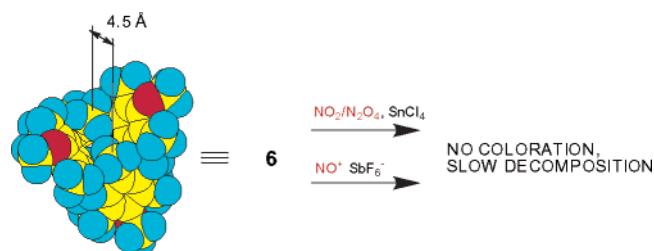


Figure 4. Mesitylene-derived calixarene **6** does not encapsulate NO^+ . Left: space-filling representation of **6**; the long alkyl chains are omitted for viewing clarity.

is known that Lewis acids stabilize arene-nitrosonium charge-transfer complexes.^{10,11} Precipitation with hexanes resulted in deeply colored, moisture sensitive solids, assigned to nitrosonium complexes **7** and **8** (>90% yield, Figures 2–4). These complexes are very stable and can be stored, in the absence of moisture, for several weeks, both in CHCl_3 solution and in the solid state. Complex **7** is dark blue, and complex **8** is deep purple.

Analysis and Characterization. Selected spectral features of the obtained nitrosonium complexes are presented in Table 1. The UV–vis spectra showed broad charge-transfer^{20,21} bands at $\lambda_{\text{max}} \sim 563$ and 524 nm, and the FTIR spectra exhibited characteristic²⁰ arene- NO^+ stretching at $\nu = 1923$ and 1955 cm^{-1} for **7** and **8**, respectively. The ^1H NMR spectra of **7** and **8** exhibited new sets of the calixarene signals as well (Figure 5). In particular, aromatic CH protons of guest-free **1** were seen as a singlet at 6.76 ppm. In nitrosonium complex **7**, these were transformed into a singlet at 6.99 ppm. The methylene bridge CH_2 protons of **1** were recorded as doublets at 4.41 and 3.12 ppm ($J = 12.5$ Hz). In complex **7**, these were seen as doublets at 4.39 and 3.44 ppm ($J = 13$ Hz). The aromatic protons of free **2** were seen as a doublet and a triplet, 2:1, at 6.92 and 6.68 ppm, respectively ($J = 7.5$ Hz). In nitrosonium complex **8**, these were transformed into a triplet and a doublet, 1:2, at 7.17 and 7.08 ppm, respectively ($J = 7.5$ Hz). The methylene bridge CH_2 and OCH_2 protons of **2** were seen as a singlet and a triplet, 1:1, at 3.62 and 3.54 ($J = 7.5$ Hz), respectively. In complex **8**, these were transformed into a singlet and a triplet, 1:1, at 3.60 and 3.87 ($J = 7.5$ Hz), respectively. Elemental analysis of extremely

Table 1. Selected Spectroscopic Data for Calix[4]arenes **1**, **2**, and **5**, and Their Nitrosonium Complexes^{a,b,c}

compd	δ , ppm	ν , cm^{-1}	λ_{max} , nm
1	6.76 (s, arom), 4.41, 3.12 (2 $\times$ d, CH_2)		
2	6.92 (d, arom), 6.68 (t, arom), 3.62 (s, CH_2), 3.54 (t, OCH_2)		
5	6.55 (s, arom), 3.83 (t, OCH_2), 3.62 (s, CH_2), 3.35 (t, OCH_2)		
5 · $\text{NO}^+\text{SbF}_6^-$	6.54 (s, arom), 3.93 (t, OCH_2), 3.76 (t, OCH_2), 3.44 (s, CH_2)	1876	600
7	6.99 (s, arom), 4.39, 3.44 (2 $\times$ d, CH_2)	1923	563
8	7.17 (t, arom), 7.08 (d, arom), 3.87 (t, OCH_2), 3.60 (s, CH_2)	1955	524

^a At 295 ± 1 K. ^b The above-reported spectral features of complexes **1**· $\text{NO}^+\text{SbF}_6^-$, **2**· $\text{NO}^+\text{SbF}_6^-$, and **5**· $\text{NO}^+\text{SbF}_6^-$ are similar to those of **7**, **8**, and **9**, respectively. ^c In CDCl_3 for ^1H NMR and FTIR, and in CHCl_3 for UV–vis.

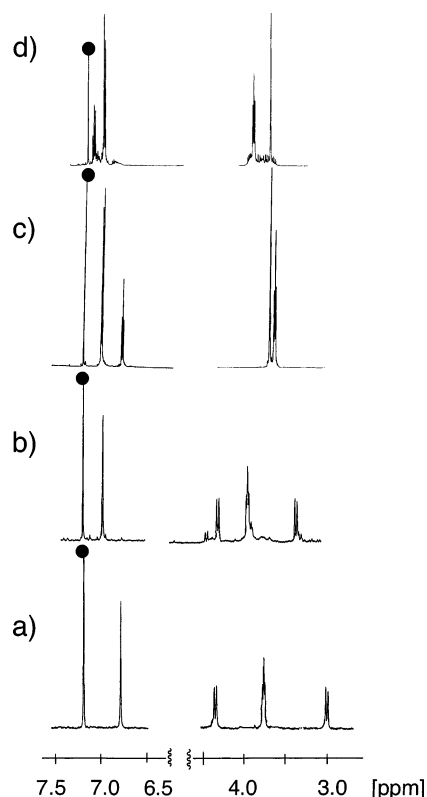


Figure 5. Portions of the ^1H NMR spectra (500 MHz, CDCl_3 , 295 ± 1 K) of: (a) calix[4]arene **1**. (b) nitrosonium complex **7**; the identical spectrum was obtained upon addition of $\text{NO}^+\text{SbF}_6^-$ to **1**. (c) calix[4]arene **2**. (d) nitrosonium complex **8**; the identical spectrum was obtained upon addition of $\text{NO}^+\text{SbF}_6^-$ to **2**. The residual CHCl_3 signals are marked “●”.

moisture sensitive and thermally unstable **7** and **8** proved to be difficult but reproducibly showed the CHN ratios corresponding to the presence of *only one* NO^+ cation in both structures.

Independent structural evidence came from the complexation experiments between calixarenes **1** and **2** and commercially available $\text{NO}^+\text{SbF}_6^-$ salt (Figure 2, Figure 3). Specifically, the CDCl_3 solutions of **1** and **2** were treated with $\text{NO}^+\text{SbF}_6^-$ at 295 K and the complexation induced changes in the UV–vis, FTIR, and ^1H NMR spectra were recorded. Under these

(20) Borodkin, G. I.; Shubin, V. G. *Russ. Chem. Rev.* **2001**, *70*, 211–230.

(21) Rosokha, S. V.; Kochi, J. K. *J. Am. Chem. Soc.* **2001**, *123*, 8985–8999.

conditions, the complexation process proved to be rather slow, however after ~ 20 h no starting calixarenes **1,2** were observed and the corresponding UV–vis, FTIR, and ^1H NMR spectra exhibited features similar to those of nitrosonium complexes **7,8**. These spectral data are in agreement with the Kochi and Rathore spectral observations.⁹

Analogously, a nitrosonium complex of calixarene **5** was obtained. The UV–vis spectrum of dark blue complex $5\cdot\text{NO}^+\text{SbF}_6^-$ showed broad band at $\lambda_{\text{max}} \approx 600$ nm, and the FTIR spectrum exhibited characteristic²⁰ arene- NO^+ stretching at 1876 cm^{-1} . The ^1H NMR spectrum of $5\cdot\text{NO}^+\text{SbF}_6^-$ is different from **5** as well. For example, the methylene bridge CH_2 and both OCH_2 protons of **5** were seen as a singlet and two triplets, 1:1:1, at 3.62, 3.83 ($J = 7\text{ Hz}$), and 3.35 ppm ($J = 7\text{ Hz}$), respectively. In complex $5\cdot\text{NO}^+\text{SbF}_6^-$, these were observed at 3.44, 3.93 ($J = 7.5\text{ Hz}$), and 3.76 ppm ($J = 7.5\text{ Hz}$), respectively.

