Synthesis and Structure of Calixarene−Fullerene Dyads[1]

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Calixarene chemistry[2] and fullerene chemistry combined forces several years ago with the independent demonstration by several research groups,[3−5] that *p-tert*-butylcalix[8]arene can form complexes with C_{60} and C_{70}. Subsequently there have been a number of studies of this intermolecular interaction between these two entities,[6] including several from this laboratory that involve calix[5]arenes.[7] In the present work the intermolecular association between calixarene and fullerene that characterizes these earlier studies has been transformed to an intramolecular arrangement through the construction of compounds in which a C_{60} moiety is covalently bonded to a calixarene framework.

The starting material for the calix[5]arene series described below was 5-allylcalix[5]arene-31,32,33,34,35-pentol (**1**), prepared by Claisen rearrangement of monoallyloxycalix[5]arene.[7b] Double bond isomerization of **1** was effected by treatment with *t*-BuOK in dry THF, which yielded **2** as a mixture of cis and trans isomers, the latter predominating but the ratio of isomers depending on the reaction conditions. Methylation with methyl tosylate yielded the pentamethyl ether **3**, which was ozonolyzed under reducing conditions to give the pentamethyl ether of *p*-monoformylcalix[5]arene (**4b**).

The functionalization of C_{60} by the 1,3-dipolar addition of azomethine ylides to a 6,6-ring junction of the fullerene has gained popularity because of the numerous ways for generating the reactive intermediates from a variety of easily available materials, a particularly successful application involving the immonium salts derived from the condensation of α-amino acids with aldehydes.[8,9] Its application in the present work employs the reaction of **4b** with sarcosine and C_{60} in refluxing toluene, which affords the cycloaddition product **5b** in 86% yield. No evidence for the formation of polyadducts was observed. Demethylation of **5b** was effected with BBr_3 to give one of the target molecules **6b**, purified by chromatography on silica gel.

A similar sequence of reactions was employed in the calix[4]arene series for which the monoaldehyde **4a** was obtained by selective monoformylation of the tetramethyl ether of calix[4]arene, following the procedure of Ungaro and co-workers.[10] Although **4a** ands **5a** are obtained as mixtures of conformers, as discerned from ^1H and ^{13}C NMR spectra, this posed no problem with respect to the target molecules because demethylations of **5a** and **5b** produce **6a** and **6b**, which exist almost exclusively in the cone conformation.

The characterizations of **6a** and **6b** and their precursors are based on satisfactory elemental analyses, FAB mass spectra showing parent ions commensurate with the proposed structures, and NMR data. Like other adducts of C_{60} with immonium ylides, the C_{60} moieties in **5a**,**b** and **6a**,**b** lack the symmetry of C_{60} itself and show a large number of resonances in their ^{13}C NMR spectra. The target molecules **6a** and **6b**, for example, show 58 and 52 resonances, respectively, in the δ 120−160 region, the theoretical number being 72 (14 for the aromatic rings of the calixarene moieties and 58 for the C_{60}). In addition are the higher field resonances for the sp^3 carbons in the C_{60} moiety and the methylene groups of the calixarene moiety. Similarly, in the ^1H NMR spectra the dissymmetry of the C_{60} moiety is manifested in the resonances of the calixarylpyrrolidine moiety. For example, the two protons of the CH_2 group of the pyrrolidine ring are nonequivalent, showing a pair of doublets centered at δ 4.24 and 4.98. The bridge CH_2 groups of the calixarene ring, however, show only a broadened resonance at δ 3.84 rather than a well-resolved pair of doublets because of the conformational mobility of the macrocyclic ring.

