ethereal CH_2N_2 (5 mL). The mixture was left at room temperature for 2 h. The solvent was evaporated and the residue was subjected to HPLC (30 cm × 3.9 mm i.d. C_{18} μ-Bondapak column). Elution with 80:20 MeOH/H_2O gave two main compounds. The first eluted (the major product) was collected and was analyzed by FABMS: M–H peaks at m/z 1043, 1045, 1047, 1049, 1051 (quintet); ^1H NMR (CD_3OD) δ 0.89 (t, J = 7 Hz), 3.53, 4.23 and 4.24 (each s, $-OCH_3$); UV (MeOH) λ_{max} 221, 277, 316, and 451 nm (ε 13 000, 7900, 6000, and 5300).

Compound **5b** (5 mg) was methylated with CH_2N_2 in a similar manner. HPLC as described above gave four compounds. The major (first eluted) compound was collected and was analzyed by FABMS: $[M - H]^-$ ions at m/z 1043, 1045, 1047, 1049, 1051 (quintet); ^1H NMR (CD_3OD) δ_H 0.23 (t, J = 7 Hz), 3.62, 4.23 and 4.24 (each s, $-OCH_3$); UV (MeOH), λ_{max} 221, 277, 316, and 451 nm (ε 12 000, 13 000, 7900, and 6000).

Isomerization of Gymnochrome B (2). A pyridine (0.5 mL) solution of gymnochrome B (8 mg) was heated at 160 °C for 20 h. The reaction was monitored by TLC (*n*-BuOH/$CHCl_3$ (1:1)). Evaporation of the pyridine gave a mixture of gymnochrome B (**2**) and its isomer, isogymnochrome B (**2a**). Purification by HPLC (30 cm × 3.9 mm i.d. C_{18} μ-Bondapak column; MeOH/H_2O (65:35)) gave pure gymnochrome B (**2**) and a mixture of isogymnochrome B **2a** and a small amount of **2**. The latter was analyzed without further purification. In addition to signals due to **2**, the ^1H NMR spectrum of the mixture showed signals at δ 1.14 (d, J = 5 Hz) and 0.07 (t, J = 7 Hz) due to the methyl protons of the C_3 and C_5 chain, respectively, characteristic of **2a**; other signals appeared at δ 4.10 and 3.70 [$ArCH_2CH(OH)-$] and δ 0.10 and 1.6 (methylene protons at C-20 and C-21 of the C_5 chains); CD (MeOH, c = 4.21 × 10^{-4} g/mL): 212 (Δε = −4.20), 233 (Δε = +2.21), 250 (Δε = −2.90), 290 (Δε = +7.03), 318 (Δε = −4.10), 358 (Δε = +1.01), 380 (sh) (Δε = +0.45), 435 (Δε = −3.8), 477 (Δε = −2.25), 542 (Δε = +1.35), and 587 (Δε = +2.62). The lower intensity of the CD spectrum is consistent with the presence of **2** (Δε of the CD curve of **2** is opposite in sign to that of **2a**).

Isomerization of 4b to Give 5b. A pyridine solution of sulfur-free gymnochrome D (**4b**, 8 mg) was heated at 160 °C. The reaction was monitored by TLC (*n*-BuOH/$CHCl_3$ (1:1)). After 20 h, the pyridine was evaporated and the residue was subjected to HPLC (30 cm × 3.9 mm i.d. C_{18} μ-Bondapak). Elution with 72:28 MeOH/H_2O gave **4b** and **5b**.

Isogymnochrome D (**5b**) was isomerized to **4b** in a similar manner.

Reaction with (±)-2-Phenylbutyric Anhydride. (±)-2-Phenylbutyric anhydride (0.5 μL) was added to a pyridine solution (30 μL) of the hexamethyl derivative (0.45 mg) formed by the methylation of **4b**. The solution was warmed at 55 °C for 6 h in a sealed vial. A parallel reaction was performed with cyclohexanol. (+)-(*R*)-α-Phenylethylamine (0.58 μL) was added to both solutions. After 30 min, the solutions were diluted with EtOAc (40 μL) and samples were analyzed by GLC–MS (0.20 mm × 25 m fused silica capillary column coated with a 0.33 μm thick film of HP-5 (cross-linked phenyl methyl silicone, 5%) temperature programmed from 120 to 220 °C at 5.00 °C/min).

The relative proportions of the amides of (−)-(*R*)- and (+)-(*S*)-α-phenylbutyric acid (retention times 28 and 29 min, respectively) were indicated by the areas of their respective GLC peaks, which were corrected by subtracting the corresponding peak areas of the product from reaction with cyclohexanol. The increment of the (*S*)-(+)-acid was 4%. When the reaction was applied to the hexamethyl derivative of **5b**, the increment of the (*S*)-(+)-acid was 8%.

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Supplementary Material Available: ^1H NMR spectra of the obtained compounds (15 pages). Ordering information is given on any current masthead page.

Synthesis of the Helicopodands: Novel Shapes for Chiral Clefts†

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Helicopodands are a new class of chiral nonmacrocyclic ("podand") receptors with a helicene backbone ("helico"). At the termini of the helix, they form a preorganized cleft of pronounced asymmetric character which is aligned with convergent hydrogen bonding functionality. The synthetic routes to the two helicopodands **2** and **3** each include two photocyclodehydrogenation reactions. The X-ray crystal structure of **14**, a direct helical precursor to **2** and **3**, confirms the main structural features of the helicopodands. MMP2 calculations give a geometric description of **14** which is in reasonable agreement with the X-ray results.

Introduction

In the mid 1980's, molecular clefts aligned with convergent functional groups for small substrate recognition through hydrogen bonding were introduced as a versatile new class of receptors by Rebek et al.[1] In subsequent rapid developments, several other research groups prepared cleft-type receptors shaped by a wide variety of structural elements and investigated the selective hydrogen bonding recognition of a diversity of substrates.[2-7] These

† We dedicate this paper to Professor Vladimir Prelog on the occasion of his 85th birthday.

(1) (a) Rebek, J., Jr. *Angew. Chem.* **1990**, *102*, 261–272; *Angew Chem., Int. Ed. Engl.* **1990**, *29*, 245–255. (b) Rebek, J., Jr. *Acc. Chem. Res.* **1990**, *23*, 399–404. (c) Novick, J. S.; Ballester, P.; Ebmeyer, F.; Rebek, J., Jr. *J. Am. Chem. Soc.* **1990**, *112*, 8902–8906.

(2) Adrian, J. C., Jr.; Wilcox, C. S. *J. Am. Chem. Soc.* **1991**, *113*, 678–680.

0022-3263/91/1956-6787$02.50/0

studies were generally performed in solvents that do not compete effectively for the hydrogen bond donor and acceptor sites on both receptors and substrates, i.e., benzene, chloroform, or tetrahydrofuran (THF).

Chiral recognition of organic substrates in designed molecular complexes has attracted increasing interest in recent years.[8] Worthwhile objectives of this research are the development of new receptors for enantiomer separations in chromatographic, crystallization, or transport experiments and the creation of chiral environments and reagents for asymmetric synthesis and catalysis. Of the large number of molecular clefts reported, only a few are chiral and have been explored as enantioselective receptors. Wilcox et al. selected chiral Tröger's base derivatives as spacers for their receptors.[9,10] Rebek et al. reported high enantioselectivity ($\Delta\Delta G^\circ \approx 2.5$ kcal mol^{-1}) in the complexation of asymmetric diketopiperazines in clefts shaped by modified Kemp's triacid derivatives.[11] Lehn and de Mendoza et al. observed differential binding of the triethylammonium salts of the D and L enantiomers of *N*-acetyltryptophane in an optically active cleft containing a rigid guanidinium subunit.[12]

In our exploration of chiral molecular recognition by synthetic receptors, we have developed a variety of new spacers that provide asymmetric binding sites in both cyclophanes[13a,b] and molecular clefts.[13c] Efficient enantioselective complexation of cinchona alkaloids was observed in chloroform with chiral clefts shaped by the major groove of the 1,1'-binaphthyl unit. For example, the diastereomeric complex formed by (*R*)-**1** and quinine is 1 kcal mol^{-1} more stable than the complex formed by (*S*)-**1**.[13c] Here, we report on the first use of helicenes as chiral backbones for molecular clefts.[14] Hexahelicene and larger [*n*]helicenes possess rigid helical structures with corresponding high optical stability.[15-19] As a result of their nonplanarity, the crystal packing forces in solid helicenes are much weaker than those in solid planar polycyclic aromatic hydrocarbons of comparable size. Therefore, despite their extended shapes, helicene-type receptors should possess satisfactory solubility[4b] in the solvents commonly used for hydrogen bonding complexation.

Scheme I

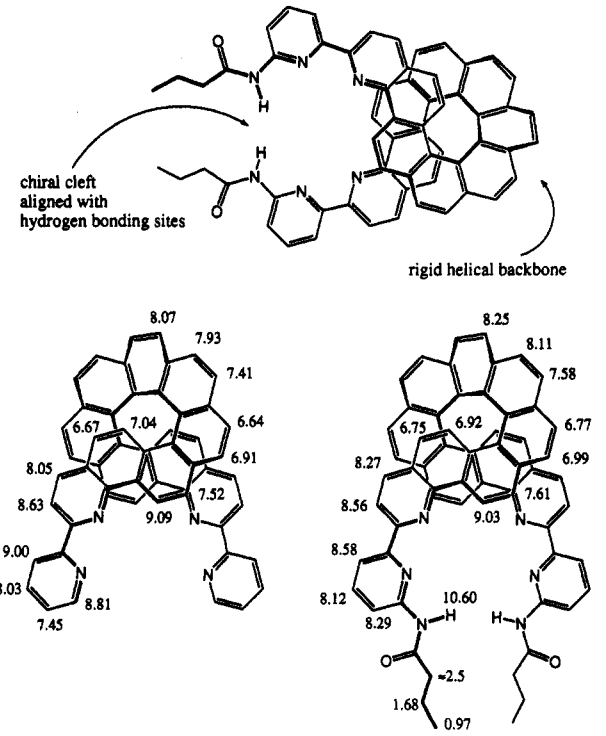
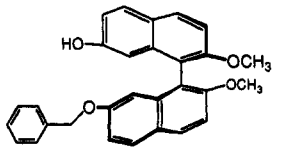
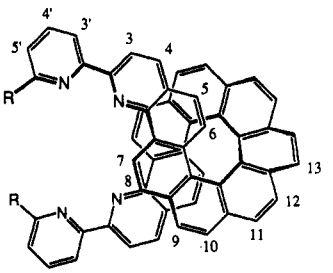


Figure 1. Assignment of the resonances in the 500-MHz ^{1}H NMR spectra of **2** in $CDCl_3$ and **3** in Me_2SO-d_6.