The association constants for the above complexes were too high to be measured by the ^1H NMR technique. Even slight excess of $\text{NO}^+\text{SbF}_6^-$ results in the complete complex formation in CDCl_3 , and no free calixarenes **1,2**, and **5** were observed after equilibration. The K_{ass} values $>10^6\text{ M}^{-1}$ ($\Delta G^{295} > 8\text{ kcal mol}^{-1}$) for the complexes were estimated, which is in agreement with the published values in CH_2Cl_2 .⁹ Although complexes $1\cdot\text{NO}^+\text{SbF}_6^-$ and $2\cdot\text{NO}^+\text{SbF}_6^-$ formed slowly, over ~ 20 h, it took only few minutes to form complex $5\cdot\text{NO}^+\text{SbF}_6^-$. Moreover, highly electrophilic NO^+ tends to further react with $5\cdot\text{NO}^+\text{SbF}_6^-$, and unidentified impurities were seen in the NMR spectrum already after several minutes. Unlike complexes $1\cdot\text{NO}^+\text{SbF}_6^-$ and $2\cdot\text{NO}^+\text{SbF}_6^-$, which are chemically stable for weeks, complex $5\cdot\text{NO}^+\text{SbF}_6^-$ decomposes within a day (^1H NMR).¹⁹

Addition of H_2O or MeOH to the freshly prepared CHCl_3 solutions of **7** and **8** and the nitrosonium complexes prepared from **1, 2**, and **5** and $\text{NO}^+\text{SbF}_6^-$, resulted in the complete complex dissociation and recovery of calixarenes **1, 2**, and **5** (preparative TLC, UV–vis, ^1H NMR).

With the above information in hands, we subsequently reexamined the spectral data for the reactions between **1** and **2** and NO_2 , in the absence of SnCl_4 . As excess NO_2 was passed through the solution of **1**, nitrosonium complex $[1\cdot\text{NO}^+]\text{NO}_3^-$ was clearly seen (UV–vis, ^1H NMR), along with the mixture of nitration products. For **2**, no signals for nitrosonium complex $[2\cdot\text{NO}^+]\text{NO}_3^-$ were detected.²² Apparently, while formed these nitrosonium species quickly react with an excess NO_2 . Overall, both reactions subsequently yield *p*-nitrated calixarenes.

(22) In the experiments between calixarene **2**, SnCl_4 and larger (~ 50 -fold) excess of $\text{NO}_2/\text{N}_2\text{O}_4$, one more prereactive complex was detected, which we assigned to nitronium species $[2\cdot\text{NO}_2^+]\text{NO}_3^- \cdot \text{SnCl}_4$. In the UV–vis spectrum, a broad charge-transfer band at $\lambda_{\text{max}} = 512\text{ nm}$ was recorded. The FTIR spectrum showed stretches at $\nu = 2356\text{ cm}^{-1}$, characteristic for NO_2^+ species. In the ^1H NMR spectrum, complex $[2\cdot\text{NO}_2^+]\text{NO}_3^- \cdot \text{SnCl}_4$ exhibits a broader doublet and a triplet, 2:1, at 7.10 and 7.00, respectively. As one possible explanation, initially formed nitrosonium complex **8** yields the electron-transfer complex $[2^{+\bullet}\text{NO}]\text{NO}_3^-$ and releases NO . The resulting cation-radical $2^{+\bullet}\text{NO}_3^-$ reacts with an excess of NO_2 , producing $[2^{+\bullet}\text{NO}_2]\text{NO}_3^-$ and further charge-transfer nitronium complex $[2\cdot\text{NO}_2^+]\text{NO}_3^-$. The structure was independently confirmed by complexation between **2** and $\text{NO}_2^+\text{SbF}_6^-$ in CDCl_3 . The obtained UV–vis, FTIR, and ^1H NMR spectra were similar to those of the complex obtained from **2**, $\text{NO}_2/\text{N}_2\text{O}_4$ and SnCl_4 . As an excess NO_2 was passed through the solution of **2**, no signals for nitrosonium complex $[2\cdot\text{NO}^+]\text{NO}_3^-$ were seen, but nitronium complex $[2\cdot\text{NO}_2^+]\text{NO}_3^-$ was detected. Complexation studies with calixarene **1** and $\text{NO}_2^+\text{SbF}_6^-$ in CDCl_3 revealed the formation of kinetically stable complex $[1\cdot\text{NO}_2^+]\text{SbF}_6^-$. Judging from the intense coloration, the calixarene walls, most probably, encapsulate NO_2^+ . Detailed description of observed calixarene-nitronium complexes will be published separately.

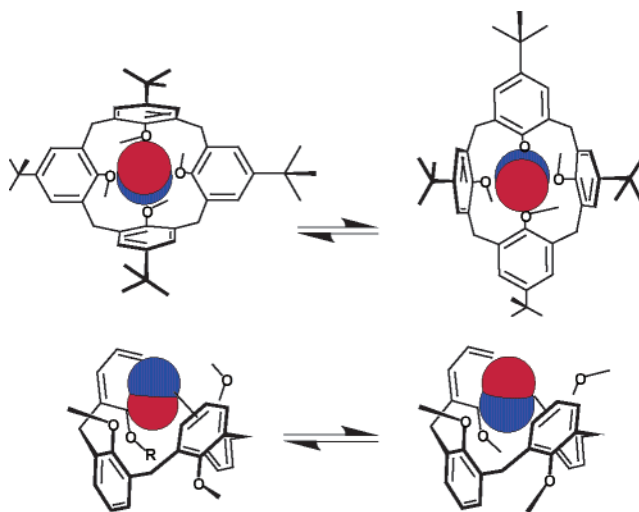


Figure 6. Proposed host–guest dynamics in calix[4]arene- NO^+ complexes.

Summarizing, reactions between $\text{NO}_2/\text{N}_2\text{O}_4$ and *O*-alkylated calix[4]arenes proceed via the NO^+ encapsulation. Calix[4]arene-nitrosonium complexes can be significantly stabilized by Lewis acids.

Host–Guest Dynamics. As evident from the ^1H NMR data, the NO^+ exchange in and out of the cavity is slow on the NMR time scale. For example, in the titration experiments between calixarenes **1** and **2** and $\text{NO}^+\text{SbF}_6^-$, both free and complexed species can be observed separately.²³ This is typical for the host–guest complexes with high $K_{\text{ass}} > 10^6\text{ M}^{-1}$ values. On the other hand, the NO^+ guest, with the van der Waals dimensions $< 2\text{ Å}$,²⁰ freely migrates within the cavity at room temperatures (Figure 6). Indeed, the ^1H NMR spectra of complexes **7,8** possess the same symmetry as guest-free calixarenes **1,2**, which in principle should be reduced upon complexation with nonsymmetrical NO^+ .

Cone calix[4]arene complex **7** should have a pinched, C_{2v} symmetrical conformation, since only two opposite, cofacial aromatic rings trap NO^+ . Instead, the observed at room-temperature NMR spectrum exhibits a C_{4v} symmetry, indicating a fast on the NMR time scale exchange between two C_{2v} structures. 1,3-Alternate calix[4]arene complex **8** should exhibit a C_{2v} symmetry, with two different top and bottom halves of the skeleton. Instead, the apparent at room-temperature symmetry is S_4 , with equal top and bottom halves.²⁴

At the same time, the complexation process is reversible, and the NO^+ guest can still leave the calixarene cavity. Addition of H_2O to the freshly prepared CHCl_3 solutions of **7,8** resulted in the complete dissociation and recovery of calixarenes **1,2**. Interestingly, complex **8** bleached within seconds, but it took several minutes to decompose complex **7**.²⁵ We propose, that the kinetics is responsible. Apparently, *t*-Bu groups at the upper

(23) Typical examples of slow exchange in open-ended host–guest complexes with cavitands: (a) Rudkevich, D. M.; Hilmersson, G.; Rebek, J., Jr. *J. Am. Chem. Soc.* **1998**, *120*, 12 216–12 225. (b) Lücking, U.; Tucci, F. C.; Rudkevich, D. M.; Rebek, J., Jr. *J. Am. Chem. Soc.* **2000**, *122*, 8880–8889.

(24) This observation also appeared in ref 9. Even at very low temperatures, it was impossible to discriminate between two halves of 1,3-alternate- NO^+ complex.

(25) In a typical experiment, deeply colored solutions of complexes **7** and **8** in CHCl_3 (1–2 mL, 5–25 mmol concentration range) were mixed with 1 mL of H_2O and vigorously stirred until decoloration. Complex **8** bleached within $30 \pm 15\text{ s}$, and it took 2–3 min to decompose complex **7**. The experiments were run at least in triplicate. The concentrations of complexes **7** and **8** were determined by ^1H NMR spectroscopy prior measurements.