The UV/vis spectra of **5a**,**b** and **6a**,**b** were measured and compared with those of the analogous fullerenes **7** and **8**, which lack the calixarene moiety, the thought being that any differences might reflect an intramolecular association between the C_{60} moiety and the cavity of the calixarene. However, all six of these compounds possess very similar spectral patterns, showing strong absorptions at 212 and 256 nm, a shoulder at 295−328 nm, and a weak absorption at 433 nm. This indicates that there is not any significant perturbation arising from intramolecular complexation, which is not surprising in view of the rigidity of the spacer separating the C_{60} and

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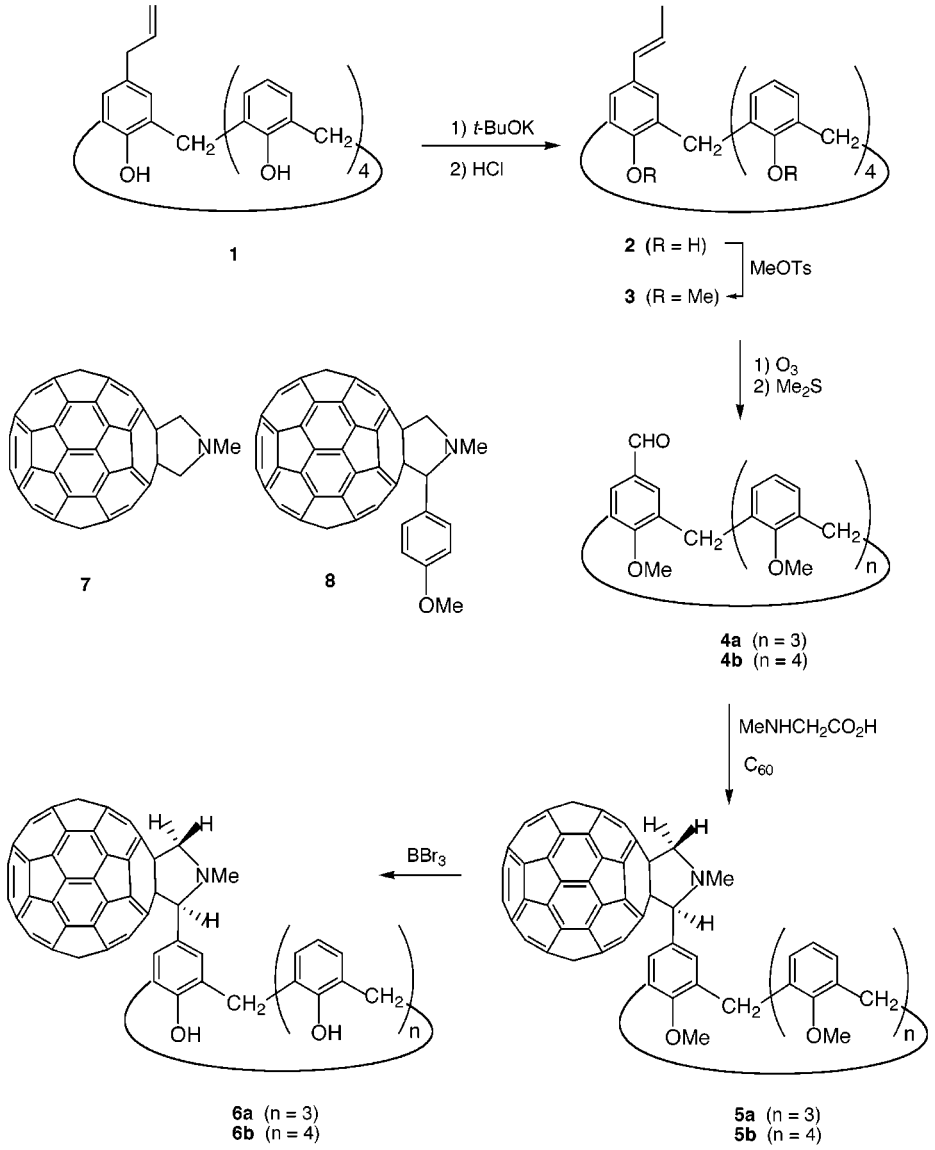

calixarene. If the spacer were more flexible (i.e., longer) intramolecular complexation might ensue, although measurements of the strengths of binding of the functionalized C_{60} molecule **7** with calix[5]arene and pentaallylcalix[5]arene give K_{assoc} values of only 7.7 and 199 M^{-1}, respectively, which are somewhat lower than the corresponding values of 30 and 292 M^{-1} for C_{60} itself.

