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Regioselective synthesis and complexation behavior of novel [60]fullerene bisadducts containing dibenzo-18-crown-6 moiety

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Abstract

The reaction of [60]fullerene with bis-*o*-quinodimethane precursor **3** containing a dibenzo-18-crown-6 moiety provided preferentially *trans*-4 bisadduct **5a** along with a small amount of *cis*-2 bisadduct **5b**. These bisadducts showed different ionophoric properties from each other; **5a** exhibited a high complexing ability toward K^+ ion, while **5b** hardly showed complexation with any alkali metal ions. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: fullerenes; Diels–Alder reaction; regioselective synthesis; crown ethers; complexation.

Although multiple addition toward [60]fullerene becomes of increasing interest from the viewpoints of electronic,[1] electrochemical,[2] photophysical,[3] and chiroptical properties,[4] it usually affords regioisomeric mixtures. Even in the bisaddition reactions occurring exclusively at [6,6]-junctions, eight regioisomers are theoretically possible. Several research groups regioselectively prepared a variety of bisfunctionalized [60]fullerene derivatives by the tether-directed remote functionalization.[5] We have succeeded in the regioselective synthesis of [60]fullerene-*o*-quinodimethane bisadducts modified within one hemisphere of [60]fullerene by connecting the two precursors with an oligomethylene linkage; **1a** (n=2) and **1b** (n=3) provide the *cis*-2 and *cis*-3 isomers, while **1c** (n=5) exclusively the *e*-isomer.[6] This regioselectivity is apparently derived from the constrained distance between the two reactive species, governed by the oligomethylene linkage. For the improvement of regioselectivity, we have designed the reaction of dibenzo-18-crown-6 derivative **3**. The macrocyclic moiety in **3**, which can serve as double bridging linkages connecting two *o*-quinodimethane precursors, should control the relative arrangement as well as the distance between the reactive species, probably leading to the preferential addition at two sites located almost in parallel. Furthermore, the resulting bisadducts seem to display ionophoric properties different from dibenzo-18-crown-6 itself. Here we report the regioselectivity produced by **3** and the intriguing complexation behavior of the resulting bisadducts. The comparison with the reaction of

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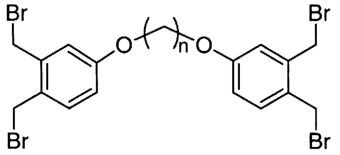
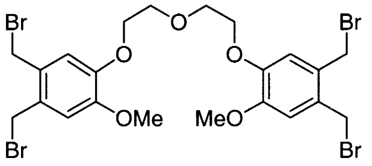
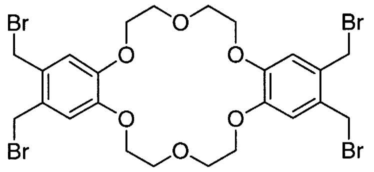
2 possessing a single oxyethylene linkage is also discussed. These investigations are expected to provide a guide for preparing specific bisadducts.



1a (n = 2)
1b (n = 3)
1c (n = 5)