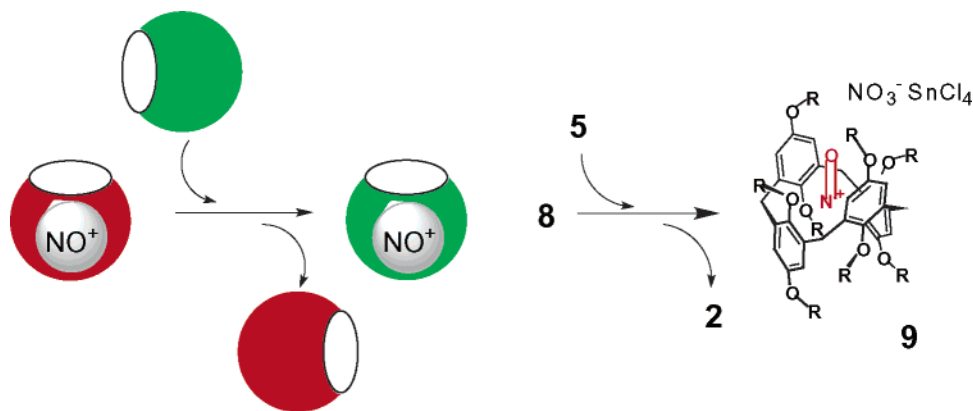


Figure 7. Left: NO^+ transfer between calixarene containers, a cartoon representation. Right: formation of complex **9** from complex **8**.

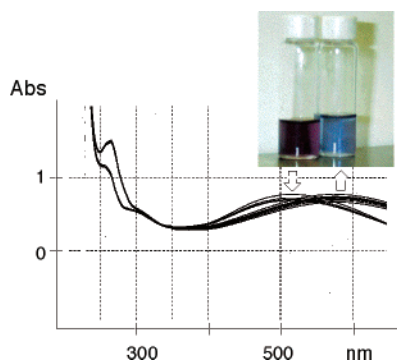


Figure 8. Nitrosonium transfer experiment. Portions of the UV-vis spectra ($[\mathbf{8}] = [\mathbf{5}] = 10^{-6}$ M, CHCl_3 , 295 ± 1 K). Band at $\lambda_{\text{max}} \approx 524$ nm belongs to nitrosonium complex **8**, band at $\lambda_{\text{max}} \approx 600$ nm is assigned to complex **9**. Visually, the exchange results in a color change from purple (left vial) to blue (right vial).

rim of the latter complex pose significant steric hindrances and protect the encapsulated NO^+ species from the entering H_2O . Such stability of the arene- NO^+ complex is without precedent.²⁰

On the other hand, NO^+ guest can be transferred from one calixarene container to another (Figure 7). Calixarene **5** was specifically designed to promote such transfer from the pre-formed complex **8**. Four additional, electron donating $\text{O}(\text{CH}_2)_5\text{CH}_3$ groups were introduced in *p*-positions to the initial set of $\text{O}(\text{CH}_2)_5\text{CH}_3$ groups. This makes cavity **5** significantly more π -electron rich and dramatically increases its affinity toward positively charged NO^+ .

For the exchange experiments, we obtained **8** by treating calixarene **2** with 3 equivalents NO_2 and 1 eq SnCl_4 in CHCl_3 . Further, complex **8** and “empty” host **5** were mixed in a 1:1 ratio at 295 K in dry chloroform, and the UV-vis and ^1H NMR spectra were recorded over 2 h. Due to the strong affinity of **2** toward NO^+ , the guest presence outside the cavity, in a bulk solution, was considered negligible, and the only source of NO^+ was **8**.

Initially, the ^1H NMR spectrum exhibited only sets of signals for **8** and free calixarene **5**, and the corresponding UV-vis spectrum showed only the characteristic absorption for charge-transfer in **8**. Within minutes however, the guest transfer was clearly detected. The band at $\lambda_{\text{max}} \approx 524$ nm, assigned to complex **8**, systematically decreased and a new band at $\lambda_{\text{max}} \approx 600$ nm, corresponding to new complex **9**, appeared.

The nitrosonium transfer can even be observed visually. The purple solution of **8** in CHCl_3 turns blue upon addition of calixarene **5** (Figure 8). When followed by ^1H NMR spectroscopy,

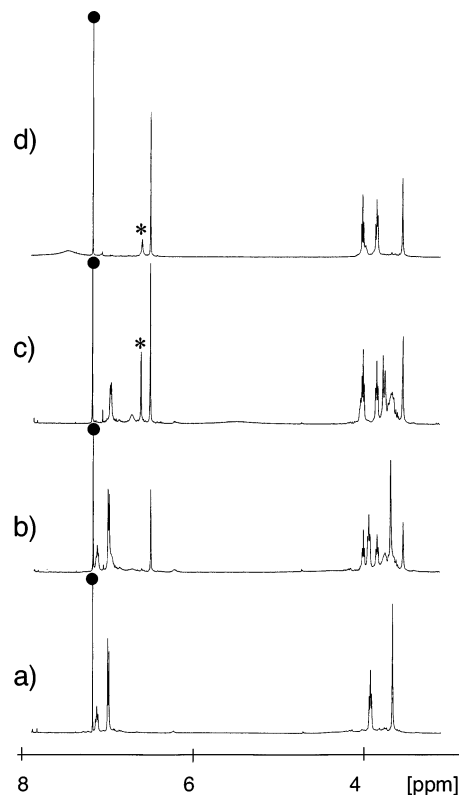
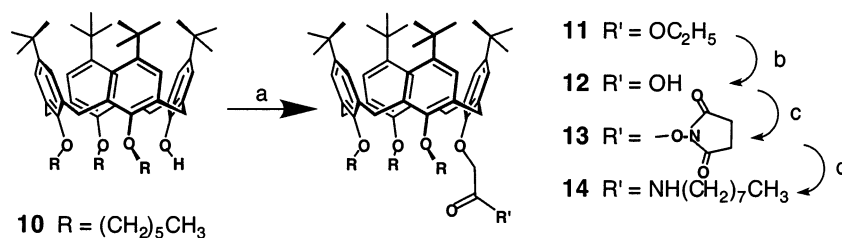


Figure 9. Portions of the ^1H NMR spectra (500 MHz, CDCl_3 , 295 ± 1 K) of: (a) nitrosonium complex **8**, obtained from **2**, NO_2 and SnCl_4 . (b) mixture of complex **8** and calixarene **5** after 20 min; $\sim 30\%$ conversion to **9**. (c) the same mixture after 1 h; complex **9** is formed with $>95\%$ conversion. (d) nitrosonium complex $5 \cdot \text{NO}^+\text{SbF}_6^-$, independently obtained from **5** and $\text{NO}^+\text{SbF}_6^-$. The residual CHCl_3 signals are marked as before, the decomposition products of **5** are marked “*”.

copy, the NO^+ exchange resulted in clean transformation of the spectra from mixture **8** + **5** to mixture **2** + **9** (Figure 9). For example, the methylene bridge CH_2 and OCH_2 protons of **8**, seen as a singlet and a triplet, 1:1, at 3.60 and 3.87 ppm ($J = 7.5$ Hz), slowly decrease in intensity. Instead, two OCH_2 triplets at 3.93 and 3.76 ppm ($J = 7.5$ Hz) and the methylene bridge CH_2 singlet at 3.44 ppm appear and grow. These were assigned to complex **9** and confirmed in the series of independent experiments between **5** and $\text{NO}^+\text{SbF}_6^-$. Signals for “empty” calixarene **2** also appear, although slightly shifted due to the presence of SnCl_4 , and signals for **8** disappear. Within an hour the nitrosonium transfer was completed; both the ^1H NMR and UV-vis spectra exhibited only the signals of complex **9** and

Scheme 4



(A) BrCH₂C(O)OC₂H₅, Na₂CO₃, MeCN, 80 °C, 12 h, 89 %. (B) KOH, THF–H₂O, 100 °C, 12 h, Then Aq HCl, >95%. (C) *N*-hydroxy Succinimide, DCC, DMAP, THF, Rt, 12 h, 83%. (D) CH₃(CH₂)₇-NH₂, Et₃N, THF, Rt, 12 h, 65%.

free calixarene **2**. No traces of initial complex **8** were detected. To our knowledge, this is the first case of a quantitative guest transfer between two different molecular containers.²⁶ Such behavior has a potential for information storage and processing since the color can be switched between two distinguishable states.

Functionalized Silica Gel. Presented here calix[4]arene-NO₂ interactions (a) are reversible, (b) result in dramatic color changes, and (c) are unique and *specific* for NO₂, which should guaranty its detection in the presence of such gases as H₂O, O₂, HCl, HBr, SO_x, and NH₃. Indeed, *none* of these vapors/gases undergoes such interactions/reactions with calixarenes! Even NO gas does not interact with calixarenes. In their excellent work on NO sensing by tetra-*O*-alkylated calix[4]-arenes,⁹ Kochi and Rathore showed that calixarenes had to be oxidatively activated, e.g., to form the corresponding cation-radicals, prior complexing NO.

