Synthesis of Calix[4]arene Triflates and Their Unusual Chemical Reactivity in Palladium-Catalyzed Reactions

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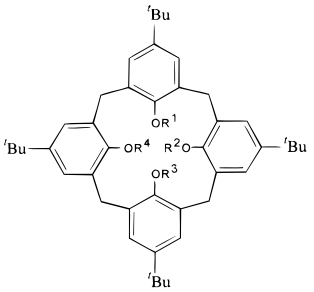
The formation of *p-tert*-butylcalix[4]arene mono-, bis-, tris-, and tetrakistriflates **3**, **2**, **4**, and **5**, respectively, and their respective reactions, under typical Pd-catalyzed carbonylative, Suzuki−Miyaura coupling, or deoxygenation conditions are described. A novel, nonsolvent-derived 1:1 clathrate (**6**) of benzophenone and **3** was formed from the palladium-catalyzed carbonylative reaction of phenylboronic acid and **2**. The X-ray crystal structure of this first nonsolvent-derived clathrate of a calix[4]arene derivative is reported. Another 1:1 clathrate of triethylamine and **3** was formed during the attempted Pd-catalyzed deoxygenation of **2**.

Introduction

Calixarenes continue to be the focus of considerable research activity since they are easily accessible compounds with interesting conformational, physicochemical, and complexation properties.[1,21,2] There are many examples of calix[4]arenes that have been modified either at the "lower rim" (phenolic hydroxyl bearing) or at the upper rim in order to assess and enhance their selectivity toward complexation of ionic or neutral species. Modifications of the upper rim are readily accessed by the sequential[3] or total removal[4] of the *tert*-butyl groups of *p-tert*-butylcalix[4]arene **1**. The majority of modifications of the lower rim, however, have involved attaching various substituents containing ether, keto, ester, and/or amide groups to the phenolic oxygens of the calix[4]arenes.[5] Lower-rim hydroxyl-depleted calixarenes have been obtained by reduction of phosphonates.[6] Recently, however, Biali et al.[7] developed novel methodologies to effect modification and/or removal of the phenolic hydroxyl groups via the spirodienone calix[4]arene derivatives.

The Stille[8] and Suzuki−Miyaura[9] coupling methods represent two different potentially very attractive one-step procedures for modification of the phenolic hydroxyl groups of calixarenes. There has been only one report involving an attempted application of a Stille coupling using the 1,3-bistriflate derivative of *p-tert*-butylcalix[4]arene **2**. Using typical Stille conditions, González et al.[10]



1: $R^1 = R^2 = R^3 = R^4 = H$
2: $R^1 = R^3 = Tf$, $R^2 = R^4 = H$
3: $R^1 = R^2 = R^3 = H$, $R^4 = Tf$
4: $R^1 = R^2 = R^3 = Tf$, $R^4 = H$
5: $R^1 = R^2 = R^3 = R^4 = Tf$
6: **3** : $(C_6H_5)_2CO$
7: **3** : $(C_2H_5)_3N$
9: $R^1 = R^3 = Nf$, $R^2 = R^4 = H$
10: $R^1 = R^2 = R^3 = H$, $R^4 = Nf$

reported an unprecedented intermolecular migration of the sulfonyl groups of **2**, without observing any of the desired coupling. The only reported application of the Suzuki−Miyaura coupling methodology with calixarenes is that of Dondoni et al.[11] Their report, however, described only *upper rim* functionalization, resulting in the synthesis of calix[4]arenylvinylene and calix[4]arenylphenylene oligomers by coupling reactions with de-*tert*-butylated precursor *p*-bromo- or *p*-iodocalix[4]arenes. More recently, Csók et al.[12] reported the synthesis and the dynamic NMR measurements of the triflate derivatives of various de-*tert*-butylated and *p-tert*-butylcalix[*n*]arenes ($n = 4, 6, 8$), including **2**. They found that **2** was conformationally rigid and also that it underwent hydrolysis in the presence of $Pd(PPh_3)_4$ to yield only the monotriflate **3**. These authors, however, failed to recognize or acknowledge the earlier work of González et al. on *p-tert*-butylcalix[4]arene triflates.