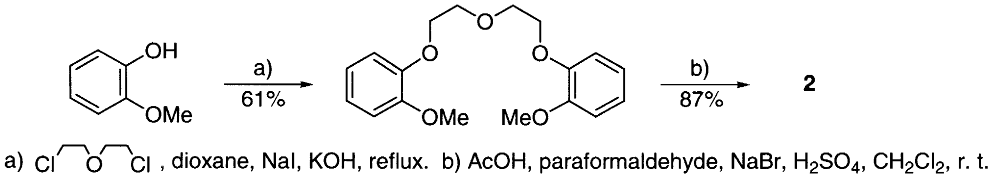


2

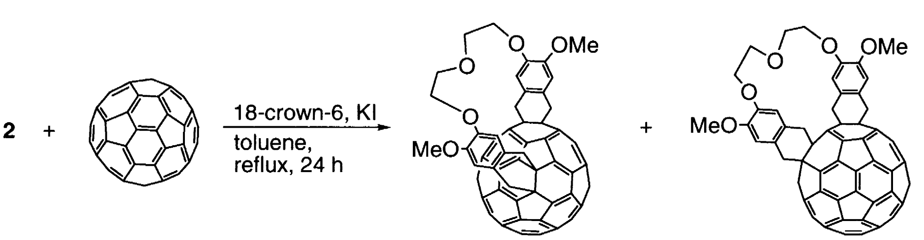


3

We have first examined the reaction using **2**, which can be regarded as a reference compound of both **1c** and **3**. The preparation of **2** is depicted in Scheme 1. Equimolar amounts of [60]fullerene and **2** were refluxed in toluene in the presence of KI (10 equiv.) and 18-crown-6 (40 equiv.) for 24 h under high-dilution conditions ($1\text{–}4\times10^{-4}$ M). After insoluble oligomeric materials were removed, the reaction mixture was purified by column chromatography (silica gel) and GPC, to give mainly two bisadduct regioisomers **4a** and **4b** in 26 and 10% yields, respectively (Scheme 2). The ^{1}H NMR spectral patterns of **4a** and **4b** were different from each other; the former shows four aromatic and two methoxy proton peaks, while the latter only two aromatic and one methoxy proton peak,[7] indicating that **4a** has C_1 symmetry and **4b** C_2 or C_s. These symmetries were also confirmed by the ^{13}C NMR spectra. It is most reasonable to assign **4a** as *e*-isomer, because the other regioisomers should usually adopt higher symmetry.[8] In **4b**, one of the aromatic proton peaks was resonated at much lower field (δ 7.60) than any protons in **4a** (δ 6.85–7.25). Since this behavior is characteristic of *cis*-2 isomers due to steric compression as reported previously,[6] **4b** is reasonably assigned as the *cis*-2 isomer. These assignments are also supported by their UV–vis spectra, which are similar to those of the bisadducts obtained from precursors **1**, since the UV–vis spectra of bisadducts are known to depend mainly on addition patterns.[3,6] The formation of *cis*-2 isomer, which was not obtained from **1c**, is ascribed to the increase in flexibility in bridging linkage of **2** due to the C–O ether bond. The presence of a single oxygen atom in **2** remarkably altered the regioselectivity.



Scheme 1.

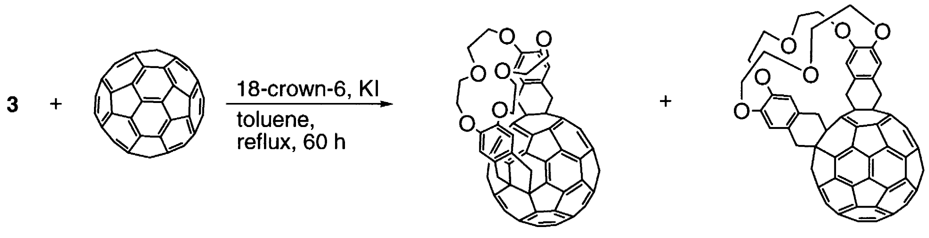


4a (*e*)
y. 26%

4b (*cis*-2)
y. 10%

Scheme 2.

Precursor **3** was prepared from commercially available dibenzo-18-crown-6 in a manner similar to that in **2**. The reaction of **3** with [60]fullerene was carried out under conditions similar to those in **2**, except for heating for 60 h (Scheme 3). Purification of the reaction mixture by GPC gave mainly two bisadducts **5a** (major) and **5b** (minor) (total 64% yield), which were successfully separated by preparative TLC. The ^{1}H and ^{13}C NMR spectra of both **5a** and **5b** apparently indicated C_2 or C_s symmetry.[9] In **5b**, downfield-shifted aromatic protons were again observed (δ 7.58), leading to the assignment as *cis*-2. The addition sites of **5a** could not be clarified by the NMR spectra alone. The UV–vis spectrum of **5a**, however, exhibits two broad maxima at 643 and 708 nm, which are characteristic of the *trans*-4 bisadduct as reported in the literature.[10] This addition pattern is compatible with the symmetry observed in the NMR spectra. The UV–vis spectrum of **5b**, similar to that of the *cis*-2 bisadduct from precursors **1a** or **1b**, supports the *cis*-2 bisaddition. The preferential formation of *trans*-4 bisadduct **5a** from **3**, in remarkable contrast with the formation of *e*-bisadduct from **1c** or **2**, seems quite reasonable, since the dibenzo-18-crown-6 moiety of **3** is expected to force the two *o*-quinodimethane precursors to be almost parallel, making favorable for *trans*-4 rather than *e*-bisaddition. Thus, the double bridging linkages proved to be effective for the regulation of relative arrangement of the two reactive species.



5a (*trans*-4)
y. 51%

5b (*cis*-2)
y. 13%

Scheme 3.