Current NO₂ sensors are mostly electrochemical and monitor changes of potential upon exposure metal surfaces to NO₂.²⁷ In many cases however, other vapors – H₂O, O₂, HCl, HBr, SO_x, and NH₃ significantly influence the detection selectivity and therefore sensitivity. Optical sensors, which are based on coloration reaction between NO₂ and certain organic compounds, are more selective as the reactions are specific.²⁸ At the same time, reversibility of such sensing processes is not easy to achieve.

For potential application in sensing technology, receptor molecules must not only be synthetically available, but also

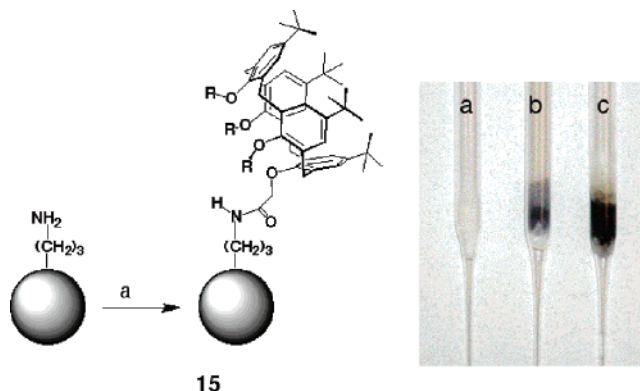


Figure 10. Left: preparation of calix[4]arene functionalized silica gel **15**: (a) Et₃N, THF, rt, 12 h. Right: NO₂ entrapment “chromatography” experiments. The columns were prepared as follows: (a) loaded with starting aminopropyl functionalized silica gel; (b) loaded with dry silica gel **15**; (c) loaded with **15** and flashed with CHCl₃. All three columns were then flashed with NO₂ (~30 s), and the pictures were made after ~2–3 min afterward.

readily immobilizable on larger (macro)molecules, solid supports or surfaces. A wide variety of polymers and nanomaterials are now commercially available. Here, we used 3-aminopropylated silica gel from Aldrich and functionalized it with calixarene modules. As follows from molecular modeling, calix[4]arene fragments are ~10 × 10 Å in their dimensions, so their attachment via *lower* rim should guaranty the proper configuration of the *upper* rim to sufficiently respond to the presence of the gas analyte.

Synthetically, tris-*O*-substituted calixarene **10**, prepared by selective alkylation of the parent calix[4]arene with *n*-hexylbromide and BaO/Ba(OH)₂²⁹ in DMF (69%), was further alkylated with ethyl bromoacetate to afford derivative **11** (Na₂CO₃, MeCN, 89%) (Scheme 4). This was hydrolyzed with KOH in THF–H₂O mixture, resulting calixarene acid **12** in a quantitative yield. Acid **12** was further activated with *N*-bromosuccinimide (DCC, DMAP, THF) to afford active ester **13** (83%). Compound **13** readily reacts with amines. Thus, amide **14** was prepared from **13** and *n*-octylamine (Et₃N, THF, 65%) and used for control experiments. Analogously, ester **13** was coupled to 3-aminopropyl-functionalized silica gel in THF in the presence of Et₃N to afford material **15** (Figure 10). The presence of a calix[4]arene fragment in **15** was confirmed by the FTIR analysis in KBr disks: $\nu(\text{CH}) \approx 2960 \text{ cm}^{-1}$ and $\nu(\text{C=O}) \approx 1650 \text{ cm}^{-1}$ were recorded, which are similar to the stretching of model calixarene amide **14**: $\nu(\text{CH}) = 2964 \text{ cm}^{-1}$ and $\nu(\text{C=O}) = 1680 \text{ cm}^{-1}$. From the CHN analysis, only ~17% calixarene loading was achieved, which may be due to the steric bulkiness of the calixarene fragment.

- (26) Usually, exchange studies follow guest's motion in and out of the cavity, see: (a) Cram, D. J.; Blanda, M. T.; Paek, K.; Knobler, C. B. *J. Am. Chem. Soc.* **1992**, *114*, 7765–7773. (b) Mogck, O.; Pons, M.; Böhmer, V.; Vogt, W. *J. Am. Chem. Soc.* **1997**, *119*, 5706–5712. See also ref. 23. In competition experiments, involving two or more different guest molecules, these replace each other within one given host-container, see: (a) Santamaria, J.; Martin, T.; Hilmersson, G.; Craig, S. L.; Rebek, J., Jr. *Proc. Natl. Acad. Sci. U.S.A.* **1999**, *96*, 8344–8347. (b) Heinz, T.; Rudkevich, D. M.; Rebek, J., Jr. *Nature* **1998**, *394*, 764–766. (c) Tucci, F. C.; Rudkevich, D. M.; Rebek, J., Jr. *J. Am. Chem. Soc.* **1999**, *121*, 4928–4929. For a combinatorial selection of capsules for one given guest see: Hof, F.; Nuckolls, C.; Rebek, J., Jr. *J. Am. Chem. Soc.* **2000**, *122*, 4251–4252.
- (27) Recent papers: (a) Filippini, D.; Rösch, M.; Aragón, R.; Weimar, U. *Sensors & Actuators B* **2001**, *81*, 83–87. (b) Steffes, H.; Imawan, C.; Solzbacher, F.; Obermeier, E. *Sensors & Actuators B* **2001**, *78*, 106–112. (c) Pijolat, C.; Pupier, C.; Sauvan, M.; Tournier, G.; Lalauze, R. *Sensors & Actuators B* **1999**, *59*, 195–202. (d) Law, M.; Kind, H.; Messer, B.; Kim, F.; Yang, P. *Angew. Chem., Int. Ed. Engl.* **2002**, *41*, 2405–2408.
- (28) Recent optical sensors for NO₂: (a) Bradford, A.; Drake, P. L.; Worsfold, O.; Peterson, I. R.; Walton, D. J.; Price, G. J. *Phys. Chem. Chem. Phys.* **2001**, *3*, 1750–1754. (b) Dooling, C. M.; Worsfold, O.; Richardson, T. H.; Tregonning, R.; Vysotsky, M. O.; Hunter, C. A.; Kato, K.; Shinbo, K.; Kaneko, F. *J. Mater. Chem.* **2001**, *11*, 392–398. (c) Baldini, F.; Capobianchi, A.; Falai, A.; Mencaglia, A. A.; Pennesi, G. *Sensors & Actuators B* **2001**, *74*, 12–17. (d) Nezel, T.; Fakler, A.; Zhylyak, G.; Mohr, G. J.; Spichiger-Keller, U. E. *Sensors & Actuators B* **2000**, *70*, 165–169. (e) Capone, S.; Mongelli, S.; Rella, R.; Siciliano, P.; Valli, L. *Langmuir* **1999**, *15*, 1748–1753. (f) Tanaka, T.; Ohya, T.; Maruo, Y. Y.; Hayashi, T. *Sensors & Actuators B* **1998**, *47*, 65–69. (g) Hu, W. P.; Liu, Y. Q.; Liu, S. G.; Zhou, S. Q.; Zhu, D. B. *Supramolecular Science* **1998**, *5*, 507–510.

- (29) For a typical procedure, see: Iwamoto, K.; Fujimoto, K.; Matsuda, T.; Shinkai, S. *Tetrahedron Lett.* **1990**, *31*, 7169–7172.

In the NO₂ entrapment experiments, stream of the gas was passed through Pasteur pipets, loaded with silica gel **15** (Figure 10). In one pipet, dry silica gel **15** was loaded, and the other contained **15** preliminary wetted with CHCl₃. Both silica gels instantly turned dark purple, indicating the NO⁺ complexation. The color of the wetted material appeared to be deeper and it stayed for hours. The dry material bleached within minutes. The FTIR spectrum, recorded in KBr disks, gave weak but reproducible stretch at $\nu \approx 1920\text{ cm}^{-1}$, indicating the presence arene-NO⁺ complexes. No coloration was observed for the pipet loaded with the starting, 3-aminopropylated silica gel. This once again emphasizes the role of calixarene cavities in the described processes.

Although requiring further synthetic optimization, silica gel **15** may still be used for NO₂ detection and even for purification of other nitrogen oxides, especially NO.

Nitrosating Reagents. Described in this paper, processes involve chemical fixation of nitrogen dioxide (NO₂)—its conversion to encapsulated nitrosonium (NO⁺) complexes, and subsequent NO⁺ transfer to the substrate. We noticed, that primary and secondary amides also reacted with **7** and **8**, which implies that these complexes may act as *nitrosating reagents*.