Experimental Section[11]

5-(1-Propenyl)calix[5]arene-31,32,33,34,35-pentol (2). To 70 mL of dry THF were added under N_2 a 0.156 g (0.27 mmol) sample of **1** and 0.6 g (5.4 mmol) of *t*-BuOK. The mixture was refluxed for 20 h and then treated with 20 mL of 1 N HCl and 30 mL of $CHCl_3$. The organic layer was separated, washed with H_2O and brine, and dried over anhydrous Na_2SO_4. It was concentrated, and the crude product that separated was recrystallized from CH_2Cl_2−hexane to give 0.15 g (95%) of **2** as a mixture of cis and trans isomers: mp > 175 °C dec; ^{1}H NMR ($CDCl_3$) δ 8.92−8.86 (m, 5H), 7.22−7.09 (m, 10H), 6.90−6.80 (m, 4H), 6.32−6.26 (m, 1H), 6.11−6.09 and 5.72−5.60 (m, 1H), 3.85 (br s, 10H), 1.87−1.77 (m, 3H); ^{13}C NMR ($CDCl_3$) δ 150.1, 150.0, 149.9, 149.8, 149.1, 131.7, 131.3, 130.2, 129.8, 129.7, 129.6, 129.2, 129.0, 128.9, 127.0, 126.9, 126.8, 126.7, 126.5, 126.4, 125.9, 124.1, 122.0, 121.9, 121.6, 31.7, 31.3, 31.0, 30.8, 29.8, 18.4, 14.6. Anal. Calcd for $C_{38}H_{34}O_5$: C, 79.98; H, 6.01. Found: C, 79.79; H, 5.99.

5-(1-Propenyl)-31,32,33,34,35-pentamethoxycalix[5]-arene (3). A suspension of 0.52 g (0.91 mmol) of **2**, 3.05 g (16.4 mmol) of methyl toluenesulfonate, and 1.89 g (13.7 mmol) of anhydrous K_2CO_3 in 60 mL of dry CH_3CN was refluxed for 18 h under N_2. The solvent was evaporated, and the residue was treated with 50 mL of $CHCl_3$ and 70 mL of 1 N HCl. The organic layer was separated, washed with H_2O and brine, and dried over anhydrous Na_2SO_4. Evaporation of the solvent yielded a white solid which was purified by flash chromatography on silica gel (eluent CH_2Cl_2−hexane, 75:25) to give 0.5 g (86%) of **3** as a mixture of cis and trans isomers in a ratio of ca. 1:2: mp > 77 °C dec; ^{1}H NMR ($CDCl_3$) δ 7.00−6.77 (m, 14H), 6.25−6.19 (m, 1H), 6.05−5.93 and 5.67−5.58 (m, 1H), 3.87−3.84 (m, 10H), 3.22−3.13 (m, 15 H), 1.82 (d, J = 6.4 Hz, 2H), 1.72 (d, J = 7.2 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 156.7, 156.6, 155.8, 1134.8, 134.7, 134.6, 134.5, 134.4, 132.9, 130.7, 129.6, 129.4, 129.3, 129.0, 128.9, 128.5, 126.5, 125.4, 125.0, 124.2, 123.5, 123.2, 60.5, 31.3, 31.1, 31.0, 30.96, 30.8, 29.7, 29.6, 18.4, 14.6. Anal. Calcd. for $C_{43}H_{44}O_5 \cdot CH_3OH$: C, 78.54; H,7.19. Found: C, 78.28; H, 6.95.

(11) The melting points of all compounds melting above 250 °C were measured in sealed and evacuated capillary tubes on a Mel-Temp apparatus (Laboratory Devices, Cambridge, MA) using a 500 °C calibrated against a thermocouple. ^{1}H and ^{13}C NMR spectra were recorded on a Varian XL-300 instrument at 300 and 75 MHz, respectively. Analytical samples were dried for at least 36 h at 100−140 °C and 1−2 mmHg of pressure and analyzed by Desert Analytics, Tucson, AZ. The mass spectra were provided by the Washington University Resource for Biomedical and Bio-organic Mass Spectrometry.