The complexation of **5a** and **5b** with alkali metal ions was investigated by electrospray ionization MS (ESI-MS). The mixed solution containing equimolar amounts of **5a** (or **5b**) and $MClO_4$ (M^+=Li^+, Na^+, K^+, Rb^+, and Cs^+) in methanol:chloroform (1:1) was subjected to ESI-MS. Each solution of **5a** afforded the peak due to the [**5a**+M]$^+$ ion, implying the complexation with the alkali metal ions in a ratio of 1:1. On the other hand, **5b** hardly showed the peaks of [**5b**+M]$^+$ with any alkali metal ions. In the competition experiments using **5a** and all the alkali metal ions listed above, the peak of [**5a**+K]$^+$ was observed with the highest intensity. The difference in complexing ability between **5a** and **5b** can be readily explained by the difference in the shape of dibenzo-18-crown-6 moiety. According to the molecular dynamics calculations, the dibenzo-18-crown-6 moiety in **5b** suffers from considerable deformation, which is apparently caused by the reduced distance and relative arrangement between the two addition sites that are not situated in parallel.

The selectivity of **5a** toward K^+ over Na^+ ion was further investigated with an ion-selective electrode.[11] The selectivity coefficients ($K_{\mathrm{Na,K}}^{\mathrm{pot}}$) for the electrode consisting of **5a** and dibenzo-18-crown-6 as a reference were determined by the separate solution method.[12] Surprisingly, the $K_{\mathrm{Na,K}}^{\mathrm{pot}}$ value (=42) for **5a** was much higher than that (=13) of dibenzo-18-crown-6 electrode, indicating high selectivity toward K^+.

In summary, in contrast with **1c** or **2** having a single bridging linkage, the reaction of [60]fullerene with **3** containing a dibenzo-18-crown-6 moiety that can be regarded as double bridging linkages connecting two *o*-quinodimethane precursors provided preferentially *trans*-4 bisadduct **5a**, which exhibits intriguing complexation behavior. This method using double bridging linkages enables the control of relative arrangement as well as distance between the reactive species and appears to be versatile for the regioselective synthesis of specific bisadducts. The reactions of *o*-quinodimethane precursors incorporated into other macrocyclic systems are now under investigation.