It is known, that reactions between NO⁺ generating agents (e.g., NOCl, N₂O₃, NO₂/N₂O₄, nitrosonium salts, etc.) and amides and short peptides proceed via *N*-nitrosation and yield biologically important nitroso-derivatives.³⁰ Nitrosation of peptides may be used in analytical protocols of protein sequencing. More importantly however, these reactions have a biological relevance, because NO_x are widely spread atmospheric pollutants and frequently interact with biological tissues and fluids.³¹ The corresponding reaction mechanisms typically incorporate an electrophilic attack of NO⁺ on a nucleophilic oxygen or nitrogen of the substrate.³²

Preparatively, 1,3-*alternate* based nitrosonium complex **8** was mixed with AlkC(O)NHMe **16a–c** (Alk = *n*-Pr, *n*-Hex, *n*-Hept) in dry CHCl₃ and stirred at room temperature for several hours (Figure 11). The corresponding *N*-nitrosoamides AlkC(O)N(NO)Me (**17a–c**) were formed in 30–40% yield. Under the same conditions, the *cone* calixarene complex **7** reacts very slow, and only traces of the *N*-nitrosoamide products were detected by ¹H NMR spectroscopy. Likewise with water, *t*-Bu groups at the upper rim of **7**, probably, impose steric hindrances and protect the encapsulated NO⁺ species from the substrate. The

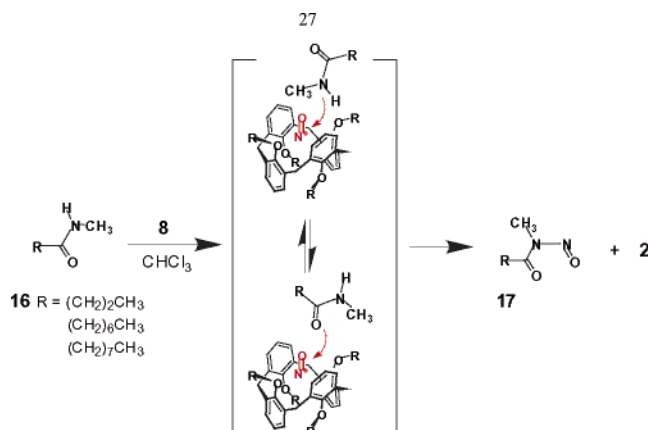


Figure 11. *N*-Nitrosation of secondary amides **16a–c** with complex **8**; formation of *N*-nitrosoamides **17a–c**. Two probable prereactive complexes are depicted.

rate limiting formation of the nitroso intermediates, most probably, should take place within the calixarene cavity, prior to the NO⁺ dissociation. Once formed, these sterically bulky species leave the interior, and undergo further transformations in bulk solution.

These transformations provide with an additional structural evidence for the discovered calixarene-NO⁺ complexes. More important however, they open new perspectives to use calixarenes as supramolecular/encapsulated nitrosating reagents.³³ Here, we refer to *encapsulated reagents* as to highly reactive species, reversibly entrapped within the host cavity, which can be released to the reaction mixture under subtle control.³⁴ The cavity offers protection from the bulk environment and thus controls the reaction rates. Reactions with encapsulated reagents may occur either within the cavity interior, or outside, upon release. As far as delicate, noncovalent forces holding the molecule-within-molecule complex together are concerned, temperature, solvent polarity and the *substrate-cavity size-shape fit* are the critical factors responsible for the reagent release and for the reaction to occur. Described here, complexes may serve as such unique encapsulated reagents for nitrosation. Supramolecular effects in these processes must be much more pronounced in *deeper* calixarenes,^{4c} where the cavities could accommodate the reaction intermediates. We are currently preparing such structures and will report on the results in the future.

Summary and Outlook

A novel NO₂ sensing and fixation process is now available, which employs simple calix[4]arenes. Calixarenes conveniently transmit the information about NO₂ binding via visible light signals. The described charge-transfer interactions are unique for NO₂ and would guaranty its detection in the presence of such gases as H₂O, O₂, HCl, SO_x, NH₃, and even NO. In principle, the resulting complexes can be used as vehicles for nitrosonium transfer and encapsulated nitrosating reagents.

- (30) (a) Wang, P. G.; Xian, M.; Tang, X.; Wu, X.; Wen, Z.; Cai, T.; Janczuk, A. *J. Chem. Rev.* **2002**, *102*, 1091–1134. (b) Garcia, J.; Gonzalez, J.; Segura, R.; Vilarrasa, J. *Tetrahedron* **1984**, *40*, 3121–3127 and literature therein.
- (31) (a) Hood, D. B.; Gettins, P.; Johnson, D. A. *Arch. Biochem. Biophys.* **1991**, *304*, 17–26. (b) Espey, M. G.; Miranda, K. M.; Thomas, D. D.; Wink, D. A. *J. Biol. Chem.* **2001**, *276*, 30 085–30 091. (c) Itoh, T.; Nagata, K.; Matsuya, Y.; Miyazaki, M.; Ohsawa, A. *Tetrahedron Lett.* **1997**, *38*, 5017–5020.
- (32) (a) Darbeau, R. W.; Pease, R. S.; Perez, E. V. *J. Org. Chem.* **2002**, *67*, 2942–2947. (b) White, E. H. *J. Am. Chem. Soc.* **1955**, *77*, 6008–6010. *N*-Nitrosation of amides may occur via two pathways. The first mechanism includes a direct attack by the lone pair of electrons of the amide nitrogen on the nitrosating agent. Subsequent deprotonation of the resulting ammonium ion yields the corresponding *N*-nitrosoamide. This mechanism is somewhat questionable, because the nonbonding pair of electrons on the amide nitrogen is delocalized over the N–C–O system. In addition, the *N*-protonated nitrosoamide intermediate is a high-energy species because the positive charge on the nitrogen is adjacent to both a carbonyl and a nitrosyl group, possessing significant positive dipoles. The more likely mechanism involves attack by the carbonyl oxygen on the nitrosating agent to generate the *O*-nitroso species. Rapid deprotonation, rotation around the C–O bond and inversion through the nitrogen derives the intermediate, in which both the nitrogen lone pair and the NO group are properly oriented for the isomerization to the *N*-nitrosoamide.

- (33) NO₂/N₂O₄ is known to react with 18-crown-6 with the formation of the crown-NO⁺ complex. This was used in *N*-nitrosation of amines, see: Zolfigol, M. A.; Zebajadian, M. H.; Chehardoli, G.; Keypour, H.; Salehzadeh, S.; Shamsipur, M. *J. Org. Chem.* **2001**, *66*, 3619–3620.
- (34) For rare examples of encapsulated reagents, see: (a) Chen, J.; Körner, S.; Craig, S. L.; Rudkevich, D. M.; Rebek, J., Jr. *Nature* **2002**, *415*, 385–386 (encapsulated DCC). (b) Körner, S. K.; Tucci, F. C.; Rudkevich, D. M.; Heinz, T.; Rebek, J., Jr. *Chem. Eur. J.* **2000**, *6*, 187–195 (encapsulated benzoyl peroxide).

These findings open wider possibilities toward more sophisticated NO₂/NO_x sensing and storing materials. We are currently exploring all these directions.

Experimental Section

General. Melting points were determined on a Mel-Temp apparatus (Laboratory Devices, Inc.) and a Buchi apparatus and are uncorrected. ¹H and ¹³C NMR spectra were recorded in CDCl₃ at 295 ± 1 °C, unless stated otherwise, on JEOL Eclipse 500 MHz spectrometer. Chemical shifts were measured relative to residual nondeuterated solvent resonances. FTIR spectra were recorded on a Bruker Vector 22 FTIR spectrometer. UV–vis spectra were measured on a JASCO V-530 spectrophotometer. Matrix-assisted laser desorption/ionization mass spectrometry (MALDI-TOF) was performed on a Bruker BiFLEX I linear time-of-flight mass spectrometer operated in delayed extraction mode. Elemental analysis was performed on a Perkin-Elmer 2400 CHN analyzer. For column chromatography, Silica Gel 60 Å (Sorbent Technologies, Inc.; 200–425 mesh) was used. All experiments with moisture- or air-sensitive compounds were run in freshly distilled, anhydrous solvents under a dried nitrogen atmosphere. Molecular modeling was performed using MacroModel 7.1.¹⁷

Parent tetrahydroxycalix[4]arenes were prepared according to the published procedures.³⁵ NO₂/N₂O₄ was generated from copper and concentrated HNO₃ or sodium nitrate and concentrated H₂SO₄. **Caution:** NO₂ has an irritating odor and is very toxic.