(*R*)-**1**



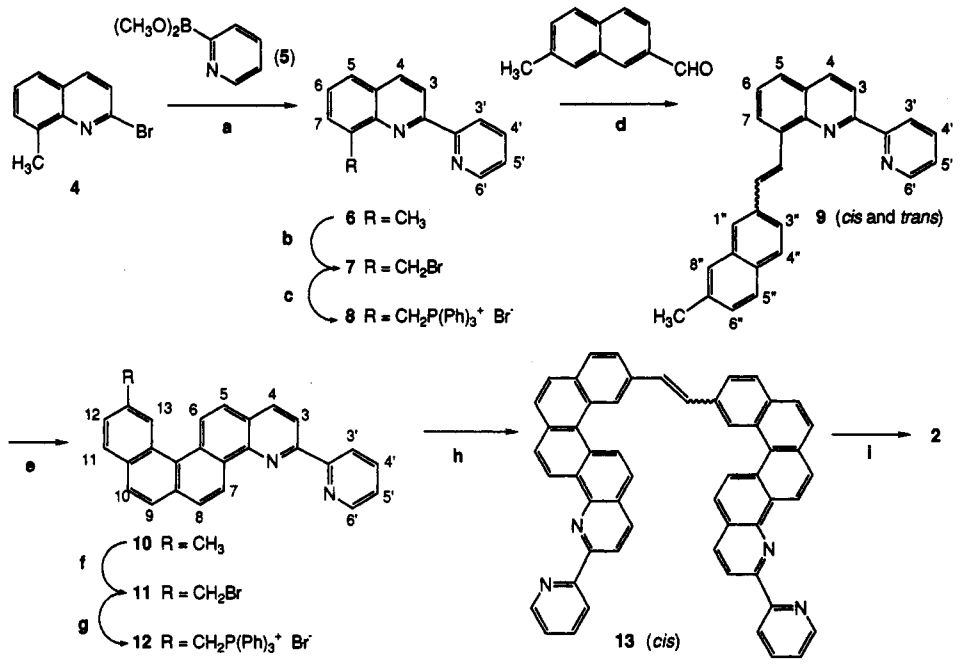
2 R = H

3 R = $NHCOC_3H_7$

The target molecules of this study, compounds **2** and **3**, are members of a new class of receptors which we term the *helicopodands*. The name "helicopodand" characterizes members of this class as nonmacrocyclic ("podand")[20] and derived from helicenes ("helico"). In **2** and **3**, a dipyrido[9]helicene acts as a rigid backbone to shape a preorganized cleft of pronounced asymmetric character at the ends of the helical turn (Scheme I). The cleft is aligned with

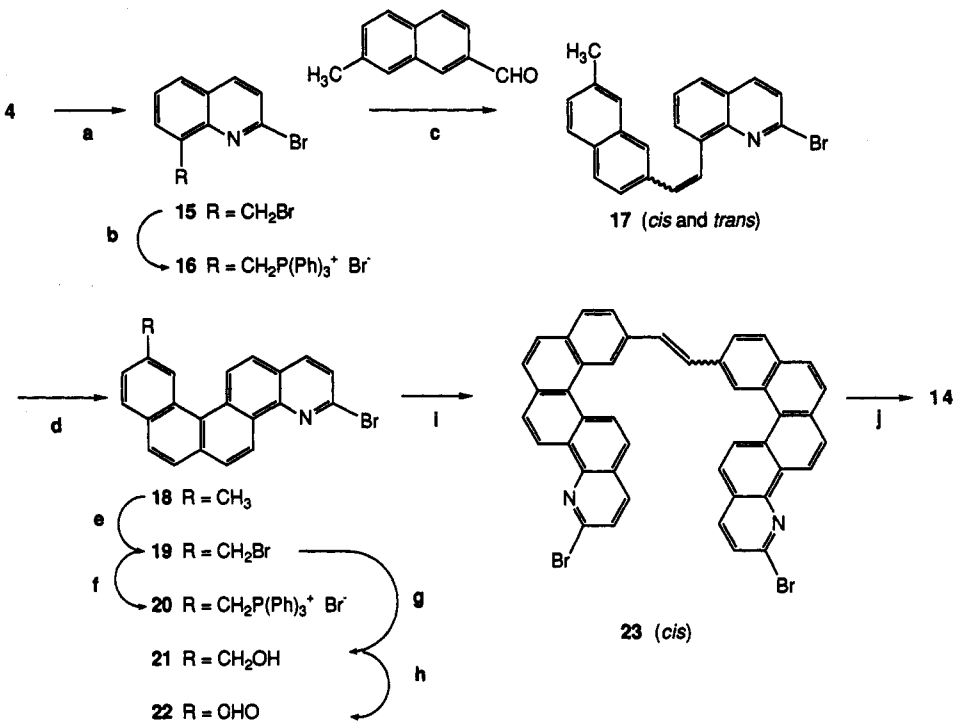
(3) Tecilla, P.; Dixon, R. P.; Slobodkin, G.; Alavi, D. S.; Waldeck, D. H.; Hamilton, A. D. *J. Am. Chem. Soc.* **1990**, *112*, 9408–9410.
(4) (a) Kelly, T. R.; Bridger, G. J.; Zhao, C. *J. Am. Chem. Soc.* **1990**, *112*, 8024–8034. (b) Kelly, T. R.; Maguire, M. P. *J. Org. Chem.* **1987**, *109*, 6549–6551.
(5) Zimmerman, S. C.; Zeng, Z.; Wu, W.; Reichert, D. E. *J. Am. Chem. Soc.* **1991**, *113*, 183–196.
(6) Bell, T. W.; Liu, J. *J. Am. Chem. Soc.* **1988**, *110*, 3673–3674.
(7) (a) Gallant, M.; Viet, M. T. P.; Wuest, J. D. *J. Org. Chem.* **1991**, *56*, 2284–2286. (b) Sijbesma, R. P.; Kentgens, A. P. M.; Nolte, R. J. M. *J. Org. Chem.* **1991**, *56*, 3199–3201. (c) Huang, C.-Y.; Cabell, L. A.; Anslyn, E. V. *Tetrahedron Lett.* **1990**, *31*, 7411–7414.
(8) (a) Pirkle, W. H.; Pochapsky, T. C. *Chem. Rev.* **1989**, *89*, 347–362. (b) Petti, M. A.; Shepodd, T. J.; Barrans, R. E., Jr.; Dougherty, D. A. *J. Am. Chem. Soc.* **1988**, *110*, 6825–6840. (c) Liu, R.; Sanderson, P. E. J.; Still, W. C. *J. Org. Chem.* **1990**, *55*, 5184–5186. (d) Bradshaw, J. S.; Huszthy, P.; McDaniel, C. W.; Zhu, C. Y.; Dalley, N. K.; Izatt, R. M.; Lifson, S. *J. Org. Chem.* **1990**, *55*, 3129–3137. (e) Puzicha, G.; Pu, Y.-M.; Lightner, D. A. *J. Am. Chem.* **1991**, *113*, 3583–3592.
(9) Adrian, J. C.; Wilcox, C. S. *J. Am. Chem. Soc.* **1989**, *111*, 8055–8057.
(10) Wilen, S. H.; Qi, J. Z.; Willard, P. G. *J. Org. Chem.* **1991**, *56*, 485–487.
(11) Jeong, K.-S.; Muehldorf, A. V.; Rebek, J., Jr. *J. Am. Chem. Soc.* **1990**, *112*, 6144–6145.
(12) (a) Echavarren, A.; Galán, A.; Lehn, J.-M.; De Mendoza, J. *J. Am. Chem. Soc.* **1989**, *111*, 4994–4995. (b) Kurzmeier, H.; Schmidtchen, F. P. *J. Org. Chem.* **1990**, *55*, 3749–3755.
(13) (a) Georgiadis, T. M.; Georgiadis, M. M.; Diederich, F. *J. Org. Chem.* **1991**, *56*, 3362–3369. (b) Diederich, F. *Cyclophanes*; Stoddart, J. F., Ed.; Royal Society of Chemistry: Cambridge, 1991; Chapter 6, pp 222–245. (c) Castro, P. P.; Georgiadis, T. M.; Diederich, F. *J. Org. Chem.* **1989**, *54*, 5835–5838.
(14) For chiral crown ethers incorporating helicene frameworks, see: Nakazaki, M.; Yamamoto, K.; Ikeda, T.; Kitsuki, T.; Okamoto, Y. *J. Chem. Soc., Chem. Commun.* **1983**, 787–788.
(15) Martin, R. H. *Angew. Chem.* **1974**, *86*, 727–738; *Angew. Chem., Int. Ed. Engl.* **1974**, *13*, 649–660.
(16) Laarhoven, W. H.; Prinsen, W. J. C. *Top. Curr. Chem.* **1984**, *125*, 63–130.
(17) Meurer, K. P.; Vögtle, F. *Top. Curr. Chem.* **1985**, *127*, 1–76.
(18) Pereira, D. E.; Leonard, N. J. *Tetrahedron* **1990**, *46*, 5895–5908.
(19) Liu, L.; Katz, T. J. *Tetrahedron Lett.* **1990**, *31*, 3983–3986.
(20) Vögtle, F.; Weber, E. *Angew. Chem.* **1979**, *91*, 813–837; *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 753–776.

Scheme II[a]



[a] Reagents and yields: (a) $[(C_6H_5)_3P]_4Pd$, $(C_2H_5)_4NBr$, KOH, benzene; 56%; (b) NBS, CCl_4; 90%; (c) $(C_6H_5)_3P$, toluene; 69%; (d) NaOEt, EtOH; 63%; (e) $h\nu$, I_2, toluene; 48%; (f) NBS, CCl_4; 78%; (g) $(C_6H_5)_3P$, toluene; 76%; (h) $NaNH_2$, benzene, O_2; 27%; (i) $h\nu$, I_2, toluene; 35%.