5-Formyl-25,26,27,28-tetramethoxycalix[4]arene (4a). To a solution of 1.61 g (14 mmol) of CH_3OCHCl_2 and 0.48 g (1 mmol) of tetramethoxycalix[4]arene in 50 mL dry $CHCl_3$ was added 3.64 g (14 mmol) of $SnCl_4$ dropwise at −10 °C. The reaction mixture was stirred for 30 min and then treated with 100 mL of H_2O. The organic phase was separated, washed with H_2O and brine, and dried over anhydrous Na_2SO_4. The solvent was evaporated under vacuum to produce a viscous oil which was flash chromatographed with hexane−EtOAc (10:1) as eluent to afford 0.24 g (75%) of **4a** as a mixture of conformers and 0.18 g of starting material: ^{1}H NMR ($CDCl_3$) δ 10.0 and 9.59 (br s, 1H), 7.90−6.20 (m, 11H), 4.37−3.01 (m, 20H); ^{13}C NMR ($CDCl_3$) δ 192.0, 191.8, 163.4, 163.0, 158.1, 158.0, 157.9, 157.8, 157.7, 157.6, 157.5, 157.4, 157.3, 157.2, 136.1, 135.6, 134.6, 134.5, 130.7, 130.4, 129.9, 129.4, 129.3, 128.9, 128.7, 128.4, 128.2, 127.9, 122.7, 122.5, 122.3, 122.1, 121.9, 61.8, 61.7, 61.4, 60.9, 60.7, 59.7, 59.6, 59.5, 59.4, 59.35, 59.32, 59.2, 59.1, 35.7, 35.3, 32.0, 31.0, 30.9, 30.5, 30.2, 29.7, 29.4. Anal. Calcd for $C_{33}H_{32}O_5 \cdot C_6H_{14}$: C, 78.76; H, 7.80. Found: C, 78.98; H, 7.77.

5-Formyl-31,32,33,34,35-pentamethoxycalix[5]arene (4b). A stream of ozonized air was passed through a solution of 0.3 g (0.47 mmol) of **3** in 40 mL of CH_2Cl_2 at −78 °C for 10 min until the color of the solution was pale blue. Nitrogen was then passed through this solution for several minutes to remove excess ozone, 1 mL of $(CH_3)_2S$ was added, and the solution was stirred overnight. The solvent was removed, and the residue was purified by flash chromatography (silicon gel, CH_2Cl_2−EtOAc, 100:1) to give 0.17 g (65%) of **4b**: mp > 216−219 °C dec; ^{1}H NMR ($CDCl_3$) δ 9.78 (s, 1H), 7.49 (s, 2H), 7.04−6.99 (m, 4H), 6.94 (d, J = 7.2 Hz, 4H), 6.85 (t, 2H, J = 7.5 Hz), 6.78 (t, 2H, J = 7.5 Hz), 3.93 (s, 4H), 3.87 (s, 6H), 3.24 (s, 6H), 3.21 (s, 6H), 3.19 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 191.6, 162.2, 156.6, 135.8, 134.8, 134.5, 134.4, 133.6, 131.8, 130.7, 129.5, 129.0, 128.9, 123.5, 123.2, 60.8, 60.5, 60.4, 31.3, 31.0, 30.9. Anal. Calcd for $C_{41}H_{40}O_6$: C, 78.32; H, 6.41. Found: C, 78.23; H, 6.77.