25,26,27,28-Tetra (*n*-hexyloxy)calix[4]arene-1,3-alternate (2). To a suspension of 25,27,26,28-tetrahydroxycalix[4]arene^{35b} (4.24 g, 0.01 mol) and K₂CO₃ (4.2 g, 0.03 mol) in MeCN (200 mL) *n*-hexylbromide (4.2 mL, 0.03 mol) was added, and the reaction mixture was refluxed under nitrogen for 48 h. The precipitate was filtered off, and the solution was evaporated to dryness. The residue was redissolved in CH₂Cl₂ (200 mL), and the solution was washed with water (3 × 150 mL) and dried over MgSO₄. After evaporation, the solid residue was treated with MeOH (200 mL) to yield pure 25,27-bis(*n*-hexyloxy)-26,28-dihydroxycalix[4]arene as a white solid (5.0 g, 84%). ¹H NMR: δ 8.23 (bs, 2 H), 7.06 (d, *J* = 8 Hz, 4 H), 6.91 (d, *J* = 8 Hz, 4 H), 6.73 (t, *J* = 8 Hz, 2 H), 6.65 (t, *J* = 8 Hz, 2 H), 4.32 (d, *J* = 13 Hz, 4 H), 4.00 (t, *J* = 7 Hz, 4 H), 3.37 (d, *J* = 13 Hz, 4 H), 2.1–2.0 (m, 4 H), 1.75–1.7 (m, 4 H), 1.45–1.4 (m, 8 H), 0.95 (t, *J* = 7 Hz, 6 H). To a suspension of 25,27-bis(*n*-hexyloxy)-26,28-dihydroxycalix[4]arene (5.92 g, 0.01 mol) and Cs₂CO₃ (50 g, 0.15 mol) in MeCN (300 mL) *n*-hexylbromide (5.74 mL, 0.04 mol) was added, and the reaction mixture was refluxed under nitrogen for 48 h. After cooling, the precipitate was filtered off and treated with a mixture of water (100 mL) and CH₂Cl₂ (100 mL). The organic layer was separated, washed with water (2 × 100 mL), dried over MgSO₄, and evaporated. The residue was recrystallized from MeOH–CHCl₃, 10:1 to give pure **2** (3.50 g, 46%). Mp 119 °C; ¹H NMR: δ 6.92 (d, *J* = 7.5 Hz, 8 H), 6.68 (t, *J* = 7.5 Hz, 4 H), 3.62 (s, 8 H), 3.54 (t, *J* = 7.5 Hz, 8 H), 1.89 (m, 8 H), 1.35 (m, 24 H), 0.85 (t, *J* = 7 Hz, 12 H); MALDI-TOF MS, *m/z* 783.9 ([M+Na⁺], calcd for C₅₂H₇₂O₄ 783.9). Anal. Calcd for C₅₂H₇₂O₄: C, 82.06; H, 9.53. Found: C, 81.61; H, 9.58.

5,11,17,23-Tetrabromo-25,26,27,28-tetrakis(*n*-hexyloxy)calix[4]arene-1,3-alternate (3). *N*-Bromosuccinimide (3.0 g, 0.017 mol) was added to a suspension of calixarene **2** (2.0 g, 2.6 mmol) in acetone (500 mL), and the mixture was stirred at room temperature for 48 h exposed to the laboratory light. The formed solid was filtered off, washed with acetone (2 × 100 mL) and used in the next step without further purification. Yield 1.5 g (53%). ¹H NMR: δ 7.12 (s, 8 H), 3.56 (s, 8 H), 3.52 (t, *J* = 7.5 Hz, 8 H), 1.6–1.4 (m, 8 H), 1.4–1.3 (m, 24 H), 0.93 (t, *J* = 7 Hz, 12 H).

5,11,17,23-Tetrahydroxy-25,26,27,28-tetrakis(*n*-hexyloxy)calix[4]arene-1,3-alternate (4). To a solution of tetrabromo derivative **3** (0.9

g, 0.83 mmol) in freshly distilled over Na and oxygen-free THF (150 mL) *n*-BuLi (30 mL of 2M solution in pentane, 60 mmol) was added at –78 °C, and the mixture was stirred at this temperature for 75 min. Trimethyl borate (14 mL, 145 mmol) was then added at –78 °C, and the mixture was allowed to warm to room temperature. After 5 h, the reaction mixture was cooled again to –78 °C, and H₂O₂ (15 mL of 30% aq solution) and NaOH (35 mL of 3N aq solution) was added. The resulting solution was stirred overnight at room temperature, after which the precipitate was filtered off. The mother liquor was cooled to 0 °C and treated with Na₂S₂O₃ (25 g), after which the mixture was filtered and the filtrate was concentrated in vacuo. The residue was treated with 5% aq HCl (100 mL), and the colorless precipitate of **4** was filtered off and washed with MeOH (50 mL). Yield 0.274 g (40%). Mp 230 °C; ¹H NMR (DMSO-*d*₆): δ 8.39 (bs, 4 H), 6.34 (s, 8 H), 3.50 (s, 8 H), 3.02 (t, *J* = 7.5 Hz, 8 H), 1.3–1.25 (m, 8 H), 1.25–1.1 (m, 16 H), 1.1–1.0 (m, 8 H), 0.87 (t, *J* = 7 Hz, 12 H); MALDI-TOF MS, *m/z* 847 ([M+Na⁺], Calcd for C₅₂H₇₂O₈ 847).

5,11,17,23,25,26,27,28-Octa(*n*-hexyloxy)calix[4]arene-1,3-alternate (5). To a suspension of **4** (0.3 g, 0.36 mmol) and NaH (0.15 g of 60% (wt.) suspension in mineral oil, 3.6 mmol) in freshly distilled DMF (50 mL) *n*-hexylbromide (0.46 mL, 3.2 mmol) was added, and the reaction mixture was stirred at 70 °C under nitrogen for 24 h. The precipitate was filtered off, and the mother liquor was treated with a mixture of crushed ice (50 g), water (50 mL) and CH₂Cl₂ (100 mL). The organic layer was separated, washed with water (2 × 100 mL), dried over MgSO₄ and evaporated. The residue was recrystallized from MeOH–CHCl₃, 10:1 to yield calixarene **5** (0.35 g, 85%). Mp 111 °C, ¹H NMR: δ 6.55 (s, 8 H), 3.83 (t, *J* = 7 Hz, 8 H), 3.62 (s, 8 H), 3.35 (t, *J* = 7 Hz, 8 H), 1.7 (m, 16 H), 1.4–1.2 (m, 48 H), 0.89 (t, *J* = 7 Hz, 24 H); ¹³C NMR: δ 153.6, 150.7, 134.4, 115.2, 71.6, 68.1, 37.8, 32.3, 31.8, 29.8, 26.0, 25.9, 22.9, 22.7, 14.3, 14.1; MALDI-TOF MS, *m/z* 1182 ([M+Na⁺], Calcd for C₇₆H₁₂₀O₈ 1183).

Tetrakis(*O*-*n*-hexyloxy)cyclophane (6). NaH (0.11 g of 60% suspension in mineral oil, 2.7 mmol) was added to the solution of Pappalardo's cyclophane^{15,16} (0.2 g, 0.34 mmol) in freshly distilled DMF (20 mL), and the mixture was stirred under nitrogen for 30 min. *n*-Hexylbromide (0.3 mL, 2.04 mmol) was then added, and the reaction mixture was stirred at 70 °C for 3 d. The precipitate was collected and dissolved in CH₂Cl₂ (20 mL). The solution was washed with water (3 × 20 mL), dried over MgSO₄ and evaporated. The residue was recrystallized from MeOH–CHCl₃ to afford **6** as a white powder. Yield 0.157 g (50%); ¹H NMR: δ 3.89 (s, 8 H), 3.58 (t, *J* = 7 Hz, 8 H), 2.30 (s, 24 H), 1.8–1.7 (m, 8 H), 1.6–1.5 (m, 16 H), 1.4–1.35 (m, 8 H), 1.07 (s, 12 H), 0.91 (t, *J* = 7 Hz, 12 H); ¹³C NMR: δ 153.9, 138.4, 131.4, 126.7, 73.2, 32.8, 32.0, 30.4, 26.0, 22.8, 17.7, 14.2, 13.7. Anal. Calcd for C₆₄H₉₆O₄: C 82.70; H 10.41. Found: C, 82.37; H, 10.25.