As part of our own investigations on the chemical modification of the lower rim of calix[4]naphthalenes[13] and calix[4]arenes, the chemistry of the triflates of the more readily accessible *p-tert*-butylcalix[4]arenes was first reexamined. We herein report the syntheses of the individual mono-, bis-, tris-, and tetrakiscalix[4]arene triflates and the unusual chemistry of these compounds.

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(1) Gutsche, C. D. *Calixarenes Revisited*; Royal Society of Chemistry, Cambridge, 1998.
(2) *Calixarenes 50th Anniversary: Commemorative Issue*; Vicens, J., Asfari, Z., Harrowfield, J. McB., Eds.; Kluwer Academic Publishers: Dordrecht, 1995.
(3) Rha, S. G.; Chang, S.-K. *J. Org. Chem.* **1998**, *63*, 2357−2359.
(4) Gutsche, C. D.; Levine, J. A.; Sujeeth, P. K. *J. Org. Chem.* **1985**, *50*, 5802−5806.
(5) See, e.g.: Ulrich, G.; Ziessel, R. *Tetrahedron Lett.* **1994**, *35*, 6299−6302.
(6) Goren, Z.; Biali, S. E. *J. Chem. Soc., Perkin Trans. 1* **1990**, 1484−1486.
(7) (a) Van Gelder, J. M.; Aleksuik, O.; Biali, S. E. *J. Org. Chem.* **1996**, *61*, 8419−8424. (b) Aleksuik, O.; Cohen, S.; Biali, S. E. *J. Am. Chem. Soc.* **1995**, *117*, 9645−9652.
(8) Stille, J. K. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 508−519.
(9) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457−2483.
(10) González, J. J.; Nieto, P. M.; Prados, P.; Echavarren, A. M.; de Mendoza, J. *J. Org. Chem.* **1995**, *60*, 7419−7423.
(11) Dondini, A.; Ghiglione, C.; Marra, A.; Scoponi, M. *J. Org. Chem.* **1998**, *63*, 9535−9539.
(12) Csók, Z.; Szalontai, G.; Czira, G.; Kollár, L. *Supramol. Chem.* **1998**, *10*, 69−77.
(13) Georghiou, P. E.; Ashram, M.; Clase, H. J.; Bridson, J. N. *J. Org. Chem.* **1998**, *63*, 1819−1826.

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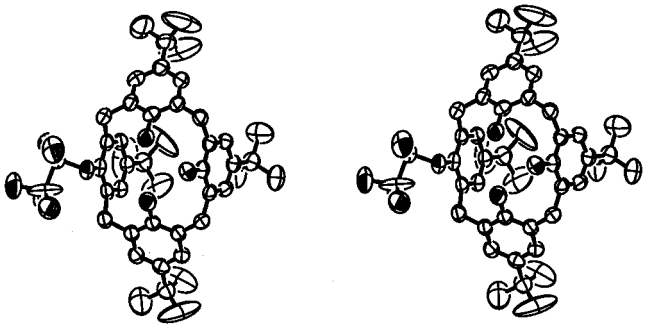

Figure 1. ORTEP stereoview of monotriflate **3**.

The reactions of these triflates are described under Suzuki–Miyaura coupling conditions and also under the deoxygenation conditions of Snieckus et al.[14] The formation of an unprecedented nonsolvent containing clathrate is also reported.

Results and Discussion

González et al.[10] and also Csók et al.[12] independently reported that they were only able to directly synthesize 1,3-bistriflate **2** but not monotriflate **3**, tristriflate **4**, or tetrakistriflate **5** using triflic anhydride with *p-tert*-butylcalix[4]arene **1** and a variety of bases. González obtained **3** and **4** indirectly, as the only products from the Stille reaction of **2**, whereas Csók obtained **3** by the Pd(0)-mediated hydrolysis of **2**.