Scheme III[a]



[a] Reagents and yields: (a) NBS, CCl_4; 75%; (b) $(C_6H_5)_3P$, toluene; 83%; (c) MeONa, MeOH; 68%; (d) $h\nu$, I_2, toluene; 88%; (e) NBS, CCl_4; 76%; (f) $(C_6H_5)_3P$, benzene; 86%; (g) $Na_2CO_3/H_2O/CH_3CN$; 69%; (h) Pyridinium chlorochromate (PCC), CH_2Cl_2; 71%; (i) MeONa, MeOH/THF; 80%; (j) $h\nu$, I_2, toluene; 76%.

convergent hydrogen bonding centers for substrate recognition. In this paper, we describe the synthesis and structural analysis of the helicopodands **2** and **3**; their complexation properties together with those of other derivatives will be discussed elsewhere.

Results and Discussion

Synthesis of Helicopodand 2. The photocyclodehydrogenation reaction leading from stilbenes to phenanthrenes is the method of choice for the preparation of helicenes.[16,21] This methodology is used twice in the key steps of the syntheses of both **2** (Scheme II) and **3** (Scheme III). The route to **2** begins with 2-bromo-8-methylquinoline (**4**),[22] which was coupled in a Suzuki reaction with the boronic ester **5** to give 2-(2-pyridyl)-8-methyl-

(21) Mallory, F. B.; Mallory, C. *Org. React.* **1984**, *30*, 1–456.
(22) Case, F. H.; Lafferty, J. J. *J. Org. Chem.* **1958**, *23*, 1375–1377.

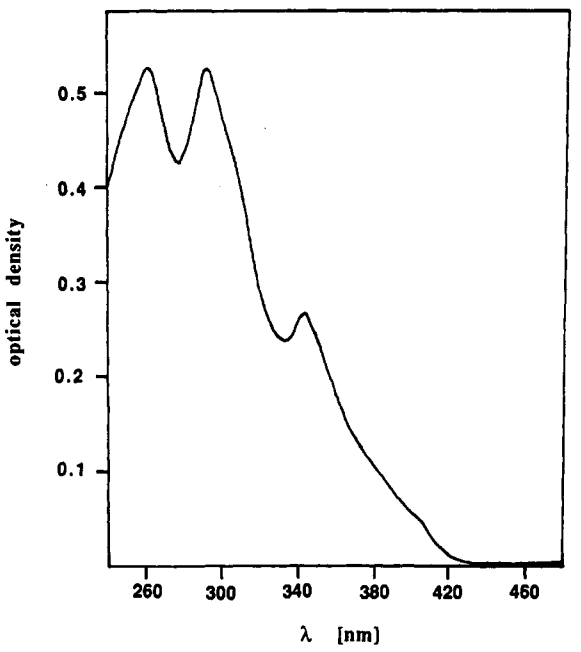


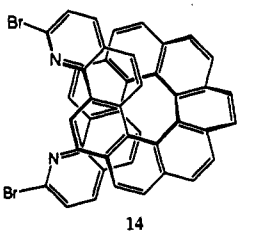
Figure 2. Electronic absorption spectrum of **2** in $CHCl_3$, d = 1 cm, $c = 8 \times 10^{-6}$ mol L^{-1}.

quinoline (**6**; Scheme II).[23] Bromination with *N*-bromosuccinimide (NBS) afforded **7**, which was converted into the phosphonium salt **8**. The Wittig reaction between **8** and 2-formyl-7-methylnaphthalene[24] led to a mixture of *cis*- and *trans*-**9** from which the pure trans isomer was isolated by recrystallization from chloroform. Irradiation of the isomeric mixture of **9** in the presence of iodine led to the phenanthro[4,3-*h*]quinoline derivative **10**. The bromide **11**, prepared by NBS bromination of **10** was subsequently transformed into the phosphonium salt **12**. The phosphorus ylide formed from **12** with sodium amide in benzene reacted with dioxygen in an autoxidation process[25] to yield olefin **13**. Only a single isomer of **13** was isolated, and it was assigned the cis conformation on the basis of its ^1H NMR spectrum.[26] Finally, photocyclodehydrogenation of **13** gave the target helicopodand **2** as yellow microcrystals. The formation of the helical structure was easily confirmed by characteristic upfield chemical shifts in the ^1H NMR spectrum.[27] The signals for protons 5,6,9, and 10 in the spectrum of helicopodand **2** (Figure 1) show particularly large upfield shifts compared to the corresponding resonances in the olefinic precursor **13**: $\Delta\delta$(ppm) = +0.38 (5-H), +1.33 (6-H), ≈ +1.0 (9-H), ≈ +1.27 (10-H). The helical structure orients these protons into shielding anisotropic regions of aromatic rings that are located one entire helical turn apart in the same molecule. The electronic absorption spectrum of **2** with the novel dipyrido[9]helicene chromophore is shown in Figure 2. The helicopodand is readily soluble in carbon tetrachloride, benzene, chloroform, and slightly soluble in benzene/hexane (1:1, v/v) or chloroform/methanol (1:1, v/v).

Synthesis of the Dibromohelicene 14. For the preparation of the second target compound in this study, a more general synthetic approach with the potential for leading to a diversity of helicopodands was developed. In this modified route, the dibromide **14** provides the helical backbone to which a variety of heteroarenes with hydrogen bonding functionality, e.g., pyridine and naphthyridine derivatives, may be attached by metal-catalyzed coupling processes such as the Suzuki[23] or the Negishi[28] reaction.

Table I. Crystal and Data Collection Parameters for 14. The Structure Was Solved by Statistical Methods (SHELX86)

T (K)	298
formula	$C_{44}H_{22}Br_2N_2$
MW	738.48
space group	$P2_1/n$
a (Å)	10.584 (1)
b (Å)	18.204 (2)
c (Å)	18.277 (2)
β (deg)	93.740 (4)
V (calcd) (Å^3)	3514
d (calcd) (g cm^{-3})	1.69
data collection instrument	Huber diffractometer
radiation	Mo K_α
scan mode	θ–2θ
total refls.	5509
total refls (I/σ>3)	2732
$2\theta_{max}$ (deg)	48
R	0.055
R_w	0.066
GOF	1.81



14

The synthesis of **14** (Scheme III) starts with the NBS bromination of 2-bromo-8-methylquinoline (**4**) to give the bromide **15**. Formation of the phosphonium salt **16** and subsequent Wittig reaction with 2-formyl-7-methylnaphthalene afforded a mixture of cis and trans alkene **17**. The pure trans isomer was obtained by crystallization from chloroform and its structure was confirmed by X-ray crystallography (supplementary material). Photocyclodehydrogenation of the isomeric mixture of **17** led to the phenanthro[4,3-*h*]quinoline derivative **18**. NBS bromination of **18** afforded the bromomethyl derivative **19**, which was transformed into the phosphonium salt **20** and, via alcohol **21**, into the aldehyde **22**. The structure of **22** was confirmed by X-ray crystallography (supplementary material). The subsequent Wittig reaction between **20** and **22** produced an 80% yield of the cis isomer of alkene **23**. Interestingly, we were unable to isolate any trans isomer from this reaction. The transition state leading to the cis alkene seems to be significantly favored over the one affording the trans isomer as a result of π–π stacking interactions between the two reacting extended phenanthro [4,3-*h*]quinoline chromophores. The target helicene **14** was obtained by photocyclodehydrogenation of **23** in an excellent yield of 76%. It is notable that the yields for the two photoreactions in the synthesis of **14** (88 and 76%, respectively) are much higher than the yields obtained for the analogous steps in the preparation of **2** (48 and 35%, respectively). This is in agreement with literature precedence for photocyclizations: azastilbenes generally give lower yields than the carbocyclic analogues, and yields

(23) Ishikura, M.; Oda, I.; Terashima, M. *Heterocycles* **1985**, *23*, 2375–2386.
(24) Gorsane, M.; Martin, R. H. *Bull. Chim. Soc. Belg.* **1985**, *94*, 205–214.
(25) (a) Bestmann, H. J.; Kratzer, O. *Chem. Ber.* **1963**, *96*, 1899–1908. (b) Martin, R. H.; Flammang-Barbieux, M.; Cosyn, J. P.; Gelbcke, M. *Tetrahedron Lett.* **1968**, 3507–3510.
(26) Lapouyade, R.; Veyres, A.; Hanafi, N.; Couture, A.; Lablache-Combier, A. *J. Org. Chem.* **1982**, *47*, 1361–1364.
(27) Defay, N.; Martin, R. H. *Bull. Soc. Chim. Belg.* **1984**, *93*, 313–321.
(28) Negishi, E.-i.; Takahashi, I.; King, A. O. *Org. Synth.* **1987**, *66*, 67–74.