Preparation of Calix[4]arene-Nitrosonium Complexes. Procedure 1. Stock solutions of NO₂ were freshly prepared upon bubbling through CHCl₃; the gas concentration was determined gravimetrically. In a typical procedure, solution of calixarene **1** (1 eq) in dry, freshly distilled CHCl₃ was mixed with the stock solution of NO₂ (~3 eq) in CHCl₃ and SnCl₄ (1.5 eq) at room temperature. After 1 h, complex **7** was precipitated upon addition of hexane, filtered off, washed with hexane (2×), and dried in vacuo. ¹H NMR: δ 6.99 (s, 8 H), 4.39 (d, *J* = 13 Hz, 4 H), 4.02 (t, *J* = 7.5 Hz, 8 H), 3.44 (d, *J* = 13 Hz, 4 H), 2.0–1.9 (m, 8 H), 1.5–1.3 (m, 24 H), 0.93 (t, *J* = 7 Hz, 12 H); UV–vis (CHCl₃): λ_{max} 563; FTIR (CDCl₃): ν 1923 (NO⁺), 1461, 1298, 1047 (NO₃[–]); Anal. Calcd for C₆₈H₁₀₄O₄·NO⁺NO₃[–]·1.8SnCl₄: C, 52.81; N, 1.81; H, 6.78. Found: C, 52.60; N, 1.67; H, 7.55. Complex **8** was obtained analogously: ¹H NMR: δ 7.17 (t, *J* = 7.5 Hz, 4 H), 7.08 (d, *J* = 7.5 Hz, 8 H), 3.87 (t, *J* = 7.5 Hz, 8 H), 3.60 (s, 8 H), 1.9–1.8 (m, 8 H), 1.4–1.3 (m, 24 H), 0.93 (t, *J* = 7 Hz, 12 H); UV–vis (CHCl₃): λ_{max} 524 nm; FTIR (CDCl₃): ν 1955 (NO⁺), 1438, 1246, 1091 (NO₃[–]); Anal. Calcd for C₅₂H₇₂O₄·NO⁺NO₃[–]·1.5SnCl₄: C, 50.21; N, 2.25; H, 5.83. Found: C, 50.23; N, 1.82; H, 5.99. Complex **9** cannot be prepared using this protocol; only dealkylation/oxidation products were detected.

(35) (a) Gutsche, C. D.; Iqbal, M. *Org. Synth.* **1990**, *68*, 234–237. (b) Gutsche, C. D.; Levine, J. A.; Sujeeth, P. K. *J. Org. Chem.* **1985**, *50*, 5802–5806.

For spectroscopic characterization, complex **9** was generated in the exchange experiment between nitrosonium complex **8** and free calix-arene **5**, as depicted in Figure 7.

Procedure 2. Calix[4]arene-nitrosonium complexes were obtained upon mixing **1,2** or **5** with an excess $\text{NO}^+\text{SbF}_6^-$ in dry CHCl_3 . Complexes **1**· $\text{NO}^+\text{SbF}_6^-$ and **2**· $\text{NO}^+\text{SbF}_6^-$ formed within 20 h. The UV-vis, FTIR and ^1H NMR spectra are identical with the respective complexes **7** and **8**. Complex **5**· $\text{NO}^+\text{SbF}_6^-$ formed immediately upon mixing: ^1H NMR: δ 6.54 (s, 8 H), 3.93 (t, $J = 7.5$ Hz, 8 H), 3.76 (t, $J = 7.5$ Hz, 8 H), 3.44 (s, 8 H), 1.8–1.75 (m, 8 H), 1.9–1.8 (m, 8 H), 1.5–1.2 (m, 48 H), 0.95 (t, $J = 7$ Hz, 12 H), 0.89 (t, $J = 7.5$ Hz, 12 H); UV-vis (CHCl_3): λ_{max} 600; FTIR (CDCl_3): ν (NO^+) 1876.

25-Hydroxy-26,27,28-trihexyloxy-*p*-tert-butylcalix[4]arene (10). A mixture of 25,26,27,28-tetrahydroxy-*p*-tert-butylcalix[4]arene^{35a} (4.0 g, 6.2 mmol), freshly distilled anhydrous DMF (80 mL), $\text{Ba}(\text{OH})_2 \cdot 8\text{H}_2\text{O}$ (6.8 g, 21.6 mmol), and BaO (6.36 g, 41.5 mmol) was stirred at room temperature for 15 min. *n*-Hexylbromide (21 mL, 184 mmol) was added, and the suspension was stirred at room temperature for another 12 h. The mixture was diluted with water (100 mL), and the product was extracted with CH_2Cl_2 (3×100 mL). The organic layer was washed with water (2×100 mL), dried over Na_2SO_4 and evaporated under reduced pressure. The residue was recrystallized from MeOH to give pure **10** as a white solid. Yield 69%; mp 134–136 °C; ^1H NMR: δ 7.11 (s, 2 H), 7.03 (s, 2 H), 6.51 (d, $J = 2.3$ Hz, 2 H), 6.49 (d, $J = 2.3$ Hz, 2 H), 5.72 (s, 1 H), 4.36 (d, $J = 13$ Hz, 2 H), 4.32 (d, $J = 13$ Hz, 2 H), 3.89 (t, $J = 8$ Hz, 2 H), 3.78 (t, $J = 8$ Hz, 4 H), 3.22 (d, $J = 13$ Hz, 2 H), 3.16 (d, $J = 13$ Hz, 2 H), 2.3–2.2 (m, 2 H), 2.0–1.8 (m, 4 H), 1.4–1.3 (m, 18 H), 1.32 (s, 9 H), 1.31 (s, 9 H), 0.92 (t, $J = 7$ Hz, 3H), 0.90 (m, 6 H), 0.81 (s, 18 H).

25-[(Ethoxycarbonyl)methoxy]-26,27,28-trihexyloxy-*p*-tert-butylcalix[4]arene (11). A mixture of calix[4]arene **10** (5.0 g, 5.6 mmol) and Na_2CO_3 (10.0 g, 94 mmol) in CH_3CN (150 mL) was refluxed for 15 min, after which ethyl bromoacetate (10 mL, 90 mmol) was added, and the reflux continued for 12 h. The inorganic salts were filtered, and the solvent was evaporated. The residue was dissolved in CH_2Cl_2 (100 mL) and washed with water (3×50 mL). The solvent was evaporated, and the product was recrystallized from MeOH. Yield 89%; mp 121–123 °C; ^1H NMR: δ 6.91 (s, 2 H), 6.90 (s, 2 H), 6.63 (d, $J = 2$ Hz, 2 H), 6.61 (d, $J = 2$ Hz, 2 H), 4.86 (s, 2 H), 4.66 (d, $J = 12.5$ Hz, 2 H), 4.38 (d, $J = 12.5$ Hz, 2 H), 4.18 (q, $J = 7$ Hz, 2 H), 3.83 (t, $J = 8$ Hz, 4 H), 3.75 (t, $J = 8$ Hz, 2 H), 3.15 (d, $J = 12.5$ Hz, 2 H), 3.10 (d, $J = 12.5$ Hz, 2 H), 2.2–2.1 (m, 2 H), 2.0–1.9 (m, 4 H), 1.4–1.3 (m, 18 H), 1.27 (t, $J = 7$ Hz, 3 H), 1.18 (s, 9 H), 1.17 (s, 9 H), 0.96 (s, 18 H), 0.9–0.8 (m, 9 H).

25-(Carbomethoxy)-26,27,28-trihexyloxy-*p*-tert-butylcalix[4]arene (12). A mixture of **11** (2.0 g 2 mmol), $\text{THF-H}_2\text{O}$, 5:1 (100 mL) and KOH (1.0 g, 17.8 mmol) was refluxed for 12 h. The pH was adjusted to 4 with aq 2 M HCl. The product was extracted with CH_2Cl_2 (2×50 mL), and the organic layer was dried over Na_2SO_4 and evaporated to give **12** as a white solid. Yield > 95%; mp 136–137 °C; ^1H NMR: δ 11.28 (s, 1 H), 7.16 (s, 2 H), 7.14 (s, 2 H), 6.59 (d, $J = 2.5$ Hz, 2 H), 6.49 (d, $J = 2.5$ Hz, 2 H), 4.67 (s, 2 H), 4.45 (d, $J = 12$ Hz, 2 H), 4.23 (d, $J = 12$ Hz, 2 H), 4.08 (t, $J = 7$ Hz, 2 H), 3.8–3.7 (m, 4H), 3.24 (d, $J = 12$ Hz, 2 H), 3.16 (d, $J = 12$ Hz, 2 H), 1.95–1.8 (m, 6 H), 1.45–1.2 (m, 18 H), 0.90 (t, $J = 7$ Hz, 9 H), 0.83 (s, 18 H); MALDI-TOF MS, m/z 959.2 (M^+ , Calcd for $\text{C}_{64}\text{H}_{94}\text{O}_6$ 960.4). Anal. Calcd for $\text{C}_{64}\text{H}_{94}\text{O}_6$: C 80.12; H 9.88. Found: C, 80.27; H, 9.88.