We were able to successfully synthesize the individual triflates **2**–**5** using various stoichiometric ratios of triflic anhydride and NaH in either CH_2Cl_2 or THF as solvent. Thus, the bistriflate **2** was obtained in 69% yield from the reaction of **1** with 2.0 mol equiv of triflic anhydride and 2.0 mol equiv of NaH. Treatment of **1** with excess (6.0 mol equiv) NaH, produced an easily separable mixture of tristriflate **4** and tetrakistriflate **5** in 60% and 11% yields, respectively. Monotriflate **3** was synthesized directly in 72% yield using 1.1 mol equiv of triflic anhydride and 1.5 mol equiv of NaH. The X-ray structure of **3**[15] reveals that in the solid state its conformation is clearly a distorted C_{2v} "pinched-cone",[12] in which the plane of the triflate-bearing phenyl group is distorted *into* the cavity (Figure 1). The dihedral angle between the least-squares planes defined by the phenyl group bearing the triflate group and the distal phenyl group (Planes 1 and 3) is 6.8°. The dihedral angle between the least-squares planes defined by the other two phenyl groups (planes 2 and 4) is 70.39°.

The reaction of either **2**, **4**, or **5** with phenylboronic acid under Suzuki–Miyaura coupling conditions with $Pd(PPh_3)_4$, $PdCl_2$dppf, or $PdCl_2(PPh_3)_2$ did not produce the anticipated corresponding lower-rim phenyl group-functionalized products. Instead, from the reactions of either **2** or **4**, only monotriflate **3** was obtained, while from **5**, only unreacted starting material was recovered. Thus, under these conditions, Pd-catalyzed disproportionation of **2** to **3** occurred, a reaction which is similar to the disproportionation observed by González et al. using Stille conditions. Having failed to obtain the desired Pd-catalyzed cross-coupled products, Pd-catalyzed carbonylative coupling reactions[16] were examined using carbon monoxide/phenylboronic acid with **2**, **4**, and **5**. Insertion of a carbonyl group between the lower rim and the phenyl group derived from an arylboronic acid to form, e.g., aryl ketones would also be a desirable lower-rim functionalization of calix[4]arenes.

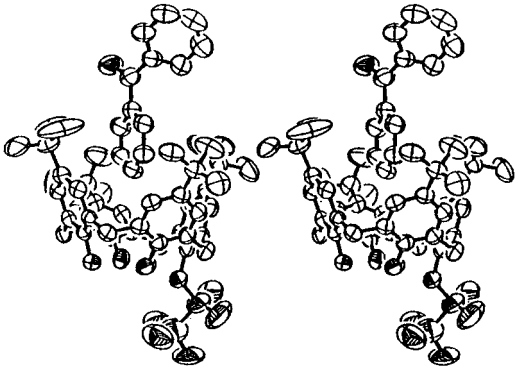

Figure 2. ORTEP stereoview of clathrate **6**.

Reaction of **4** or **5** with phenylboronic acid under Pd-catalyzed carbonylative conditions[17] failed to give any of the desired products. However, with **2** a crystalline product **6** (mp 262–264 °C) was obtained, whose NMR spectra in various solvents clearly indicated additional aromatic signals (10 ^{1}H signals; four ^{13}C signals) as well as a carbonyl group. The latter gave rise to an absorption at 1661 cm^{-1} (Nujol) in its ir spectrum. Definitive structural elucidation of this product was only obtained from its single-crystal X-ray data.[15] As can been seen from the X-ray structure shown in Figure 2, the product **6** is a 1:1 clathrate[18] formed between monotriflate **3** and benzophenone. It has one of the phenyl groups of the benzophenone situated within the cavity of the calixarene that is in a pinched-cone conformation. The least-squares plane of the phenyl group of the guest benzophenone is near-parallel to the planes of the triflate-bearing phenyl group, and the distal phenolic group, with the dihedral angles between the respective planes being 19.8° and 22.3°. The dihedral angle between the least-squares planes defined by the phenyl groups of the other two phenolic units is 86.9°, to accommodate the enclosed phenyl group of the benzophenone. Andreetti and co-workers[18a–e] identified the *p-tert*-butyl groups to be of critical importance for favorable $CH_3 \cdots \pi$ interactions between the methyl groups and the π-system of a guest molecule. The structure of **6** is consistent with this postulate.

The ^{1}H NMR spectrum of **6** in either $CDCl_3$, CD_2Cl_2, or CD_3CN solution did not reveal unequivocal evidence for the existence of the clathrate in solution. In each case,

(14) Chowdhury, S.; Zhao. B.; Snieckus, V. *J. Polycyclic Aromatic Hydrocarbons* **1994**, *5*, 27–34.