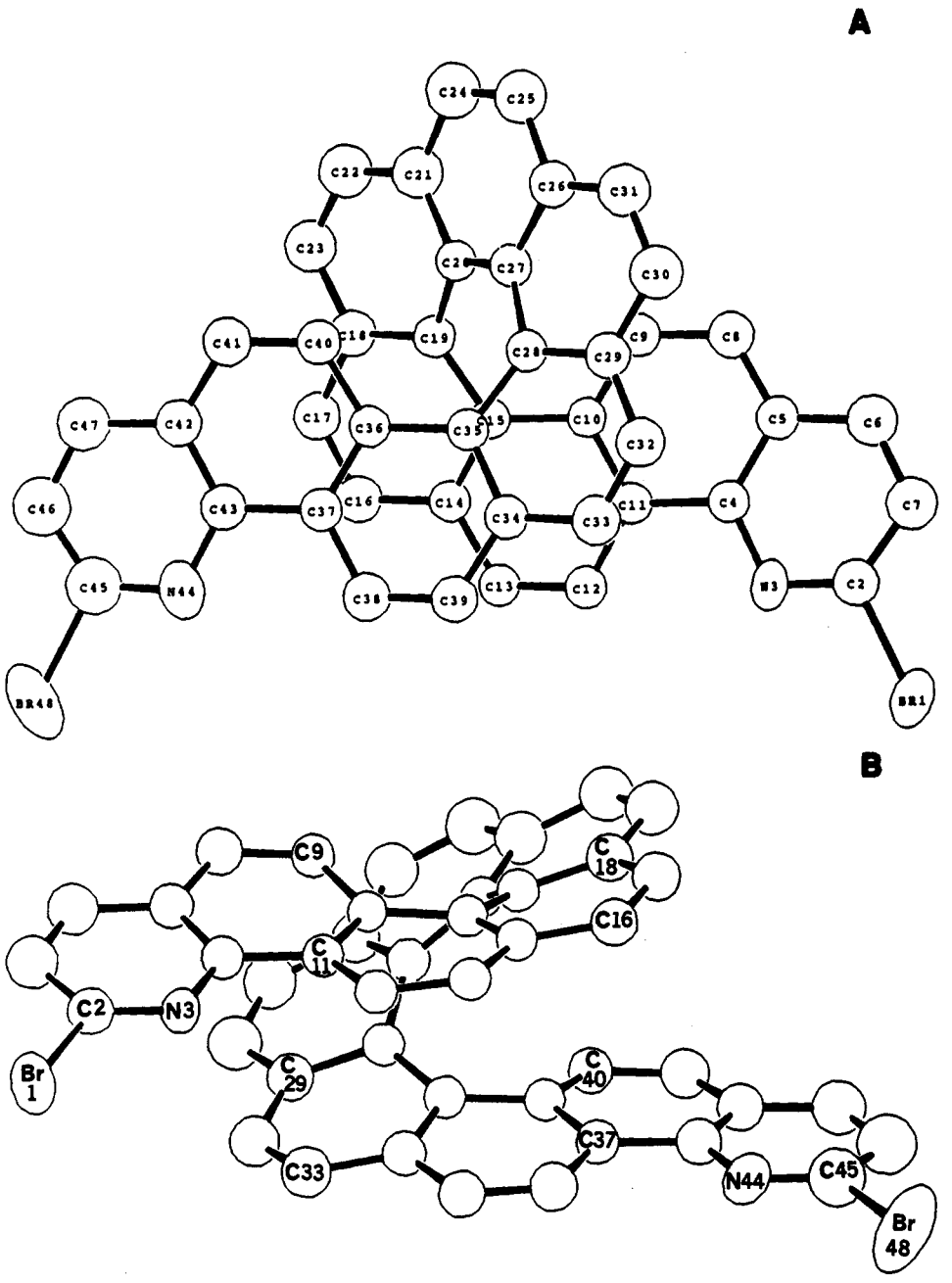


Figure 3. Molecular structure of 14 in a view (A) along the helix axis and (B) perpendicular to the helix axis.

decrease with increasing numbers of nitrogen atoms in the stilbene derivative.[21]

X-Ray Crystal Structure of the Dibromohelicene 14. Slow evaporation of a chloroform solution provided single crystals of 14 which were suitable for X-ray diffraction. Table I shows the crystal and data collection parameters for 14. The molecular structure is represented in Figures 3 and 4. Carbon atoms, separated by one helix turn in the same molecule, are located at van der Waals distance from each other. Short van der Waals contacts are 3.452 (C11···C33), 3.460 (C18···C40), 3.517 (C9···C29), and 3.558 (C16···C37) Å. The distances between symmetry-related atoms at the helix termini, which define the width of the clefts in 2 and 3, are 8.69 (N3···N44), 11.19 (C2···C45), and 12.87 (Br1···Br48) Å.

We have carried out MMP2(85)[29] calculations for 14 based on the X-ray structure.[30,31] Several parameters related to the Br atoms were missing in the original force field. However, since the shape of the spiral backbone and interplanar distances would not be influenced by the

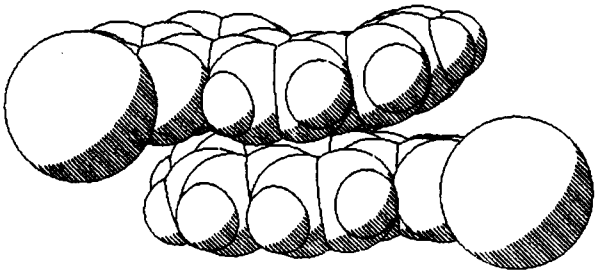


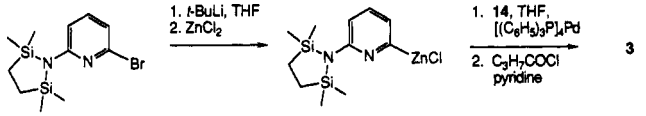
Figure 4. Space-filling representation of the molecular structure of 14.

(29) Allinger, N. L. QCPE program MM2(85).
(30) Prinsen, W. J. C.; Laarhoven, W. H.; Bosman, W. P.; Behm, H.; Beurskens, P. T. *Recl. Trav. Chim. Pays-Bas* **1988**, *107*, 575–582.
(31) (a) Somers, J. B. M.; Borkent, J. H.; Laarhoven, W. H. *Recl. Trav. Chim. Pays-Bas* **1981**, *100*, 110–114. (b) Herndon, W. C.; Conner, D. A.; Lin, P. *Pure Appl. Chem.* **1990**, *62*, 435–444. (c) Herndon, W. C. *J. Am. Chem. Soc.* **1990**, *112*, 4546–4547.

Table II. Selected Intramolecular Distances and Torsional Angles of 14 Obtained from X-ray and MMP2(85) Calculations

	X-ray	MMP2
	Distances (Å)	
11-33	3.452	3.437
18-40	3.460	3.421
9-29	3.517	3.413
16-37	3.558	3.446
1-2	1.909	1.855
3-44	8.685	8.547
2-45	11.190	11.043
1-48	12.869	12.556
13-39	3.452	3.407
14-34	3.749	3.795
	Dihedral angles (Å)	
1-2-7-6	-179.2	-180.0
2-7-6-5	-0.2	-0.6
7-6-5-8	179.0	178.4
6-5-8-9	175.4	177.9
5-8-9-10	2.3	-2.4
8-9-10-15	179.1	-174.0
9-10-15-19	20.8	20.3
10-15-19-20	27.7	24.8
15-19-20-27	25.0	24.7
19-20-27-28	21.4	22.9

Scheme IV



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termini where the Br atoms are located, standard geometry parameters for Br without further parametrization were applied. The minimized structure and parameters used are reported in the supplementary material.

The calculated structure gives a reasonable geometric description of helicene 14 according to the X-ray results. Some characterstic intramolecular distances and torsional angles are shown in Table II. The calculated distances between terminal atoms of 8.55 (N3···N44), 11.04 (C2···C45), and 12.56 (Br1···Br48) Å are slightly shorter than observed in the X-ray structure. The same shortening of distances between terminal atoms has also been found in MMP2 calculations of the hexahelicene system.[30]

Preparation of Helicopodand 3. The formation of 3 by coupling of two aminopyridyl units to the helix termini in 14 followed by acylation was unexpectedly difficult. Starting from the protected bromide 24, we were unable to form the boronic ester for use in the Suzuki coupling. Similarly, all attempts to generate trialkyltin derivatives of 24 for use in tin-mediated coupling reactions[32] failed. Finally, we achieved modest success by using the method described by Negishi for the formation of biaryl derivatives.[28] Metal-halogen exchange on 24 followed by quenching with the soft electrophile $ZnCl_2$ gave the corresponding zinc derivative which was then coupled under Pd^0 catalysis to the dibromohelicene 14 (Scheme IV). The silyl protecting groups were removed during the course of the reaction, and the bis(aminopyridine)helix was isolated as the direct precursor to 3. Acylation of the crude diamine with butyryl chloride produced the yellow target compound 3 in 7% yield (from 14). Figure 1 shows the ^1H NMR data for 3 in Me_2SO-d_6, which closely resemble those measured for 2 in $CDCl_3$. In contrast to system 2, the helicopodand 3 is only modestly soluble in benzene and chloroform. The two helices 2 and 3 and, to a lesser extent also 14, show a remarkable, sponge-like tendency for incorporating solvents and other small molecules into their solid state lattices. These compounds cannot be removed by drying under reduced pressure.

In conclusion, this paper describes the synthesis of the two helicopodands 2 and 3 in multistep routes which each contain two photocyclodehydrogenations as key conversions. At the termini of a dipyrido[9]helicene backbone, these new systems define chiral molecular clefts aligned with hydrogen bonding functionality. The X-ray crystal structure of 14, a direct helical precursor to 2[33] and 3, confirms the main structural features of the helicopodands. MMP2 calculations give a geometric description of 14 which is in reasonable agreement with the X-ray results. Molecular recognition studies with the two helicopodands 2 and 3 as well as with other derivatives derived from [7]- and [9]helicenes are in progress and will be described elsewhere.

Experimental Section

General. Analytics. ^1H NMR spectra were measured at 293 K in $CDCl_3$ if not stated otherwise. Spectral assignments are supported by $^1H,^1H$-COSY and long-range $^1H,^1H$-COSY NMR spectra.[34] Protons are labeled as shown in Scheme II and in the drawing of compounds 2 and 3. These labels serve for NMR spectral comparisons and do not follow the numbering in the nomenclature of the individual compounds. Electron impact mass spectra (EI-MS) were obtained at 20 eV; fast-atom bombardment spectra (FAB-MS) were determined in *m*-nitrobenzyl alcohol as the matrix. The *m/z* values listed below are followed by relative intensities given in parentheses. IR and UV/vis spectra, measured for all new compounds, were recorded in $CDCl_3$. Melting points are uncorrected. Elemental analyses were effected by Spang microanalytical laboratory, Eagle Harbor, MI. Column chromatography was performed on silica gel 70–230 mesh from E. Merck.

Materials. Reagents and solvents used were reagent grade. Diethyl ether and THF were distilled from sodium benzophenone ketyl. Dimethylformamide (DMF), benzene, and toluene were dried over 3-Å molecular sieves. Oil-free sodium hydride was obtained by rinsing the 60% suspension in oil three times with pentane on a glass frit under argon. Dry O_2 was obtained by passing a stream of the gas through concentrated H_2SO_4.

Reactions. Reactions were performed under argon unless otherwise noted. The general reaction workup included separation of the product-containing organic phase from aqueous layers, drying with $MgSO_4$, and evaporation of the solvent in vacuo. All photocyclodehydrogenations were accomplished at 20 °C under Ar in the presence of an excess of iodine in a water-cooled Pyrex photoreactor using a 450-W medium-pressure Hg arc lamp. NBS brominations were performed under irradiation and heating with a 150-W sun lamp and worked up by filtration of the succinimide from the ice-cold CCl_4 reaction mixture, washing the filter cake with ice-cold CCl_4, and evaporating the combined CCl_4 solutions.