***N*-Succinimide Ester of 25-(Carbomethoxy)-26,27,28-trihexyloxy-*p*-tert-butylcalix[4]arene (13).** A suspension of **12** (1.0 g, 1.05 mmol), *N*-hydroxy succinimide (1.0 g, 8.70 mmol), DCC (210 mg 1.05 mmol) and DMAP (40 mg, 0.32 mmol) in THF (50 mL) was stirred at room temperature for 12 h under nitrogen. After filtration, the solvent was evaporated, and the residue was redissolved in hexane (50 mL) and filtered again. The hexane solution was evaporated and the residue was purified by column chromatography (CH_2Cl_2 -hexane, 1:1) to afford **13** as a white solid. Yield 83%; mp 75–78 °C; ^1H NMR: δ 6.95 (s, 2 H),

6.92 (s, 2 H), 6.62 (d, $J = 2.5$ Hz, 2 H), 6.56 (d, $J = 2.5$ Hz, 2 H), 5.28 (s, 2 H), 4.56 (d, $J = 13$ Hz, 2 H), 4.41 (d, $J = 13$ Hz, 2 H), 3.89 (t, $J = 8$ Hz, 2 H), 3.79 (t, $J = 8$ Hz, 2 H), 3.75 (t, $J = 8$ Hz, 2 H), 3.18 (d, $J = 13$ Hz, 2 H), 3.12 (d, $J = 13$ Hz, 2 H), 2.82 (s, 4 H), 2.15–2.1 (m, 2 H), 1.95–1.85 (m, 4 H), 1.45–1.35 (m, 18 H), 1.20, 1.19 ($2 \times$ s, 18 H), 0.93 (s, 18 H), 0.9–0.8 (m, 9 H). Ester **13** appeared to be relatively unstable, and attempts to obtain the MALDI-TOF and/or CHN analytical data failed. The structure of **13** was confirmed through its transformation to calixarene amide **14**.

25-[(*n*-Octylcarbamoylmethoxy)-26,27,28-trihexyloxy-*p*-tert-butylcalix[4]arene (14). To the solution of ester **13** (75 mg, 70 μmol) in THF (10 mL), *n*-octylamine (18 mg, 0.14 mmol) and Et_3N (70 mg, 0.7 mmol) were added, and the reaction mixture was stirred at room temperature for 12 h. The precipitate was filtered off, and the solution was evaporated. The residue was redissolved in CH_2Cl_2 (20 mL), washed with 2 M aq HCl (2×5 mL) and water (5 mL), and dried over Na_2SO_4 . The organic layer was then evaporated and the residue was recrystallized from CH_3CN to afford **14** as a white solid. Yield 65%; ^1H NMR: δ 8.43 (t, $J = 6$ Hz, 1 H), 6.99 (s, 2 H), 6.97 (s, 2 H), 6.57 (s, 4 H), 4.71 (s, 2 H), 4.38, 4.35 ($2 \times$ d, $J = 13$ Hz, 4 H), 3.9–3.7 ($2 \times$ m, 6 H), 3.42 (dt, $J = 6$ Hz, $J = 7$ Hz, 2 H), 3.23 (d, $J = 13$ Hz, 2 H), 3.14 (d, $J = 13$ Hz, 2 H), 2.0–1.8 ($3 \times$ m, 8 H), 1.5–1.3 (m, 30 H), 1.25 (s, 9 H), 1.23 (s, 9 H), 0.93 (s, 18 H), 0.95–0.85 (m, 12 H). FTIR (KBr): ν 3346 (NH), 2964, 1680 (C=O), 1537, 1473. Anal. Calcd for $\text{C}_{72}\text{H}_{111}\text{NO}_5 \cdot 0.5\text{CH}_3\text{CN}$: C, 80.35; H, 10.39; N, 1.93. Found: C 80.02; H 10.09; N, 1.91. Compound **14** was also independently synthesized from the acid chloride of **12** (prepared with SOCl_2), *n*-octylamine and Et_3N in CHCl_3 .

Calix[4]arene Functionalized Silica Gel (15). A suspension of ester **13** (100 mg, 95 μmol), 3-aminopropyl-functionalized silica gel (Aldrich) (226 mg, 155 μmol) and Et_3N (92.9 mg, 0.92 mmol) in THF (50 mL) was stirred at room temperature for 12 h. The solid was filtered off, washed with CH_2Cl_2 , MeOH, water, MeCN, and THF, and then dried under reduced pressure for 3 days. Afford white powder. FTIR (KBr): ν 3383, 2960, 1650, 1556, 1477. Anal. Found for 3-aminopropyl silica gel (0.687 meq/g, $\text{C}_9\text{H}_{23}\text{NO}_3\text{Si}$): C, 7.42; H, 1.80; N, 1.91. Anal. Calcd for silica gel **15** (17% loading, 0.117 meq/g, $\text{C}_{73}\text{H}_{115}\text{NO}_6\text{Si}$): C, 15.43; H, 2.68; N, 1.82. Found: C 15.34; H 2.97; N, 1.70.

***N*-Nitrosation of Amides by Calix[4]arene-Nitrosonium Complexes; General Procedure. Caution: *N*-Nitrosoamides are Potential Carcinogens and Should be Treated with Extreme Care.**³⁶ Complex **8** (1 eq) was added to the solution of amide $\text{AlkC}(\text{O})\text{NHMe}$ **16a–c** (2–3 eq) in freshly distilled CHCl_3 , and the reaction mixture was stirred at room temperature for 5 h. The solvent was evaporated, and the residue was analyzed by ^1H NMR spectroscopy and further separated by preparative TLC. The spectral data for the obtained *N*-nitroso compounds $\text{AlkC}(\text{O})\text{N}(\text{NO})\text{Me}$ **17a–c** were identical with those independently obtained from $\text{AlkC}(\text{O})\text{NHMe}$ and $\text{NO}_2/\text{N}_2\text{O}_4$ or $\text{NO}^+\text{SbF}_6^-$, and also previously published.³⁷ $\text{CH}_3(\text{CH}_2)_6\text{C}(\text{O})\text{NHCH}_3$ (**16b**): ^1H NMR: δ 6.13 (bs, 1 H, NH), 2.73 (d, $J = 5$ Hz, 3 H, N-CH_3), 2.13 (t, $J = 7.5$ Hz, 2 H, $\text{C}(\text{O})\text{CH}_2$), 1.6–1.5 (m, 2 H, CH_2), 1.3–1.1 (m, 8 H, CH_2), 0.83 (t, $J = 7.5$ Hz, 3 H, CH_3). $\text{CH}_3(\text{CH}_2)_6\text{C}(\text{O})\text{N}(\text{NO})\text{CH}_3$ (**17b**): ^1H NMR: δ 3.13 (t, $J = 8$ Hz, 2 H, $\text{C}(\text{O})\text{CH}_2$), 3.03 (s, 3 H, $\text{N}(\text{NO})\text{-CH}_3$), 1.8–1.7 (m, 2 H, CH_2), 1.4–1.2 (m, 8 H, CH_2), 0.84 (t, $J = 7.5$ Hz, 3 H, CH_3).

Acknowledgment. Financial support is acknowledged from the University of Texas at Arlington and, in part, from the donors of the Petroleum Research Fund, administered by the

- (36) (a) Mirvish, S. S. *Cancer Lett.* **1995**, 93, 17–48. (b) Hoffman, D.; Hoffman, I.; El-Bayoumy, K. *Chem. Res. Toxicol.* **2001**, 14, 767–790. (c) Pfeiffer, S.; Mayer, B.; Hemmens, B. *Angew. Chem., Int. Ed. Engl.* **1999**, 38, 1714–1731. (d) Tamir, S.; Burney, S.; Tannenbaum, S. R. *Chem. Res. Toxicol.* **1996**, 9, 821–827. (e) Lewis, R. S.; Tannenbaum, S. R.; Deen, W. M. *J. Am. Chem. Soc.* **1995**, 117, 3933–3939. (f) Kirsch, M.; Korth, H.-G.; Sustmann, R.; de Groot, H. *Chem. Res. Toxicol.* **2000**, 13, 451–461. (37) Garcia, J.; Gonzalez, J.; Segura, R.; Urpi, F.; Vilarrasa, J. *J. Org. Chem.* **1984**, 49, 3322–3327.

American Chemical Society. We are grateful to Prof. Gary R. Kinsel and Jiang Zhang for the expert MALDI-TOF analysis and also thank Stephen P. Stampp and Heng Xu for experimental advice. Prof. Wim Verboom is acknowledged for advice on the calix[4]arene preparation. We also thank Profs. V. G. Shubin

and M. Kirsch for providing reprints of their valuable work. This paper is dedicated to Prof. C. David Gutsche on the occasion of his retirement.

JA029166L