Calix[4]arene−C_{60} Dyad 5a. A mixture of 72 mg (0.1 mmol) of C_{60}, 18 mg (0.2 mmol) of *N*-methylglycine, and 51 mg (0.1 mmol) of **4a** was refluxed in 60 mL of toluene under argon for 20 h. The resulting brown solution was washed with 100 mL of H_2O, dried over Na_2SO_4, and concentrated under vacuum. The crude product was purified by flash chromatography (silica gel, eluent CH_2Cl_2−hexane, 3:1) and recrystallized from $CHCl_3$−MeOH to give 0.045 g eluent (64%) of **5a** as a mixture of conformers, mp > 350 °C dec. The room temperature ^{1}H NMR in $CDCl_3$ is very complicated, showing many sharp peaks for methoxyl groups. The following NMR spectral data were obtained at 120 °C in $CDCl_2CDCl_2$: ^{1}H NMR δ 7.80−6.10 (br m, 11H), 4.97 and 4.24 (d, 1H each, J = 6.8 Hz), 4.82 (s, 1H), 3.62 (m, 20H), 2.77 (br s, 3H). ^{13}C NMR ($CDCl_3$) δ 160.7, 159.0, 158.9, 158.8, 158.1, 157.4, 157.3, 157.0, 156.9, 156.8, 156.7, 156.3, 154.2, 154.1, 154.0, 153.9, 153.7, 147.3, 147.2, 146.7, 146.6, 146.5, 146.4, 146.3, 146.2, 146.1, 146.0, 145.6, 145.4, 145.3, 145.2, 144.7, 144.6, 144.5, 143.2, 143.0, 142.7, 142.6, 142.5, 142.4, 142.3, 142.2, 142.1, 142.0, 141.9, 141.7, 141.5, 140.2, 140.1, 139.9, 139.8, 138.3, 137.2, 137.0, 136.9, 136.8,136.7, 136.6, 135.8, 134.1, 133.8, 133.7, 133.4, 133.3, 133.2, 133.0, 132.9, 132.8, 132.76, 132.71, 132.7, 132.5, 132.0, 131.9, 131.0, 130.9, 130.8, 130.7, 130.6, 130.3, 130.2, 130.0, 129.9, 129.8, 129.5, 129.2, 129.0, 128.9, 128.8, 128.7, 128.6, 128.4, 128.2, 128.1, 128.0, 127.8, 127.7, 127.6, 127.5, 127.3, 127.2, 127.0, 126.8, 123.6, 123.4, 122.9, 122.7, 122.5, 122.2, 122.0, 121.9, 121.8, 121.7, 82.9, 70.1, 69.0, 62.4, 60.8, 60.7, 60.6, 60.5, 40.2, 40.1, 36.6, 35.7, 35.6, 30.9, 30.6, 30.5, 29.7, 29.6, 29.4. Anal. Calcd. for $C_{95}H_{37}O_4N \cdot 2CH_3OH$: C, 88.34; H, 3.4. Found: C, 88.75; H, 3.55. MALDI-FAB MS m/z 1255 (M^+).

Calix[5]arene−C_{60} dyad 5b was prepared by using the procedure described for **5a** and was isolated in 86% yield as a mixture of conformers: mp > 290 °C dec. The ^{1}H NMR in $CDCl_3$ at room temperature is very complicated. The following spectral data were obtained at 55 °C in $CDCl_3$: ^{1}H NMR ($CDCl_3$) δ 7.62 (br s, 2H), 6.99 (d, 2H, J = 7.0 Hz), 6.91 (d, 2H, J = 7.4 Hz), 6.78 (t, 4H, J = 7.5 Hz), 6.66 (br s, 2H), 6.38 (br s, 2H), 4.99 and 4.28 (d, 1H each, J = 9.5 Hz), 4.92 (s, 1H), 3.86 (br s, 10H), 3.37 and 3.20 (s, 6H each), 2.88 (s, 3H), 2.87 (s, 3H); ^{13}C NMR ($CDCl_3$, 40 mM $Cr(acac)_3$) δ 157.3, 156 8, 156.3, 156.0, 154.1, 153.7, 153.5, 147.3, 146.9, 146.6, 146.5, 146.3, 146.3, 146.18, 146.12, 145.9, 145.8, 145.6, 145.5, 145.4, 145.3, 145.2, 145.1, 144.7, 144.5, 144.4, 144.3, 143.2, 143.1, 143.0, 142.7, 142.6, 142.3, 142.2, 142.1, 141.9, 141.7, 141.6, 141.5, 140.2, 140.1, 139.9, 139.3, 136.8, 136.7, 135.9, 135.8, 134.6, 134.5, 134.1, 131.4, 129.4, 129.0, 128.1, 127.7, 123.2, 82.8, 70.1, 69.0, 60.8, 60.5, 40.2, 31.4, 30.6, 30.2. Anal. Calcd for $C_{103}H_{45}O_5N \cdot CH_3OH/CH_2Cl_2$: C, 84.57; H, 3.41. Found: C, 84.77; H, 3.54. MALDI-FAB MS m/z 1375 (M^+).