Synthesis. 8-Methyl-2-(2-pyridinyl)quinoline (6). A mixture of 0.89 g (4 mmol) of 4, 0.7 g (12 mmol) of KOH, 0.44 g (2 mmol) of Et_4NBr, 1.1 g (7.2 mmol) of 5,[23] and 0.4 g (0.35 mmol) of $[(C_6H_5)_3P]_4Pd$ in benzene was heated to reflux for 2.5 h. After evaporation of the solvent, the residue was partitioned between CH_2Cl_2 and water. Workup followed by chromatography (EtOAc/hexane (96:4)) gave 0.49 g (56%) of 6 as white needles (hexane): mp 79 °C; ^1H NMR (200 MHz) δ 2.92 (s, 3 H), 7.35 (m, 1 H, 5′-H), 7.44 (m, 1 H, 6-H), 7.58 (d, J = 6.9 Hz, 1 H, 7-H), 7.69 (d, J = 8.6 Hz, 1 H, 5-H), 7.87 (m, 1 H, 4′-H), 8.25 (d, J =

(32) (a) Kashin, A. N.; Bumagina, I. G.; Bumagin, N. A.; Bakunin, V. N.; Beletskaya, I. P. *Zh. Org. Kh.* **1981**, *17*, 905–911. (b) Yamamoto, Y.; Yanagi, A. *Chem. Pharm. Bull.* **1982**, *30*, 1731–1737. (c) Yamamoto, Y. Azuma, Y.; Mitoh, H. *Synthesis* **1986**, 564–565. (c) Bailey, T. R. *Tetrahedron Lett.* **1986**, *27*, 4407–4410. (e) Unheim, K.; Sandersham, J. *Acta Chem. Scand.* **1989**, *43*, 684–689. (f) Majeed, A. J.; Antonsen, Ø.; Benneche, T.; Unheim, K. *Tetrahedron* **1989**, *45*, 993–1006.

(33) Helicopodand 2 was obtained in 50–60% yield in the Suzuki coupling between 14 and 2 equivalents of 5.

(34) Bax, A.; Freeman, R. *J. Magn. Reson.* **1981**, *44*, 542–561.

8.5 Hz, 1 H, 4-H), 8.57 (d, J = 8.5 Hz, 1 H, 3-H), 8.72 (d, $J \approx 6.2$ Hz, 1 H, 6'-H), 8.75 (d, J = 7.5 Hz, 1 H, 3'-H); UV λ_{max} (nm) 234 (ϵ 20300), 257 (36100), 310 (11400); EI-MS 220 (M^+, 100). Anal. Calcd for $C_{15}H_{12}N_2$ (220.3): C, 81.79, H, 5.49; N, 12.72. Found: C, 81.71; H, 5.37; N, 12.65.

8-(Bromomethyl)-2-(2-pyridinyl)quinoline (7). A solution of 490 mg (2.2 mmol) of **6** and 431 mg (2.42 mmol) of NBS in 11 mL of CCl_4 was irradiated during 45 min to give 600 mg (90%) of colorless crystals of **7**: mp 120 °C; ^{1}H NMR (200 MHz) δ 5.34 (s, 2 H), 7.38 (m, 1 H, 5'-H), 7.51 (m, 1 H, 6-H), 7.81 (d, J = 8.7 Hz, 1 H, 5-H), 7.82 (d, J =6.7 Hz, 1 H, 7-H), 7.91 (m, 1 H, 4'-H), 8.29 (d, J = 8.6 Hz, 1 H, 4-H), 8.63 (d, J = 8.6 Hz, 1 H, 3-H), 8.73 (dd, J = 8.7 and $\approx$2 Hz, 1 H, 6'-H), 8.80 (d, J = 8.0 Hz, 1, H, 3'-H); EI-MS 300/298 (M^+, 18), 219 (100). Anal. Calcd for $C_{15}H_{11}BrN_2$ (299.2): C, 60.22; H, 3.71; N, 9.36. Found: C, 59.89; H, 3.80; N, 9.12.

2-Bromo-8-(bromomethyl)quinoline (15). The reaction of 2.06 g (9.3 mmol) of **4** with 1.65 g (9.3 mmol) of NBS in 50 mL of CCl_4 afforded after 8 h 2.10 g (75%) of **15**: mp 114–115 °C (hexane/CH_2Cl_2 (9:1)); ^{1}H NMR (360 MHz) δ 5.16 (s, 2 H), 7.53 (dd, J = 7.9 and 6.9 Hz, 1 H, 6-H), 7.54 (d, J = 8.5 Hz, 1 H, 3-H), 7.77 (d, J = 7.9 Hz, 1 H, 5-H), 7.86 (d, J = 6.9 Hz, 1 H, 7-H), 7.98 (d, J = 8.5 Hz, 1 H, 4-H). Anal. Calcd for $C_{10}H_7Br_2N$ (301.0): C, 39.91; H, 2.34; N, 4.65. Found: C, 39.97; H, 2.37; N, 4.69.

8-[(Triphenylphosphonio)methyl]-2-(2-pyridinyl)-quinolinyl Bromide (8). A solution of 0.650 g (2.2 mmol) of **7** and 0.976 g (3.5 mmol) of $(C_6H_5)_3P$ in 10 mL of toluene was refluxed for 14 h. The precipitated product was filtered and dried to yield 0.850 g (69%) of **8**: mp 191–193 °C dec; ^{1}H NMR (Me_2SO-d_6, 360 MHz) δ 5.87 (d, J = 15.4 Hz, 2 H), 7.4–7.8 (m, 18 H), 7.9–8.05 (m, 2 H, 5-H, 7-H), 8.28 (d, J = 8.8 Hz, 1 H, 3'-H), 8.40 and 8.42 (AB, J = 8.6 Hz, 2 H, 3-H, 4-H), 8.75 (d, $J \approx 8$ Hz, 1 H, 6'-H); FAB-MS 561/559 (M^+, 12), 481 (M^+ – Br, 100).

2-Bromo-8-[(triphenylphosphonio)methyl]quinolinyl Bromide (16). The reaction of 6.6 g (0.022 mol) of **15** and 6.05 g (0.022 mol) of $(C_6H_5)_3P$ in refluxing toluene (50 mL) afforded after 8 h 10.3 g (83%) of **16** as a colorless precipitate: mp 246 °C dec; ^{1}H NMR (Me_2SO-d_6, 500 MHz) δ 5.34 (d, J = 14.7 Hz, 2 H), 7.42 (d, J = 8.6 Hz, 1 H, 3-H), 7.46 (dd, J = 8.6 and 7.4 Hz, 1 H, 6-H), 7.56 (m, 12 H), 7.64 (d, J = 7.4 Hz, 1 H, 7-H), 7.72 (m, 3 H), 7.88 (d, J = 8.6 Hz, 1 H, 5-H), 8.09 (d, J = 8.6 Hz, 1 H, 4-H); HRMS m/z (M^+ – Br, $C_{28}H_{22}BrNP$) calcd 482.0673, obsd 482.0664. Anal. Calcd for $C_{28}H_{22}Br_2NP$ (563.3): C, 59.71; H, 3.94. Found: 59.69; H, 4.37.

***trans*-8-[2-(7-Methyl-2-naphthalenyl)ethenyl]-2-(2-pyridinyl)quinoline (9).** A total of 1.6 mL (0.31 mmol) of a 0.2 M solution of NaOEt in EtOH was added to 51 mg (0.30 mmol) of 2-formyl-7-methylnaphthalene. After the addition of 167 mg (0.30 mmol) of **8**, the mixture was stirred for 30 min. The solvent was evaporated and the residue partitioned between CH_2Cl_2 and water. Workup and chromatography (hexane/toluene/EtOAc (1:1:0.05)) yielded 70 mg (63%) of a mixture of cis and trans isomers from which pure *trans*-**9** was separated by recrystallization: mp 219 °C ($CHCl_3$); ^{1}H NMR (500 MHz) δ 2.54 (s 3 H), 7.31 (dd, J = 8.3 and 1.4 Hz, 1 H, 6''-H), 7.39 (m, 1 H, 5'-H), 7.60 (m, 1 H, 6-H), 7.61 (d, J = 16.5 Hz, 1 H, Naph-C*H*=), 7.65 (s, br, 1 H, 8''-H), 7.75 (d, J = 8.3 Hz, 1, H, 5''-H), 7.79 (d, J = 7.7 Hz, 1 H, 7-H), 7.86 (d, J = 8.5 Hz, 1 H, 4''-H), 7.91 (s, br, 1 H, 1''-H), 7.93 (d, J = 8.5 Hz, 1 H, 3''-H), 7.94 (m, 1 H, 4'-H), 8.13 (d, J = 7.2 Hz, 1 H, 5-H), 8.30 (d, J = 8.6 Hz, 1 H, 4-H), 8.64 (d, J = 8.6 Hz, 1 H, 3-H), 8.75 (d, J = 16.5 Hz, 1 H, Quin-C*H*=), 8.76 (d, J = 8.0 Hz, 1 H, 6'-H), 8.81 (d, J = 7.9 Hz, 1 H, 3'-H); UV λ_{max} (nm) 240 (ϵ 20400), 278 (20200), 342 (8000); EI-MS 373 (M^+ + 1, 28), 372 (M^+, 100); HRMS m/z (M^+ + 1, $C_{27}H_{20}N_2$) calcd 373.1705, obsd 373.1719.