(15) Atomic coordinates of the structures of **3** and **6** have been deposited with the Cambridge Crystallographic Data Centre. These are available, on request, from the Director, Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EK, U.K.

(16) Ishiyama, T.; Kizaki, H.; Hayashi, T.; Suzuki, A.; Miyaura, N. *J. Org. Chem.* **1998**, *63*, 4726–4731.

(17) Tristriflate **4** was recovered unchanged (36 h at 80 °C.; carbon monoxide 130 psi). Under the same conditions, tetrakistriflate **5** afforded a product (mp 265–272 °C) whose ^{1}H NMR spectrum reveals it to be **3** together with *five* included benzophenone molecules. We have not as yet been able to obtain a single crystal suitable for X-ray structure determination.

(18) (a) Andreetti, G. D.; Ugozzoli, F.; Ungaro, R.; Pochini, A. In *Inclusion Compounds, Vol. 4*; Atwood, J. L., Davies, J. E. D., MacNicol, D. D., Eds.; Oxford University Press: Oxford, 1991; pp 64–122. (b) Andreetti, G. D.; Ungaro, R.; Pochini, A. *J. Chem. Soc., Chem. Comun.* **1979**, 1005–1007. (c) Coruzzi, M.; Andreetti, G. D.; Bocchi, V.; Pochini, A. *J. Chem. Soc., Perkin Trans. 2* **1982**, 1133–1138. (d) Andreetti, G. D.; Pochini, A.; Ungaro, R. *J. Chem. Soc., Perkin Trans. 2* **1983**, 1773–1779. (e) Rizzoli, C.; Andreetti, G. D.; Ungaro, R.; Pochini, A. *J. Mol. Struct.* **1982**, *82*, 133–141.

the spectra were indistinguishable from those of equimolar mixtures prepared from **3** and benzophenone in each of the respective solvents. Evaporation of the deuterated solvents from the appropriate solutions of **6** afforded residues having only a slightly lower melting point (with decomposition), whereas removal of the solvent from the equimolar mixtures, afforded residues having a much lower and broader range melting points than those of **6**. The melting point of the recovered single crystal which produced the X-ray structure was found to be identical to that of the bulk sample. To our knowledge, the X-ray structure reported herein, is the first crystal structure of a clathrate of a calix[4]arene containing a neutral guest molecule that is not solvent-derived but is likely derived from a secondary reaction.

Allowing equimolar mixtures of **3** and benzophenone to slowly crystallize failed to produce **6** thereby establishing that the clathrate was not merely formed by a simple cocrystallization of its two components. When **3** and benzophenone in anisole alone were pressurized with carbon monoxide under the same conditions which were employed for the carbonylative conditions but omitting the Pd catalyst and base, no formation of **6** was observed. The mechanism of formation of this unusual clathrate is still unclear. It can be noted, however, that using the same carbonylative conditions in the presence of either **1** or **3**, phenylboronic acid produced benzophenone without any evidence being observed for formation of the corresponding clathrates. Furthermore, the homocoupling of phenylboronic acid to give benzophenone itself was not reported by Ishiyama et al.[15] among the extensive list of biaryl ketones which they synthesized via Pd-catalyzed cross-coupling of various arylboronic acids with aryl electrophiles. Thus, the formation of benzophenone from phenylboronic acid alone is unusual, and its formation, in our case, appears to be assisted by the presence of the calixarenes.[19]