Calix[4]arene−C_{60} Dyad 6a. A solution of 40 mg (0.031 mmol) of **5a** in 10 mL of CH_2Cl_2 was cooled in an ice bath under N_2 and then treated dropwise with 1 mL of 1 M BBr_3 in CH_2Cl_2. The mixture was stirred for 2 h at low temperature and overnight at rt, and 10 mL of ice−water was added. The organic layer was separated, washed with H_2O and brine, dried over anhydrous Na_2SO_4, and condensed under vacuum. The crude product was purified by flash chromatography (silica gel, CH_2Cl_2−hexane, 75:25), which produced 0.025 g (66%) of **6a**. Recrystallization from CS_2−hexane afforded a black solid: mp > 470 °C dec; ^{1}H NMR ($CDCl_3$) δ 10.12 (br s, 4H), 7.50 (br s, 2H), 7.02 (bs, 6H), 6.70 (br s, 3H), 4.93 and 4.19 (d, 1H each, J = 9.5 Hz), 4.76 (s, 1H), 4.22 and 3.54 (br s, 4H each), 2.72 (br s, 3H); ^{13}C NMR (CS_2−$CDCl_3$, 40 mM $Cr(acac)_3$) δ 156.5, 154.2, 153.8, 153.7, 153.6, 149.2, 148.9, 148.7, 147.6, 147.5, 147.0, 146.7, 146.6, 146.52, 146.5, 146.4, 146.3, 146.2, 146.0, 145.9, 145.8, 145.7, 145.6, 145.5, 145.4, 145.0, 144.7, 143.39, 143.3, 143.0, 142.9, 142.9, 142.8, 142.6, 142.5, 142.4, 142.38, 142.35, 142.3, 142.0, 140.6, 140.3, 140.0, 136.9, 136.1, 136.0, 129.5, 129.3, 129.1, 128.9, 128.4, 128.0, 127.7, 127.3, 127.2, 127.0, 126.7, 123.0, 82.9, 77.2, 70.1, 69.1, 39.8, 32.2, 32.0, 30.4, 30.3. Anal. Calcd for $C_{91}H_{29}O_4N \cdot 1.5C_6H_{14}$: C, 90.51; H, 3.72. Found: C, 90.10, H, 3.62. MALDI-FAB MS m/z 1199 (M^+).

Calix[5]arene−C_{60} dyad 6b was prepared by using the procedure described for **6a** and was isolated in 68% yield as a black solid. The sample for analysis was obtained by recrystallization from $CHCl_3$−MeOH: mp > 460 °C dec; ^{1}H NMR ($CDCl_3$) δ 8.88−8.79 (m, 5H), 7.65 (br s, 2H), 7.20−7.16 (m, 8 H), 6.82 (t, 2 H, J = 7.5 Hz), 6.72 (br s, 2H), 4.98 and 4.24 (d, J = 9.5 Hz, 1H each), 4.84 (s, 1H), 3.84 (br s, 10H), 2.79 (s, 3H); ^{13}C NMR (5:l CS_2−C_6D_6, 40 mM $Cr(acac)_3$) δ 156.4, 154.0, 153.7, 153.6, 150.5, 150.0, 147.4, 147.3, 146.7, 146.6, 146.5, 146.0, 146.2, 146.0, 145.8, 145.7, 145.6, 145.5, 145.4, 145.3, 144.8, 144.7, 144.5, 143.2, 143.1, 142.8, 142.7, 142.6, 142.5, 142.4, 142.3, 142.2, 142.1, 141.8, 141.7, 141.4, 140.3, 140.2, 140.0, 139.9, 137.5, 136.7, 136.4, 135.9, 130.0, 129.6, 129.2, 126.6, 126.4, 126.3, 122.1, 122.0, 83.1, 77.4, 70.1, 68.9, 40.0, 31.8, 30.4. Anal. Calcd for $C_{98}H_{35}O_5N \cdot 1.5\ CH_3OH$: C, 88.34; H, 3.02. Found: C, 88.42; H, 3.30. MALDI-FAB MS m/z 1305 (M^+).

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