***trans*-2-Bromo-8-[2-(7-methyl-2-naphthalenyl)ethenyl]-quinoline (17).** To a solution of 2.95 g (5.2 mmol) of **16** in 50 mL of dry MeOH was added 160 mg (6.7 mmol) of NaH. After 5 min, 0.89 g (5.2 mmol) of 2-formyl-7-methylnaphthalene was added. After being stirred for 2 h, the precipitated product (1.34 g, 68%) was isolated by filtration and identified by ^{1}H NMR as a $\approx$1:1 mixture of *cis*- and *trans*-**17**. Slow evaporation of a $CHCl_3$ solution of the isomers provided crystals of pure *trans*-**17**: mp 148–149 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.53 (s, 3 H), 7.30 (d, J = 8.2 Hz, 1 H, 6''-H), 7.53 (d, J = 16.6 Hz, 1 H, Naph-C*H*), 7.54 (d, J = 8.5 Hz, 1 H, 3-H), 7.61 (dd, J = 8.0 and 7.0 Hz, 1 H, 6-H), 7.65 (s, br, 1 H, 8''-H), 7.72 (d, J = 8.0 Hz, 1 H, 7-H), 7.73 (d, J = 8.2 Hz, 1 H, 5''-H), 7.82 (d, J = 7.9 Hz, 1 H, 3''-H), 7.87 (d, J = 7.9 Hz, 1 H, 4''-H), 7.88 (s, 1 H, 1''-H), 7.98 (d, J = 8.5 Hz, 1 H, 4-H), 8.12 (d, J = 7.0 Hz, 1 H, 5-H), 8.45 (d, J = 16.6 Hz, 1 H, Quin-C*H*); UV λ_{max} (nm) 240 (ϵ 20600), 264 (25200), 353 (15900); EI-MS 375/373 (M^+, 100); Anal. Calcd for $C_{22}H_{16}BrN$ (374.3): C, 70.60; H, 4.31. Found: C, 70.68; H, 4.54. For X-ray crystal structure, see supplementary material.

11-Methyl-3-(2-pyridinyl)phenanthro[4,3-*h*]quinoline (10). A solution of 391 mg (1.05 mmol) of *cis*- and *trans*-**9** in 350 mL of dry toluene containing I_2 was irradiated for 200 min. The solvent was evaporated and the residue chromatographed (hexane/toluene/EtOAc (1:1:0.05)) to give 188 mg (48%) of **10** after recrystallization from hexane: mp 174 °C; ^{1}H NMR (360 MHz) δ 2.69 (s, 3 H), 7.39 (m, 1 H, 5'-H), 7.51 (dd, J = 8.3 and 1.4 Hz, 1 H, 12-H), 7.86 (AB, J = 8.6 Hz, 1 H, 9-H), 7.91 (AB, J = 8.6 Hz, 1 H, 10-H), 7.94 (d, J = 8.3 Hz, 1 H, 11-H), 7.95 (m, 1 H, 4'-H), 7.96 (d, J = 8.9 Hz, 1 H, 5-H), 8.13 (d, J = 8.4 Hz, 1 H, 8-H), 8.42 (d, J = 8.3 Hz, 1 H, 4-H), 8.77 (d, J = 8.3 Hz, 1 H, 3-H), 8.78 (m, 1 H, 6'-H), 8.89 (s, br, 1 H, 13-H), 8.98 (d, J = 7.9 Hz, 1 H, 3'-H), 9.16 (d, J = 8.9 Hz, 1 H, 6-H), 9.68 (d, J = 8.4 Hz, 1 H, 7-H); UV/vis λ_{max} (nm) 242 (ϵ 26100), 297 (39100), 309 (40000), 337 (34400), 375 (4900), 395 (3100); EI-MS 370 (M^+, 100). Anal. Calcd for $C_{27}H_{18}N_2$ (370.5): C, 87.54; H, 4.90; N, 7.56. Found: C, 87.21; H, 4.73; N, 7.35.

3-Bromo-11-methylphenanthro[4,3-*h*]quinoline (18). A stirred solution of 0.440 g (1.18 mmol) of **17** and 0.24 g (0.9 mmol) of I_2 in 550 mL of dry toluene was irradiated for 4 h. The solvent was evaporated and the residue partitioned between CH_2Cl_2 and saturated $Na_2S_2O_5$. The organic layer was washed with water, and workup followed by recrystallization from benzene/hexane (9:1) afforded 388 mg (88%) of **18**: mp 163–165 °C; ^{1}H NMR (500 MHz) δ 2.65 (s, 3 H), 7.49 (d, J = 8.1 Hz, 1 H, 12-H), 7.68 (d, J = 8.2 Hz, 1 H, 3-H), 7.83 (d, J = 8.5 Hz, 1 H, 9-H), 7.87 (d, J = 9.2 Hz, 1 H, 5-H), 7.90 (d, J = 8.5 Hz, 1 H, 10-H), 7.94 (d, J = 8.1 Hz, 1 H, 11-H), 8.09 (d, J = 8.2 Hz, 1 H, 4-H), 8.10 (d, J = 8.6 Hz, 1 H, 8-H), 8.80 (s, 1 H, 13-H), 9.15 (d, J = 9.2 Hz, 1 H, 6-H), 9.37 (d, J = 8.6 Hz, 1 H, 7-H); UV/vis λ_{max} (nm) 240 (ϵ 22700), 300 (50200), 331 (29600), 372 (2200), 390 (1500); EI-MS 373/371 (M^+, 100). Anal. Calcd for $C_{22}H_{14}NBr$ (372.3): C, 70.98; H, 3.79. Found: C, 70.72; H, 3.77.

11-[(Triphenylphosphonio)methyl]-3-(2-pyridinyl)-phenanthro[4,3-*h*]quinoline (12). The reaction of 54 mg (0.15 mmol) of **10** with 31 mg (0.17 mmol) of NBS in 3 mL of CCl_4 for 8 h at reflux yielded 70 mg of a solid containing the desired product **11** (78%, ^{1}H NMR), the corresponding geminal dibromide (15%), and residual starting material (7%). This material was used without further purification in the following conversion. Pure monobromide **11** was obtained by recrystallization from toluene/hexane: mp 187 °C; ^{1}H NMR (360 MHz) δ 4.83 (s, 2 H), 7.40 (m, 1 H, 5'-H), 7.69 (dd, J = 8.2 and 1.6 Hz, 1 H, 12-H), 7.9–8.05 (m, 5 H, 5-H, 9-H, 10-H, 11-H, 4'-H), 8.14 (d, J = 8.6 Hz, 1 H, 8-H), 8.42 (d, J = 8.3 Hz, 1 H, 4-H), 8.78 (m, 1 H, 6'-H), 8.78 (d, J = 8.3 Hz, 1 H, 3-H), 8.96 (d, J = 7.9 Hz, 1 H, 3'-H), 9.06 (d, J = 8.9 Hz, 1 H, 6-H), 9.08 (s, br, 1 H, 13-H), 9.71 (d, J = 8.6 Hz, 1 H, 7-H); EI-MS ($C_{27}H_{17}N_2Br$) 450/448 (M^+, 7), 370 (100). The crude bromide **11** (50 mg, 0.11 mmol) and $(C_6H_5)_3P$ (36 mg, 0.13 mmol) were refluxed in 2 mL of toluene for 12 h. The filtered precipitate was dried to give 60 mg (76%) of **12** ($C_{45}H_{32}BrN_2P$, MW 711.6): mp 241 °C dec; ^{1}H NMR δ 6.08 (d, J = 14.2 Hz, 2 H), 7.15–8.2 (m, 25 H), 8.46 (d, J = 8.3 Hz, 1 H, 3-H), 8.57 (s, br, 1 H, 13-H), 8.78 (m, 1 H, 6'-H), 8.96 (d, J = 7.9 Hz, 1 H, 3'-H), 9.46 (d, J = 8.8 Hz, 1 H, 7-H); FAB-MS 632 (M^+ – Br, 100).

3-Bromo-11-(bromomethyl)phenanthro[4,3-*h*]quinoline (19). The bromination of 0.370 g (1.0 mmol) of **18** with 0.178 g (1.0 mmol) of NBS in 30 mL of CCl_4 afforded after 3 h a mixture of starting material and mono- and dibrominated product (1:7:1, ^{1}H NMR) which, upon recrystallization from hexane/CH_2Cl_2, gave 0.342 g (76%) of **19**: mp 215 °C dec; ^{1}H NMR (360 MHz) δ 4.81 (s, 2 H), 7.69 (dd, J = 8.2 and 1.6 Hz, 1 H, 12-H), 7.70 (d, J = 8.1 Hz, 1 H, 3-H), 7.92 (s, 2 H, 9-H, 10-H), 7.92 (d, J = 9.2 Hz, 1 H, 5-H), 8.02 (d, J = 8.2 Hz, 1 H, 11-H), 8.10 (d, J = 8.8 Hz, 1 H, 8-H), 8.12 (d, J = 8.1 Hz, 1 H, 4-H), 9.02 (d, J = 1.6 Hz, 1 H, 13-H), 9.07 (d, J = 9.2 Hz, 1 H, 6-H), 9.41 (d, J = 8.8 Hz, 1 H, 7-H); EI-MS 453 (20), 451 (45), 449 (20), 372/370 (100). Anal. Calcd for $C_{22}H_{13}Br_2N$ (451.2): C, 58.57; H, 2.90; N, 3.10; Br, 35.42.

Found: C, 58.44; H, 3.06; N, 3.09; Br, 35.41.

3-Bromo-11-[(triphenylphosphonio)methyl]phenanthro[4,3-*h*]quinolinyl Bromide (20). A solution of 0.280 g (0.62 mmol) of **19** and 0.170 g (0.62 mmol) of $(C_6H_5)_3P$ in 30 mL of refluxing benzene afforded after 8 h 0.385 g (86%) of **20** as a colorless precipitate: mp 245–247 °C dec; ^1H NMR (360 MHz) δ 6.12 (d, J = 14.9 Hz, 2 H), 7.21 (d, J = 8.2 Hz, 1 H, 12-H), 7.32 (d, J = 8.2 Hz, 1 H, 11-H), 7.45–7.85 (m, 21 H), 8.29 (d, J = 9.1 Hz, 1 H, 6-H), 8.47 (s, br, 1 H, 13-H), 8.93 (d, J = 8.6 Hz, 1 H, 7-H); FAB-MS 634/632 (M^+ – Br, 100). Anal. Calcd for $C_{40}H_{28}Br_2NP\cdot0.5\,H_2O$ (722.8): C, 66.52; H, 4.51; N, 1.94. Found: C, 66.77; H, 4.32; N, 1.91.