Snieckus et al.[14] reported a general Pd(II)-catalyzed procedure for the deoxygenative replacement of the hydroxyl functionalities of phenols by a hydrogen atom via the corresponding triflates. This procedure was therefore examined as a possible alternative method to reduction of calix[4]arene phosphonates described by Goren and Biali[6] to obtain hydroxyl-depleted calix[4]arenes. Tristriflate **4** was therefore treated with $Pd(OAc)_2/PPh_3/Et_3N/HCO_2H$ in refluxing DME for 16 h. After workup and flash column chromatography, a crystalline product **7** (80%) was obtained whose ^{1}H NMR spectral data revealed among other signals, a well-defined quartet centered at $\delta = 3.14$ (apparent $J = 7.3$, 14.6 Hz) coupled to a well-defined triplet at $\delta = 1.31$ ppm, whose integration values suggested the presence of three ethyl groups. Suitable crystals for X-ray structure determination have thus far not been attainable. However, FAB-mass spectroscopy revealed M^+ ions at $m/z = 780$ and 101 corresponding to monotriflate **3** and triethylamine respectively, suggesting that the structure of this product is a 1:1 complex of **3** and triethylamine, formed from **2** and triethylamine under the Pd(II) reaction conditions. The signals of the methylene and methyl groups of the complexed triethylamine in **7** are shifted 0.54 and 0.20 ppm downfield compared to those of the corresponding signals obtained from 1:1 or 1:3 mixtures of **3** itself and triethylamine. Gutsche's group has studied the interaction of *p*-allylcalix[4]arenes **8** and amines.[20,2120,21] On the basis of NOE ^{1}H NMR spectral data, Gutsche concluded that **8** formed an endo-type complex in which the amine "guests" were complexed within the cavity formed by the aryl groups of **8**, rather than an exo one, in which the complex is bound to the lower rim of **8**. Chemical shift differences or T_1 differences between uncomplexed amine and 1:1 mixtures were unequivocal. In our example, when **7** was subjected to a NOE experiment, no enhancement of the signals due to either the methylene or methyl group was observed upon irradiation of the *tert*-butyl methyl signals. On the basis of this observation, it can be concluded that **7** is an exo-type complex.

While the work described above was in progress, Lipshutz et al.[22] reported that aryl triflates and nonaflates could be efficiently reductively deoxygenated using Pd(0)-catalyzed reaction with dimethylamine•borane. These same reductive conditions were examined using **2**, but again, only **3** and **4** were obtained as the major products, with no evidence for reductive deoxygenation. Finally, bisnonaflate **9** was prepared and subjected to typical Stille-coupling conditions with tetramethylstannane, but only monononaflate **10**, which is analogous to **3**, was obtained.

From the results that were obtained, it is possible that the oxidative addition step[9,16] requiring a square-planar intermediate[23] that is presumed to form in the Pd(0)–Pd(II) catalytic cycle might not be occurring in the case of these calix[4]arene triflates, likely due to a prohibitively large steric encumberance. Instead, the ArCO–Pd–Ar intermediate which is the putative precursor to the benzophenone could become complexed within the calixarene cavity enabling a facile formation of benzophenone to occur, and in the case of **6** further strong binding of the formed benzophenone.

In conclusion, we have demonstrated that each of the four calix[4]arene triflates can be easily synthesized and characterized. However, possibly because of steric restrictions, oxidative addition does not appear to occur with any of these triflates to form Pd(II) intermediates which are required for effective Pd(0)-catalyzed Suzuki–Miyaura coupling, carbonylative coupling or deoxygenation. Instead, in the Suzuki–Miyaura coupling reaction, disporportionation reactions involving the triflate or nonaflate groups occurred. In the case of Pd(0)-catalyzed carbonylative coupling using bistriflate **2**, an unprecedented nonsolvent molecule-derived 1:1 clathrate **6** was formed, but for the Pd(II)-catalyzed deoxygenation reaction with **2**, an exo-type 1:1 clathrate **7** was formed.

Experimental Section

General Methods. For general experimental data, see ref 13. ^{1}H NMR and ^{13}C NMR spectra in $CDCl_3$ were recorded at

(19) Recently, it has been reported that some calixarenes can act as inverse phase-transfer catalysts showing typical enzyme-like effects on Pd-catalyzed Stille coupling reactions: Schatz J.; Schildbach, R.; Baur, M. In *Abstracts of The Fifth International Conference on Calixarene Chemistry*; 19–23 Sep, 1999, Perth, Australia.

(20) Bauer, L. J.; Gutsche, C. D. *J. Am. Chem. Soc.* **1985**, *107*, 6063–6069.

(21) Gutsche, C. D.; Iqbal, M.; Alam, I. *J. Am. Chem. Soc.* **1987**, *109*, 4314–4320.

(22) Lipshutz, B. H.; Buzard, D. J.; Vivian, R. W. *Tetrahedron Lett.* **1999**, *40*, 6871–6874.

