Asymmetric Bisosmylation of C_{60}: Novel Chiral π-Systems

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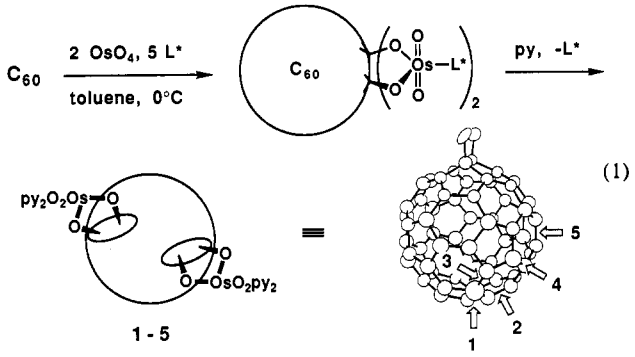
The addition of substituents to C_{60} lowers the symmetry of the carbon framework and increases the topological complexity of the π-system. In particular, osmylation yields 1:1 and 2:1 adducts with cup- and band-shaped π-systems, respectively.[1,2] Five regioisomers of the 2:1 adduct $C_{60}(OsO_4L_2)_2$ are formed, including two isomers which are chiral by virtue of the substitution pattern on the icosahedral carbon cluster.[2,3] Here, we report the asymmetric bisosmylation of C_{60}, yielding enantiomerically enriched chiral (C_2) isomers **2** and **3**, and an analysis of the novel chiral band-shaped π-systems of these fullerene derivatives by circular dichroism (CD) spectroscopy.

The regiochemistry and stereochemistry of the bisosmylation of C_{60} are affected by the ligands on osmium (eq 1, Table I). Both



(1)

osmyl groups add to the fusion of two six-membered rings, with the first group directing the second oxidation away from the proximate hemisphere.[2] The tendency of the second osmyl group to add away from the first is only marginally increased by bulkier ligands on osmium (compare entries 1 and 2). The isomer ratios are affected considerably more by the various Sharpless cinchona alkaloid ligands (entries 3–10),[4] and these ligands were tested for asymmetric induction. Treatment of C_{60} with 2 equiv of OsO_4 and 5 equiv of chiral ligand, followed by complete exchange of the chiral ligands on osmium for pyridine and chromatography on silica gel,[5] yielded chiral isomers **2** and **3** with optical rotations up to 3700°. The CD spectra of both enantiomers of **2** and **3** show mirror image spectra for the mirror image molecules (Figures 1 and 2). Chromatography of racemic **2** and **3** on a chiral bound phase HPLC column (Pirkle column)[6] gave a slight separation of the enantiomers. Partially resolved adducts prepared by shaving HPLC peaks from the Pirkle column showed CD spectra identically shaped (but lower in magnitude) as those found for

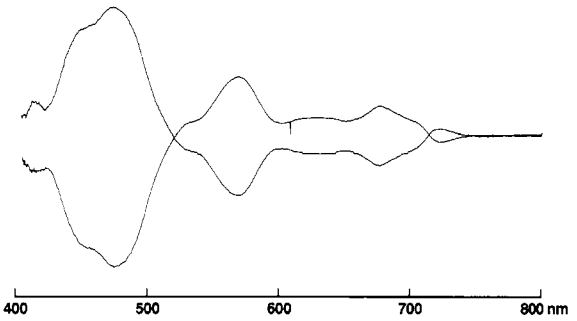


Figure 1. CD spectrum of (+)-**2** (entry 7 of Table I, negative at 477 nm) superimposed on the CD spectrum of (–)-**2** (entry 6 of Table I, positive at 477 nm). (+)-**2** (1.46×10^{-3} M in CH_2Cl_2), λ ($\Delta\epsilon$): 456 (sh, –5.92), 477 (–6.95), 535 (sh, +0.84), 572 (+3.19), 628 (+1.05), 677 (+1.70), 725 (–0.43).

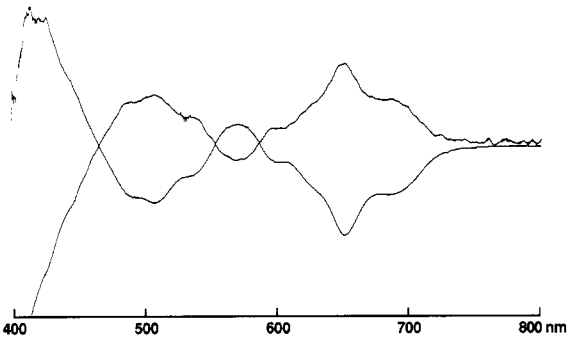


Figure 2. CD spectrum of (+)-**3** (entry 9 of Table I, negative at 652 nm) superimposed on the CD spectrum of (–)-**3** (entry 8 of Table I, positive at 652 nm). (+)-**3** (6.69×10^{-4} M in CH_2Cl_2), λ ($\Delta\epsilon$): 490 (sh, –8.57), 507 (–9.65), 540 (sh, –4.58), 572 (+3.44), 652 (–15.3), 690 (–8.38).