3-Bromo-11-(hydroxymethyl)phenanthro[4,3-*h*]quinoline (21). A mixture of 0.345 g (0.76 mmol) of **19**, 0.10 g (0.94 mmol) of Na_2CO_3, and 5.0 mL of H_2O in 50 mL of CH_3CN/THF (1:1) was refluxed for 48 h. The solvents were removed in vacuo, and the residue was chromatographed (CH_2Cl_2) to yield 0.204 mg (69%) of **21**: mp 203–204 °C; ^1H NMR (500 MHz) δ 1.86 (t, J = 5.6 Hz, 1 H, OH), 5.02 (d, J = 5.6 Hz, 2 H, CH_2), 7.66 (d, J = 8.2 Hz, 1 H, 12-H), 7.68 (d, J = 8.3 Hz, 1 H, 3-H), 7.85 (d, J = 9.2 Hz, 1 H, 5-H), 7.88 (d, J = 8.6 Hz, 1 H, 9-H), 7.92 (d, J = 8.6 Hz, 1 H, 10-H), 8.02 (d, J = 8.2 Hz, 1 H, 11-H), 8.07 (d, J = 8.3 Hz, 1 H, 4-H), 8.09 (d, J = 8.6 Hz, 1 H, 8-H), 8.98 (s, 1 H, 13-H), 9.10 (d, J = 9.2 Hz, 1 H, 6-H), 9.38 (d, J = 8.6 Hz, 1 H, 7-H); EI-MS 389/387 (M^+, 100). Anal. Calcd for $C_{22}H_{14}BrNO$ (388.3): C, 68.06; H, 3.63. Found: C, 67.89; H, 3.77.

3-Bromophenanthro[4,3-*h*]quinoline-11-carboxaldehyde (22). A mixture of 0.186 g (0.48 mmol) of **21** and 0.110 g (0.51 mmol) of PCC in 20 mL of dry CH_2Cl_2 was stirred for 3.5 h at 20 °C. Filtration through Celite (CH_2Cl_2) and chromatography (CH_2Cl_2/hexane (4:1)) yielded 131 mg (71%) of **22** as a white solid. Slow evaporation of a $CHCl_3$ solution provided crystals for X-ray crystallography (see supplementary material): mp 222 °C dec; IR ν(C=O) 1693 cm^{-1}; ^1H NMR (500 MHz) δ 7.73 (d, J = 8.5 Hz, 1 H, 3-H), 7.96 (d, J = 9.2 Hz, 1 H, 5-H), 7.99 (d, J = 8.6 Hz, 1 H, 9-H), 8.06 (d, J = 8.6 Hz, 1 H, 10-H), 8.14 (m, 4 H, 4-H, 8-H, 11-H, 12-H), 9.06 (d, J = 9.2 Hz, 1 H, 6-H), 9.46 (d, J = 8.6 Hz, 1 H, 7- H), 9.48 (s, 1 H, 13-H), 10.28 (s, 1 H, CHO); UV λ_{max} (nm) 271 (ϵ 26 500), 302 (36 500), 310 sh, (33 400), 330 (24 500), 349 (12 600), 379 (2600), 400 (2200); EI-MS 387/385 (M^+, 100). Anal. Calcd for $C_{22}H_{12}BrNO$ (386.3): C, 68.41; H, 3.13; N, 3.63. Found: C, 68.20; H, 3.11; N, 3.63.

***cis*-11,11′-(1,2-Ethenediyl)bis[3-(2-pyridinyl)phenanthro[4,3-*h*]quinoline] (13).** A total of 10 mL of NH_3 was condensed at –78 °C into a 50-mL flask and dried over sodium. Subsequently, 5 mL of the dry NH_3 was distilled into a second flask to which 36 mg (1.5 mmol) of sodium was added. When the reaction mixture turned blue, a few crystals of $Fe(NO_2)_3$ were added, and the solution was vigorously refluxed to give a grayish brown precipitate of $NaNH_2$. After evaporation of NH_3, the sodium amide was suspended in 3 mL of dry benzene, and 250 mg (0.35 mmol) of **12** was added. The solution turned dark red, and a gentle stream of dry O_2 gas was bubbled through for 10 min while the reaction was brought to reflux. The gas insertion was stopped, an additional 2 mL of benzene was added, and the reaction was refluxed for 15 h under dry O_2 from a balloon. The yellow turbid solution was poured into 100 mL of CH_2Cl_2 and filtered. The residue obtained by evaporation of the filtrate was chromatographed (gradient of 0–10% EtOAc in CH_2Cl_2) to give 40 mg (30%) of **10** together with 35 mg (27%) of **13**: mp 295 °C; ^1H NMR δ 7.05 (d, J = 9.3 Hz, 2 H, 5-H), 7.14 (s, 2 H, C*H*=), 7.38 (m, 2 H, 5′-H), 7.77 (dd, J = 8.3 and 1.6 Hz, 2 H, 12-H), 7.91 and 7.92 (AB, J = 8.2 Hz, 4 H, 9-H, 10-H), 7.95 (m, 1 H, 4′-H), 8.03 (d, J = 8.6 Hz, 2 H, 4-H), 8.05 (d, J = 8.3 Hz, 2 H, 11-H), 8.11 (d, J = 8.6 Hz, 2 H, 8-H), 8.37 (d, J = 9.3 Hz, 2 H, 6-H), 8.64 (d, J = 8.6 Hz, 2 H, 3-H), 8.74 (m, 2 H, 6′-H), 8.92 (d, J = 7.9 Hz, 2 H, 3′-H), 9.11 (s, 2 H, 13-H), 9.65 (d, J = 8.6 Hz, 2 H, 7-H); UV/vis λ_{max} (nm) 273 (ϵ 59 500), 308 (63 800), 340 sh (58 500), 374 sh (29 000), 396 sh (17 000); FAB-MS 737 (M^+ + H, 100); HRMS m/z (M^+ + H, $C_{54}H_{33}N_4$) calcd 737.2705, obsd 737.2716.

***cis*-11,11′-(1,2-Ethenediyl)bis(3-bromophenanthro[4,3-*h*]quinoline) (23).** To a solution of 0.123 g (0.17 mmol) of **20** in 6 mL of dry MeOH was added 10 mg (0.42 mmol) of oil-free NaH. To the orange mixture was added by syringe a solution of 0.066 g (0.17 mmol) of **22** of 6 mL of dry THF. The reaction was stirred for 1 h at 20 °C. The formed precipitate was isolated by filtration, washed with 2 × 10 mL of MeOH, and dried to yield 100 mg (80%) of **23** as a light yellow solid: mp >300 °C; ^1H NMR (360 MHz) 6.88 (d, J = 9.2 Hz, 1 H, 5-H), 7.11 (s, 2 H, CH=), 7.56 (d, J = 8.4 Hz, 2 H, 3-H), 7.66 (d, J = 8.4 Hz, 2 H, 4-H), 7.72 (d, J = 8.2 Hz, 2 H, 12-H), 7.86 (d, J = 8.6 Hz, 2 H, 10-H), 7.90 (d, J = 8.6 Hz, 2 H, 9-H), 8.01 (d, J = 8.3 Hz, 2 H, 11-H), 8.07 (d, J = 8.6 Hz, 2 H, 8-H), 8.31 (d, J = 9.2 Hz, 2 H, 6-H), 9.00 (s, 2 H, 13-H), 9.34 (d, J = 8.6 Hz, 2 H, 7-H); EI-MS 743/741/739 (M^+, 50, 100, 50). Anal. Calcd for $C_{44}H_{24}Br_2N_2$ (740.5): C, 71.37; H, 3.27; N, 3.78. Found: C, 71.22; H, 3.37; N, 3.64.

3,20-Di(2-pyridinyl)benzo[2″,1″:5,6;3″,4″:5′,6′]diphenanthro[4,3-*h*:4′,3′-*h*′]diquinoline (2). A solution of 20 mg (0.03 mmol) of **13** and a few crystals of iodine in 300 mL of toluene was irradiated for 120 min. The solvent was evaporated, and chromatography (gradient of 2–10% EtOAc in 1:1 hexane/toluene) of the residue afforded 7 mg (35%) of a yellow solid: mp 238 °C (CH_2Cl_2/$(CH_3)_2CHOH$); ^1H NMR (500 MHz, for assignments, see Figure 1) δ 6.64 (d, J = 8.1 Hz), 6.67 (d, J = 8.9 Hz), 6.91 (d, J = 8.1 Hz), 7.04 (d, J = 8.9 Hz), 7.41 (d, J = 8.0 Hz), 7.45 (m), 7.52 (d, J = 8.5 Hz), 7.93 (d, J = 8 Hz), 8.03 (m), 8.05 (d, J = 8.3 Hz), 8.07 (s), 8.63 (d, J = 8.3 Hz), 8.81 (m), 9.00 (d, J = 7.8 Hz), 9.09 (d, J = 8.5 Hz); UV/vis λ_{max} (nm) 262 (ϵ 64 000), 292 (63 500), 343 (32 000), 398 sh (14 100); EI-MS 734 (M^+, 100); HRMS (FAB) m/z (M^+ + H, $C_{54}H_{31}N_4$) calcd 735.2549, obsd 735.2538.

3,20-Dibromobenzo[2″,1″:5,6;3″,4″:5′,6′]diphenanthro[4,3-*h*:4′,3′-*h*′]diquinoline (14). A solution of 63 mg (0.085 mmol) of **23** and 20 mg (0.079 mmol) of I_2 was irradiated in 400 mL of dry toluene for 3 h at 20 °C. The solvent was evaporated and the residue partitioned between CH_2Cl_2 and saturated $Na_2S_2O_5$. The organic phase was washed with water and worked up. Recrystallization from CH_2Cl_2/hexane (1:1) yielded 48 mg (76%) of **14** as orange crystals. X-ray-quality crystals were obtained by slow evaporation of a $CDCl_3$ solution: mp >300 °C; ^1H NMR (500 MHz) δ 6.56 (d, J = 9.1 Hz, 2 H, 5-H), 6.69 (d, J = 8.2 Hz, 2 H, 10-H), 7.00 (d, J = 8.2 Hz, 2 H, 9-H), 7.04 (d, J = 9.1 Hz, 2 H, 6-H), 7.38 (d, J = 8.1 Hz, 2 H, 11-H), 7.51 (d, J = 8.6 Hz, 1 H, 8-H), 7.56 (d, J = 8.2 Hz, 2 H, 3-H), 7.76 (d, J = 8.2 H, 2 H, 4-H), 7.90 (d, J = 8.1 Hz, 2 H, 12-H), 8.04 (s, 2 H, 13-H), 8.78 (d, J = 8.6 Hz, 2 H, 7-H); UV/vis λ_{max} (nm) 262 (ϵ 97 600), 297 (68 100), 337 (30 700), 395 (8000); EI-MS 741/739/737 (M^+, 50/100/50). For X-ray crystal structure, see Results and Discussion and supplementary material.