(23) See, e.g., a recent communication: Cotter, W. D.; Barbour, L.; McNamara, K. L.; Hechter, R.; Lachicotte, R. J. *J. Am. Chem. Soc.* **1998**, *120*, 11016–11017. This communication reports the first direct observation and spectroscopic characterization of a triflato-Pd(II) intermediate en route to transmetalation in a Stille coupling reaction.

300 and 75.47 MHz, respectively. All reactions were carried out under Ar unless otherwise noted. Chromatography was performed with 60 mesh silica gel and preparative layer (1 mm) chromatography with standard TLC grade silica gel to which gypsum binder (14%) was added during formation of the slurry used to prepare the 20 × 20 cm plates.

***p-tert*-Butylcalix[4]arene 1,3-Bistriflate (2).** To a solution of *tert*-butylcalix[4]arene (**1**) (2.59 g, 4.00 mmol) in THF (120 mL) at 0 °C was added in two portions, with stirring, NaH (60% suspension in oil, 317 mg, 8.00 mmol). The mixture was stirred for a further 30 min at 0 °C, and then trifluromethanesulfonic anhydride (1.33 mL, 8.00 mmol) was added slowly. The reaction mixture was allowed to warm to rt and was stirred overnight, after which time it was quenched by the addition of an aqueous saturated solution (20 mL) of NH_4Cl. The THF was removed from the reaction mixture before it was extracted using CH_2Cl_2 (2 × 30 mL). The combined organic layers were dried ($MgSO_4$) and evaporated to afford a crude yellow product that was triturated with hexane to give **2** as a white solid (2.50 g, 69%): mp 285−287 °C (305 °C from MeOH/benzene,[10] 255 °C from $CHCl_3$[12]) whose spectral characteristics were identical with those reported.[10,12]

***p-tert*-Butylcalix[4]arene Triflate (3).** To a solution of **1** (2.59 g, 4.00 mmol) in THF (120 mL) at 0 °C was added, with stirring, NaH (60% suspension in oil, 175 mg, 4.40 mmol). The mixture was stirred for a further 30 min at 0 °C, and then trifluromethanesulfonic anhydride (1.00 mL, 6.00 mmol) was added slowly. The reaction was conducted and worked up as described for **2** to afford a crude yellow product that was chromatographed (5:95 EtOAc−hexane) to give **3** as a white crystalline solid (2.25 g, 72%): mp 234−236 °C (228−230 °C from hexane,[10] 225 °C from $CHCl_3$[12]) whose spectral characteristics apart from singlets at δ = 6.81 (2H) and 8.34 (1H), which are D_2O-exchangeable, were identical with those reported.[10,12]

X-ray Data for 3. Crystal (EtOAc−hexane) data for **3** (mp 234−236 °C): $C_{45}H_{55}F_3O_6S$, monoclinic, space group $P2_1$ (#14), a = 12.382(4) Å, b = 16.795(2) Å, c = 21.825(2) Å, β = 105.31(1)°, V = 4378(1) Å^3, Z = 4, D_{calc} = 1.185 g/cm^3, crystal size = 0.25 × 0.25 × 0.40 mm. Intensity data were measured at 299.1 K on a Rigaku AFC6S diffractometer with graphite-monochromated Cu Kα radiation to $2\theta_{max}$ (deg) = 120.2°; 6758 unique reflections converged to a final R = 0.084 for 4155 reflections with $I > 2.00\sigma(I)$; R_w = 0.084, gof = 3.86.

***p-tert*-Butylcalix[4]arene Tristriflate (4) and *p-tert*-Butylcalix[4]arene Tetraksitriflate (5).** To a solution of **1** (2.59 g, 4.00 mmol) in THF (120 mL) at 0 °C was added in four to five portions with stirring NaH (60% suspension in oil, 955 mg, 24.0 mmol). The mixture was stirred for a further 30 min at 0 °C, and then trifluromethanesulfonic anhydride (3.36 mL, 20.0 mmol) was added slowly. The reaction was conducted and worked up as described for **3** to afford a crude yellow product that was chromatographed (5:95 EtOAc−hexane) to give **4** (2.51 g, 60%) [mp 248−250 °C (239−240 °C from hexane[10])] and **5** (517 mg, 11%) (mp 260−262 °C): ^{1}H NMR δ 1.13 (s, 36H), 3.58 (d, J = 14.4 Hz, 4H), 4.55 (d, J = 14.3 Hz, 4H), 7.00 (s, 8H); ^{13}C NMR δ 31.2, 34.4, 116.5, 120.8, 126.9, 133.5, 141.4, 150.6; MS (FAB) m/z 1176 (M$^+$).