2 and **3** prepared via eq 1, establishing that the optical activity is not alkaloid based.

Certain ligands favor particular regioisomers of bisosmylated C_{60}. Compared to the isomer ratios obtained with the pyridine and 4-chlorobenzoylalkaloid ligands (entries 1–4), isomers **2**, **3**, **4**, and **5** are favored in entries 7, 9, 10, and 8, respectively. This effect does not appear to be steric in origin, as the distance between the osmyl groups in the favored isomers is not related to the size of the ligands. The highest enantioselectivities for **2** and **3** correspond to the cases where these regioisomers are favored (entries 7 and 9). This suggests that enantioselectivity results from attractive rather than repulsive interactions. Attractive interactions favoring one enantiomer of a particular regioisomer would increase the total amount of that regioisomer relative to the others. Conversely, if enantioselectivity resulted from steric repulsion disfavoring one enantiomer of a regioisomer, then that regioisomer would be disfavored as a whole. Thus, both regiochemistry and stereochemistry in this system appear to be controlled by attractive electronic interactions.[7] Close contacts

(1) Hawkins, J. M.; Meyer, A.; Lewis, T. A.; Loren, S.; Hollander, F. J. *Science* **1991**, *252*, 312. Hawkins, J. M. *Acc. Chem. Res.* **1992**, *25*, 150.

(2) Hawkins, J. M.; Meyer, A.; Lewis, T. A.; Bunz, U.; Nunlist, R.; Ball, G. E.; Ebbesen, T. W.; Tanigaki, K. *J. Am. Chem. Soc.* **1992**, *114*, 7954.

(3) For the preparation of C_{60} derivatives which are chiral by virtue of chiral substituents (sugars), see: Vasella, A.; Uhlmann, P.; Waldraff, C. A. A.; Diederich, F.; Thilgen, C. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 1388.

(4) Sharpless, K. B.; Amberg, W.; Beller, M.; Chen, H.; Hartung, J.; Kawanami, Y.; Lübben, D.; Manouri, E.; Ogino, Y.; Shibata, T.; Ukita, T. *J. Org. Chem.* **1991**, *56*, 4585. Sharpless, K. B.; Amberg, W.; Bennani, Y. L.; Crispino, G. A.; Hartung, J.; Jeong, K.-S.; Kwong, H.-L.; Morikawa, K.; Wang, Z.-M.; Xu, D.; Zhang, X.-L. *J. Org. Chem.* **1992**, *57*, 2768.

(5) The reaction mixture was evaporated to dryness under vacuum, dissolved in pyridine, and column chromatographed on silica gel with pyridine. This exchanges the chiral alkaloid ligands for pyridine and separates the 2:1 adducts from any unreacted C_{60}, 1:1 adduct, or higher order adducts which may be present. $C_{60}(OsO_4py_2)_2$ isomers **2** and **3** were separated from the fraction containing **1**–**5** by preparative HPLC on silica gel (10% pyridine in chloroform). To assure that **2** and **3** were completely free of the chiral alkaloid ligands, they were subjected to a second HPLC purification under conditions where **2** and **3** (as the 4-*tert*-butylpyridine complexes) separate widely from L* (silica gel, 5% 4-*tert*-butylpyridine in chloroform). To convert the 4-*tert*-butylpyridine complexes back into pyridine complexes, **2** and **3** were dissolved in pyridine and evaporated to dryness under vacuum three times. Throughout this procedure, care was taken not to alter diastereomeric or enantiomeric purities by crystallization.

(6) Pirkle, W. H.; Finn, J. M.; Hamper, B. C.; Schreiner, J.; Pribish, J. R. In *Asymmetric Reactions and Processes in Chemistry*; Eliel, E. L., Otsuka, S., Eds.; ACS Symposium Series 185; American Chemical Society: Washington, DC, 1982; Chapter 18.