1-Aza-1-(6-bromo-2-pyridinyl)-2,2,5,5-tetramethyl-2,5-disilacyclopentane (24). A mixture of 0.92 g (3.96 mmol) of 1,4-bis(dimethylamino)-1,1,4,4-tetramethyl-1,4-disilabutane, 0.626 g (3.94 mmol) of 2-amino-6-bromopyridine, and a catalytic amount (≈2 mg) of ZnI_2 was stirred at 140 °C for 8 h.[35] The product was directly distilled from the reaction flask under reduced pressure to provide 0.90 g (72%) of **24**. The collected liquid, which eventually crystallized, was 98% pure (^1H NMR) after one distillation and was used without further purification: mp 45–46 °C; ^1H NMR (500 MHz) δ 0.32 (s, 12 H, $SiCH_3$), 0.84 (s, 4 H, $SiCH_2$), 6.50 (d, J = 8.1 Hz, 1 H, 3-H), 6.79 (d, J = 7.5 Hz, 1 H, 5-H), 7.26 (dd, J = 8.1 and 7.5 Hz, 1 H, 4-H); EI-MS 316/314 (M^+, 98/100), 234 (M^+ – Br, 35).

3,20-Bis[6-(butanamido)-2-pyridinyl]benzo[2″,1″:5,6;3″,4″:5′,6′]diphenanthro[4,3-*h*:4′,3′-*h*′]diquinoline (3). To a solution of 0.60 g (1.90 mmol) of **24** in 3.4 mL of THF at –100 °C was added 2.6 mL (4.16 mmol) of a 1.6 M solution of *tert*-butyllithium in hexane over a period of 15 min. The solution was warmed to –78 °C and stirred for 1 h, after which it was warmed to 20 °C. It was then cooled to –78 °C, and 2.0 mL (2.0 mmol) of a 1 M solution of $ZnCl_2$ in THF followed by an additional 4.0 mL of THF was added. The mixture was slowly warmed to 20 °C and, after stirring for 1 h, added via syringe into a solution of 0.071 g (0.096 mmol) of **14** and 0.040 g (0.035 mmol) of $[(C_6H_5)_3P]_4Pd$ in 3 mL of THF. The mixture was stirred at 20 °C for 24 h, after which the solvent was removed in vacuo. The residue was chromatographed (hexane/EtOAc (6:4)) providing the bis(aminopyridine)-helix along with ca. 10% of other material. The crude product was dissolved in 2 mL of distilled pyridine, and 0.2 mL (0.205 g, 1.92 mmol) of freshly distilled butyryl chloride was added. The solution was stirred for 20 h, then quenched with

(35) Guggenheim. T. L. *Tetrahedron Lett.* **1984**, *25*, 1253–1254.

saturated $NaHCO_3$. The resulting material was partitioned between CH_2Cl_2 and water. Workup and chromatography (gradient of 1–3% THF in CH_2Cl_2) yielded 6.3 mg (7%) of **3** as a yellow solid: mp >360 °C; IR ν(NH) 3320, (C=O) 1690 cm^{-1}; ^1H NMR (500 MHz, Me_2SO-d_6, for assignments, see Figure 1) δ 0.97 (t, J = 7.3 Hz), 1.68 (m), ≈2.5 (obscured by solvent), 6.75 (d, J = 9.2 Hz), 6.77 (d, J = 8.3 Hz), 6.92 (d, J = 9.2 Hz), 6.99 (d, J = 8.3 Hz), 7.58 (d, J = 8.1 Hz), 7.61 (d, J = 8.6 Hz), 8.11 (d, J = 8.1 Hz), 8.12 (dd, J = 8.6 and 6.3 Hz), 8.25 (s, 2 H), 8.27 (d, J = 8.1 Hz), 8.29 (d, J = 8.6 Hz), 8.56 (d, J = 8.1 Hz), 8.58 (d, J = 6.3 Hz), 9.03 (d, J = 8.6 Hz), 10.60 (s, br); FAB-MS 906 (M^+ + 1, 100).

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Registry No. (±)-**2**, 136805-53-3; (±)-**3**, 136827-14-0; **4**, 99073-81-1; **5**, 136805-54-4; **6**, 107027-36-1; **7**, 136805-55-5; **8**, 136805-56-6; (*Z*)-**9**, 136805-57-7; (*E*)-**9**, 136805-52-2; **10**, 136805-58-8; **11**, 136805-59-9; **12**, 136805-60-2; **13**, 136805-61-3; (±)-**14**, 136805-62-4; **15**, 136805-63-5; **16**, 69743-36-8; (*Z*)-**17**, 136805-64-6; (*E*)-**17**, 136805-72-6; **18**, 136805-65-7; **19**, 136805-66-8; **20**, 136805-67-9; **21**, 136805-68-0; **22**, 136805-69-1; (*Z*)-**23**, 136805-70-4; **24**, 136805-71-5; 2-formyl-7-methylnaphthalene, 52988-18-8; 1,4-bis(dimethylamino)-1,1,4,4-tetramethyl-1,4-disilabutane, 91166-50-6; 2-amino-6-bromopyridine, 19798-81-3.

Supplementary Material Available: ^1H NMR spectra including ^1H, ^1H COSY, and long-range ^1H, ^1H COSY's of the helices **2**, **3**, and **14**; experimental details of the X-ray crystal structure analyses of **14**, *trans*-**17**, and **22**, tables of the atomic coordinates, equivalent isotropic thermal parameters, bond angles and bond lengths, and intramolecular and intermolecular distances (**14**, *trans*-**17**, **22**); MMP2(85) structure of **14** and assigned values for missing parameters in the force field (37 pages). Ordering information is given on any current masthead page.

Protonation and Sulfinylation of Isomeric Isopropylpyrenes, 2,7-Di-*tert*-butylpyrene, and Tetracyclohexyl- and Tetracyclopentylpyrenes: Remarkably Stable, Sterically Crowded Pyrenium Cations†

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1-Isopropyl- (**1**), 2-isopropyl- (**2**), 4-isopropyl- (**3**), 1,3,6,8-tetraisopropyl- (**4**), and 1,3,5,7,9-pentaisopropylpyrene (**5**), 2,7-di-*tert*-butylpyrene (**6**), and 1,3,5,8-tetracyclohexyl- (**7**) and 2,4,7,9-tetracyclopentylpyrene (**8**) in FSO_3H or CF_3SO_3H (TfOH) in SO_2 or SO_2ClF solvent gave stable monopyrenium ions. In agreement with theory, exclusive α protonation occurred at low temperature (−75 → −65 °C) irrespective of the position of the substituents. The position of α-protonation is controlled by inductive stabilization of the alkyl (cycloalkyl) groups. Unlike hexahydropyrene which is diprotonated in FSO_3H-SbF_5 (1:1) Magic acid, with isopropylpyrenes stable dications could not be generated; in SO_2 solvent the Wheland intermediates of sulfinylation were observed, whereas in SO_2ClF solvent oxidation and monoprotonation were competitive. Charge distribution patterns in the sulfinylation σ-complexes are similar to those of protonated pyrenium ions. Stable pyrenium cations deprotonate or desulfinylate on quenching without dealkylation or disproportionation. At higher temperatures (ca. −40 °C), ipso-protonated **4** undergoes isomerization in FSO_3H/SO_2 solvent; other alkyl (cycloalkyl)pyrenium cations show no isomerization/disproportionation. Upon standing in Magic Acid, hexahydropyrene is oxidized to pyrene.

Introduction

Due to their carcinogenic/mutagenic activity and widespread presence in polluted environments, the synthesis, electrophilic chemistry, and spectroscopic studies of pyrene, alkylpyrenes, nitropyrenes, hydropyrenes, as well as their benzo-, indeno-, cyclopenta-annulated and methylene-bridged derivatives, are currently receiving considerable attention.[1-13]

For parent pyrene (Figure 1), simple Hückel MO[3,14] and PI-DEWAR calculations[15] predict the positions (1, 3, 6, 8) to be significantly more reactive. The Wheland intermediate of protonation at an α position is predicted to be 8.8 kcal/mol lower in energy than the σ-complex of $\alpha\beta$ attack and 20.5 kcal/mol more stable than the σ-complex of attack at a β position.[15] Since sites within 5 kcal/mol are considered possible candidates for substitution, attack at $\alpha\beta$ positions is possible but β attack is clearly not favored. Substitution of a methyl at the 1-position renders the ipso, followed by the 8, 6, and 3 positions most favored.[3] In

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(1) (a) Berg, A.; Lam, J.; Hansen, P. E. *Acta. Chem. Scand.* **1986**, *B40*, 665, (b) Hansen, P. E.; Berg, A.; Lund, H. *Acta Chem. Scand.* **1976**, *B30*, 267.

(2) Rodenburg, L.; Brandsma, B.; Tintel, C.; Van Thuijl, J.; Lugtenburg, J.; Cornelisse, J. *Recl. Trav. Chim. Pays-Bas* **1986**, *105*, 156 and references cited therein.

(3) Cerfontain, H.; Laali, K.; Lambrechts, H. J. A. *Rec. Trav. Chim. Pays-Bas* **1983**, *102*, 210 and references cited therein.

(4) Hansen, P. E.; Berg, A. *Acta. Chem. Scand.* **1981**, *B35*, 131.

(5) Hansen, P. E. *Magn. Res. Rev.* **1985**, *10*, 1.

(6) Dietrich, A. M.; Guenat, C. R.; Ball, L. M. Abstracts of the 35th ASMS Conference on Mass Spectrometry and Allied Topics, Denver, CO, May 1987.

(7) Hansen, P. E.; Blaabjerg, O.; Berg, A. *Acta. Chem. Scand.* **1978**, *B32*, 720.

(8) Rodenberg, L.; deBlock, R.; Erkelens, C.; Lugtenberg, J.; Cornelisse, J. *Recl. Trav. Chim. Pays-Bas* **1988**, *107*, 529.

(9) Minabe, M.; Cho, B. P.; Harvey, R. G. *J. Am. Chem. Soc.* **1989**, *111*, 3809.

(10) (a) Young, R. J.; Harvey, R. G. *Tetrahedron Lett.* **1989**, *30*, 6603 and references cited therein. (b) Sahali, Y.; Skipper, P. L.; Tannenbaum, S. R. *J. Org. Chem.* **1990**, *55*, 2918.

0022-3263/91/1956-6795$02.50/0