Acknowledgements

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7. Selected spectroscopic data of **4a** and **4b** are as follows. Compound **4a**: ^{1}H NMR (CDCl$_3$, 500 MHz) δ 7.25 (1H, s), 7.04 (1H, s), 7.00 (1H, s), 6.85 (1H, s), 4.67 (1H, m), 4.48 (1H, d, J=12.8 Hz), 4.45 (1H, m), 4.43 (1H, d, J=12.8 Hz), 4.23 (1H, m), 4.21 (1H, d, J=13.4 Hz), 4.12 (1H, d, J=13.7 Hz), 4.07 (1H, m), 3.99 (3H, s), 3.96 (3H, s), 3.90 (1H, d, J=12.8 Hz), 3.88 (1H, m), 3.88 (1H, d, J=13.7 Hz), 3.83 (1H, d, J=12.8 Hz), 3.72 (1H, m), 3.65 (1H, m), 3.55 (1H, m), 3.10 (1H, d, J=13.4 Hz); ^{13}C NMR (CDCl$_3$, 125 MHz) δ 162.13, 161.07, 155.60, 155.41, 155.27, 155.13, 154.70, 154.40, 150.29, 149.29, 149.14, 148.48, 148.13, 148.03, 147.97, 147.91, 147.53, 147.26, 146.56, 146.47, 146.23, 146.01, 145.94, 145.71, 145.65, 145.45, 145.25, 145.04, 144.94, 144.77, 144.72, 144.65, 144.61, 144.57, 144.52, 144.19, 143.57, 143.50, 143.01, 142.92, 142.58, 142.48, 142.25, 142.20, 142.11, 141.96, 141.58, 141.19, 140.97, 140.07, 140.03, 136.64, 136.47, 136.24, 135.70, 135.49, 133.46, 131.83, 130.86, 128.90, 118.88, 118.61, 113.74, 113.51, 113.29, 113.23, 112.09, 111.84, 70.21, 69.95, 69.51, 69.14, 66.53, 65.73, 64.75, 57.23, 56.95, 45.02, 43.68, 42.87, 42.57; FAB MS *m/z* 1090 (M$^+$). Compound **4b**: ^{1}H NMR (CDCl$_3$, 500 MHz) δ 7.60 (2H, s), 6.97 (2H, s), 4.68 (2H, m), 4.63 (2H, d, J=14.2 Hz), 4.40 (2H, m), 4.24 (2H, m), 4.08 (2H, m), 4.05 (2H, d, J=14.2 Hz), 3.93 (2H, d, J=14.0 Hz), 3.92 (6H, s), 3.90 (2H, d, J=14.0 Hz); ^{13}C NMR (CDCl$_3$, 125 MHz) δ 160.63, 159.08, 150.47, 149.47, 147.48, 147.37, 147.30, 147.15, 147.00, 146.68, 146.20, 145.95, 145.49, 145.21, 145.14, 145.01, 144.77, 144.61, 144.56, 144.29, 144.29, 143.68, 142.65, 141.47, 141.15, 138.70, 133.19, 131.36, 131.15, 129.71, 128.28, 128.12, 117.40, 111.51, 111.16, 71.81, 71.40, 63.03, 62.56, 55.65, 44.84, 42.63; FAB MS *m/z* 1090 (M$^+$).
8. The regioisomers such as *cis*-2, *cis*-3, and *trans*-4 can also adopt C_1 symmetry under the unsymmetrical bridging mode, but they were excluded by the UV–vis spectra and molecular dynamics calculations.
9. Selected spectroscopic data of **5a** and **5b** are as follows. Compound **5a**: ^{1}H NMR (CDCl$_3$, 500 MHz) δ 7.01 (2H, s), 6.75 (2H, s), 4.5–4.6 (6H, m), 4.28 (4H, m), 4.15 (2H, m), 3.97 (2H, d, J=12.5 Hz), 3.79 (2H, d, J=13.2 Hz), 3.73 (2H, m), 3.54 (2H, m), 3.18 (4H, m); ^{13}C NMR (CDCl$_3$, 125 MHz) δ 155.57, 155.24, 153.21, 151.06, 149.35, 148.83, 148.57, 146.30, 146.22, 145.98, 145.69, 145.56, 144.85, 144.61, 143.14, 142.87, 142.02, 141.93, 141.64, 141.12, 140.76, 138.86, 136.75, 136.46, 135.38, 131.44, 129.95, 129.23, 122.05, 115.29, 69.10, 68.83, 68.59, 67.40, 66.15, 65.74, 44.35, 43.37; FAB MS *m/z* 1132 (M$^+$). Compound **5b**: ^{1}H NMR (CDCl$_3$, 500 MHz) δ 7.58 (2H, s), 6.98 (2H, s), 4.70 (4H, m), 4.51 (2H, m), 4.33 (2H, m), 4.31 (2H, d, J=14.4 Hz), 4.1 (2H, m), 4.09 (2H, d, J=14.4 Hz), 3.99 (2H, d, J=13.2 Hz), 3.95 (2H, m), 3.62 (2H, d, J=13.2 Hz), 3.37 (2H, m), 2.69 (2H, m); ^{13}C NMR (CDCl$_3$, 125 MHz) δ 162.03, 158.20, 151.07, 149.71, 149.37, 149.11, 147.76, 147.25, 147.07, 146.92, 146.71, 146.51, 145.96, 145.95, 145.88, 145.74, 145.31, 145.14, 144.89, 144.62, 144.46, 144.27, 144.24, 143.42, 142.56, 141.86, 141.42, 136.60, 134.51, 133.57, 133.06, 132.93, 129.14, 122.19, 116.45, 71.95, 70.46, 70.45, 68.72, 64.03, 63.65, 43.09, 43.05; FAB MS *m/z* 1132 (M$^+$).
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11. Ion sensitive membrane of the poly(vinyl chloride) matrix type was prepared as follows: **5a** (0.9 mg), *o*-nitrophenyl octyl ether (63 mg), poly(vinyl chloride) (25 mg), and potassium tetrakis(*p*-chlorophenyl)borate (0.6 mg) were dissolved in THF (1 mL). The solution was injected to fill the final 4 mm of the tip of a glass pipette (0.74 mm i.d.). A transparent membrane was obtained by evaporation of the solvent at room temperature. The electrode was conditioned by soaking in 0.3 M KCl solution during 15 h before use. The reference electrode was an Ag·AgCl electrode with agar bridge containing 50 mM NaCl. The electrode cell for emf measurement is as follows: Ag·AgCl/4 M KCl/PVC membrane/sample solution/0.05 M NaCl agar bridge/4 M KCl/AgCl·Ag. Emf was measured at 25±0.5°C with a digital mV meter. The $K_{i,j}^{pot}$ (i, primary ion; j, interfering ion) values were calculated from response potential in a 0.1 M cation chloride solution by the separate solution method.
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