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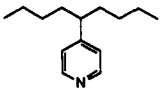
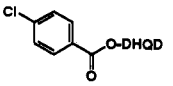
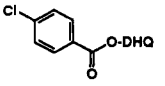
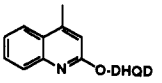
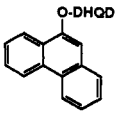
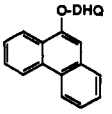
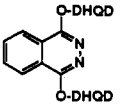
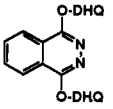
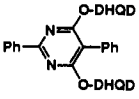
Table I. Regiochemistry and Stereochemistry of the Bisosmylation of C_{60}

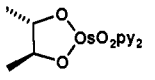
entry	ligand[a]	ratio[b] of $C_{60}(OsO_4py_2)_2$ isomers **1**:**2**:**3**:**4**:**5**	isomer **2** $[\alpha]_{436}$ ($[\alpha]_D$)	isomer **3** $[\alpha]_{436}$ ($[\alpha]_D$)
1		2:17:27:13:41		
2		4:20:28:11:38		
3		4:21:26:12:36	low	low
4		4:17:28:11:39	low	low
5		2:18:23:20:36	low	low
6		3:20:23:14:39	−707° (−69.6°)	(23°)
7		2:28:24:10:35	957° (88.6°)[c]	−52° (−25.8°)
8		1:16:18:13:52	324° (10°)	−564° (−227°)
9		3:17:36:11:33	150° (12°)	3700° (1740°)[d]
10		2:16:9:52:21		

[a] DHQD = dihydroquinidine, DHQ = dihydroquinine. [b] Measured by HPLC integration, detected at 400 nm. [c] *c* 0.226, CH_2Cl_2. [d] *c* 0.0122, CH_2Cl_2.

between arenes and fullerenes have been observed in several crystal structures.[8] Attractions between the arene components of the cinchona alkaloid ligands and the fullerene surface may dictate the enantioselectivity and regioselectivity observed here.

These C_{60} derivatives contain two chromophores, the C_{60}-based π-system and the osmyl groups. For isomers **2** and **3**, the peaks in the CD spectra may arise from three sources: (1) the chiral band-shaped π-systems, (2) the local asymmetries at the osmyl groups, and (3) the spacial relationships between the asymmetrically disposed osmyl groups. The UV–visible spectra of isomers **2**–**5** differ the most in the 500–800-nm region. These differences most likely reflect the differently contoured band-shaped π-systems of these species, as the osmyl group chromophores should be very similar for **2**–**5**.[9] The CD spectrum of **6**, chosen to model local asymmetry at an osmyl group, shows only a broad tail in this region. Thus the CD peaks in the 500–800-nm region likely reflect the novel chiral band-shaped π-systems of **2** and **3**.[10]

This chemistry, demonstrating enantioselective reactions on a fullerene surface, and the osmylation of C_{70}, demonstrating the



6

regioselective osmylation of a higher fullerene,[11] provided the basis for the kinetic resolution of the chiral fullerenes C_{76}, C_{78}, and C_{84} by asymmetric osmylation.[12] Existing reagents[4] provided sufficient asymmetric induction to prepare **2** and **3** with substantial optical rotations and C_{76} with >97% ee.[12] Reagents designed to optimize attractive electronic interactions between reagent π-systems and fullerene surfaces could allow complete stereo- and regiocontrol in fullerene chemistry.

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(7) For an example of attractive electronic interactions controlling enantioselection in a Diels-Alder system, see: Hawkins, J. M.; Loren, S. *J. Am. Chem. Soc.* **1991**, *113*, 7794.

(8) Balch, A. L.; Catalano, V. J.; Lee, J. W.; Olmstead, M. M. *J. Am. Chem. Soc.* **1992**, *114*, 5455 and references therein. See also: Izuoka, A.; Tachikawa, T.; Sugawara, T.; Saito, Y.; Shinohara, H. *Chem. Lett.* **1992**, 1049.

(9) **2** UV (CH_2Cl_2) λ (ε): 472 (1324), 618 (244), 648 (235), 656 (sh, 212), 680 (151), 718 (202). **3** UV (CH_2Cl_2) λ (ε): 520 (sh, 851), 600 (sh, 302), 624 (sh, 227), 654 (sh, 143), 686 (sh, 89).

(10) The chiral fullerenes C_{76}, C_{78}, and C_{84} also show CD peaks in this region.[12]

(11) Hawkins, J. M.; Meyer, A.; Solow, M. A. *J. Am. Chem. Soc.* **1993**, *115*, 7499.

(12) Hawkins, J. M.; Meyer, A. *Science* **1993**, *260*, 1918. Hawkins, J. M.; Nambu, M.; Meyer, A., manuscript in preparation.