***p-tert*-Butylcalix[4]arene Triflate/Benzophenone Clathrate (6).** A mixture of **2** (150 mg, 0.164 mmol), phenylboronic acid (44 mg, 0.36 mmol), $PdCl_2(PPh_3)_2$ (23 mg, 20 mol %), K_2CO_3 (68 mg, 0.49 mmol), and anisole (15 mL) were placed in stainless steel high-pressure reaction vessel. The reaction was flushed once and then charged with CO (130 Psi) and heated at 80 °C for 3 d. After releas e of CO, the crude mixture was partitioned between water (15 mL) and ethyl acetate (3 × 15 mL). The organic layer was dried ($MgSO_4$) and evaporated to afford a crude product, which was chromatographed by PLC using 1:5 benzene/hexane as eluent to give **6** (90 mg, 57%): mp 262−264 °C; ^{1}H NMR δ 0.99 (s, 9H), 1.14 (s, 9H), 1.27 (s, 18H), 3.48 (d, J = 14.1 Hz, 2H), 3.57 (d, J = 14.1 Hz, 2H), 4.15 (s, J = 14.1 Hz, 2H), 4.33 (s, J = 14.1 Hz, 2H), 6.81 (s, 2H), 6.94 (s, 2H), 6.96 (s, 2H), 7.09 (d, J = 2.2 Hz, 2H), 7.13 (d, J = 2.3 Hz, 2H), 7.46−7.51 (t, J = 7.6 Hz, 14.8 Hz, 4H), 7.57−7.62 (t, J = 7.4 Hz, 14.8 Hz, 2H), 7.79−7.82 (m, 4H); ^{13}C NMR δ 30.7, 31.2, 31.5, 32.3, 32.4, 33.9, 34.0, 34.2, 116.6, 120.9, 121.7, 125.6, 125.7, 125.9, 127.1, 127.2, 127.3, 127.5, 128.2, 128.5, 129.4, 130.0, 133.5, 137.5, 141.0, 143.6, 144.1, 146.5, 148.9, 151.0, 196.7.

X-ray Data for 6. Crystal (hexane/cyclohexane) data for **6** (mp 262−264 °C dec): $C_{58}H_{65}F_3O_7S$, triclinic, space group $P1$ (#2), a = 12.5828(9) Å, b = 17.514(2) Å, c = 12.474(1) Å, α = 98.015(8)°, β = 101.715(7)°, γ = 92.392(7)°, V = 2658.6(4) Å^3, Z = 2, D_{calc} = 1.203 g/cm^3, crystal size = 0.30 × 0.30 × 0.20 mm. Intensity data were measured at 299.1 K on a Rigaku AFC6S diffractometer with graphite-monochromated Cu Kα radiation to $2\theta_{max}$ (deg) = 120.2°; 7916 unique reflections converged to a final R = 0.069 for 5558 reflections with $I > 2.00\sigma(I)$; R_w = 0.075, gof = 3.21.

***p-tert*-Butylcalix[4]arene Triflate/Triethylamine Clathrate (7).** A mixture of **4** (522 mg, 0.500 mmol), $Pd(OAc)_2$ (13 mg, 0.060 mmol), PPh_3 (31 mg, 0.12 mmol), formic acid (0.11 mL, 3.0 mmol), Et_3N (1.25 mL, 9.0 mmol), and DMF (10 mL) was heated at 60−70 °C for 16 h. The crude reaction mixture was washed with H_2O (3 × 10 mL), and the organic layer was extracted with ethyl acetate (3 × 15 mL), dried ($MgSO_4$), and evaporated to afford a crude product that was chromatographed (5:95 EtOAc−hexane) to give **7** (350 mg, 80%): mp 194−196 °C; ^{1}H NMR δ 1.03 (s, 9H), 1.19 (s, 9H), 1.24 (s, 18H), 1.29−1.34 (t, J = 7.3 Hz, 14.6 Hz, 9H), 3.10−3.17 (q, J = 7.3 Hz, 14.6 Hz, 6H), 3.34 (d, J = 13.1 Hz, 2H), 3.37 (d, J = 13.0 Hz, 2H), 4.12 (d, J = 13.0 Hz, 2H), 4.43 (d, J = 12.9 Hz, 2H), 6.91 (s, 4H), 6.96 (d, J = 2.4 Hz, 2H), 6.98 (2, 2H), 7.07 (d, J = 2.4 Hz, 2H); ^{13}C NMR δ 30.9, 31.5, 31.7, 32.4, 33.8, 34.1, 34.6, 45.7, 120.3, 125.0, 125.2, 125.3, 126.8, 129.6, 132.9, 139.9, 141.2, 142.8, 149.3, 151.5, 152.7; MS (FAB) m/z 881 (M$^+$), 780, 101.

***p-tert*-Butylcalix[4]arene 1,3-Bisnonaflate (9).** To a solution of *tert*-butylcalix[4]arene (**1**) (0.648 g, 1.00 mmol) in THF (40 mL) at 0 °C was added in two portions, with stirring, NaH (60% suspension in oil, 192 mg, 5.00 mmol). The mixture was stirred for a further 45 min at 0 °C, and then perfluoro-1-butanesulfonyl chloride (0.9 mL, 5.00 mmol) was added slowly. The reaction was conducted and worked up as described for **2** to afford a crude yellow product that was chromatographed (10:90 EtOAc−hexane) to give the bisnonaflate **9** as a colorless crystalline solid (0.68 g, 56%): mp 277−279 °C; ^{1}H NMR δ 0.88 (s, 18H), 1.34 (s, 18H), 3.52 (d, J = 14.5 Hz, 4H), 4.19 (s, 2H, OH), 4.25 (d, J = 14.3 Hz, 4H), 6.76 (s, 4H), 7.17 (s, 4H); ^{13}C NMR δ 30.6, 30.7, 31.5, 31.6, 31.7, 31.8, 32.1, 32.1, 34.0, 34.1, 120.3, 125.7, 126.9, 127.9, 132.8, 140.4, 143.5, 149.7, 150.9; MS (FAB) m/z 1212 (M$^+$).

***p-tert*-Butylcalix[4]arene Nonaflate (10).** To a mixture of **9** (121 mg, 0.10 mmol), $Pd(dba)_2$ (3 mg, 5 mol %), dppf (3 mg, 2 mol %), LiCl (21 mg, 0.50 mmol), and tetramethylstannane (0.04 mL, 0.3 mmol) under Ar was added dioxane (5 mL). The mixture was heated at reflux for 2 days. After the mixture was cooled to room temperature, the organic layer was poured into saturated aqueous NH_4Cl solution (10 mL), extracted with EtOAc (3 × 15 mL), and dried over $MgSO_4$ and the solvent evaporated. The crude product was chromatographed by PLC to obtain **9** (60 mg) and **10** (30 mg, 40%): ^{1}H NMR δ 0.96 (s, 9H), 1.13 (s, 9H), 1.28 (s, 18H), 3.46 (d, J = 14.2 Hz, 2H), 3.56 (d, J = 14.2 Hz, 2H), 3.71 (2H), 4.11 (d, J = 14.0 Hz, 2H), 4.34 (d, J = 14.0 Hz), 6.75 (s, 2H, OH), 6.90 (s, 2H), 6.94 (s, 2H), 7.09 (d, J = 3.4 Hz, 2H), 7.13 (d, J = 3.4 Hz); ^{13}C NMR δ 29.7, 30.7, 31.2, 31.4, 31.5, 32.1, 32.4, 33.9, 34.2, 67.1, 120.3, 125.6, 125.9, 127.1, 127.6, 133.0, 140.7, 143.6, 144.1, 146.4, 148.9, 151.0; MS (FAB) m/z 929 (M$^+$).

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Supporting Information Available: NMR spectra for compounds **2**−**7**, **9**, and **10**. This material is available free of charge via the Internet at http://pubs.acs.org.

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