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Synthesis and Host-abilities of some New Corands Bearing Uncommon Chiral Spacer Units

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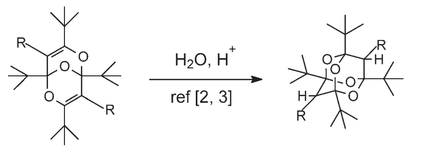
Benzo- and naphtho-ethylene glycols are prepared from dihydroxy-benzenes or -naphthalenes and the corresponding chloroethoxyethanols using known procedures. Cyclocondensation reactions of these open-chain diols with the chiral and concave tetra-*t*-butyl-2,6,9-trioxabicyclo[3.3.1]nonadiene ("bridged bisdioxine") bisacid chloride afford several new corands. In one case, besides the expected macrocycle, an open-chain podand is obtained and further cyclized to a large 2:2 macrocycle. The bridged bisdioxine spacer may also be converted into the tetraoxaadamantane scaffold as shown with an example. Extraction experiments employing selected corands towards various metal ions show a significant host-property towards Hg(II) salts for those macrocycles having *o*-disubstituted aryl groups incorporated, thus forming 1:1 complexes. NMR titration studies with sodium thiocyanate as well as with some organic guests do not exhibit significant host–guest interactions, in the case of Hg(II) thiocyanate a weak complexation was determined.

INTRODUCTION

2,6,9-Trioxabicyclo[3.3.1]nona-3,7-dienes ("bridged bisdioxines", **1**) and 2,4,6,8-tetraoxaadamantanes (**2**) both represent rare chiral heterocyclic systems, which can easily be obtained by the addition of various nucleophiles to dimeric dipivaloylketene [1,2] and subsequent acidic hydrolysis of the primarily formed bisdioxine derivatives [3]. Recently, these uncommon molecules were incorporated into a variety of macrocyclic polyethers, in order to investigate their abilities to serve as novel host systems [4].



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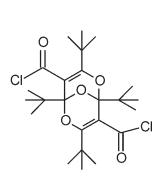

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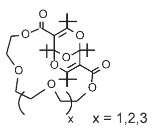
Cyclocondensation reactions of the chiral bridged bisdioxine acid chloride **3** [2] with various ethylene glycols afford macrocyclic systems of the hemi-crown ether type, either as racemates (1:1 molecules) **4** or diastereomeric mixtures (2:2 molecules) **5** [4].



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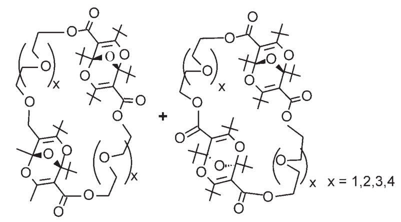

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Selected examples of type-**4** and type-**5** macrocycles were checked for their binding properties towards hard and soft metal cations employing liquid–liquid extraction experiments [4]. Compared to the extraction power of simple crown ethers [5,6] the extractabilities were found rather low in general. These results were possibly due to the introduction of the sterically crowded bisdioxine spacer as well as a rather high flexibility of the whole macrocycle, which might lead to an unfavourable arrangement of the oxygen donor

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atoms in the molecules. Consequently, we have now tried to make those macrocycles more rigid by introducing aromatic ring systems into the polyether chain.

RESULTS AND DISCUSSION

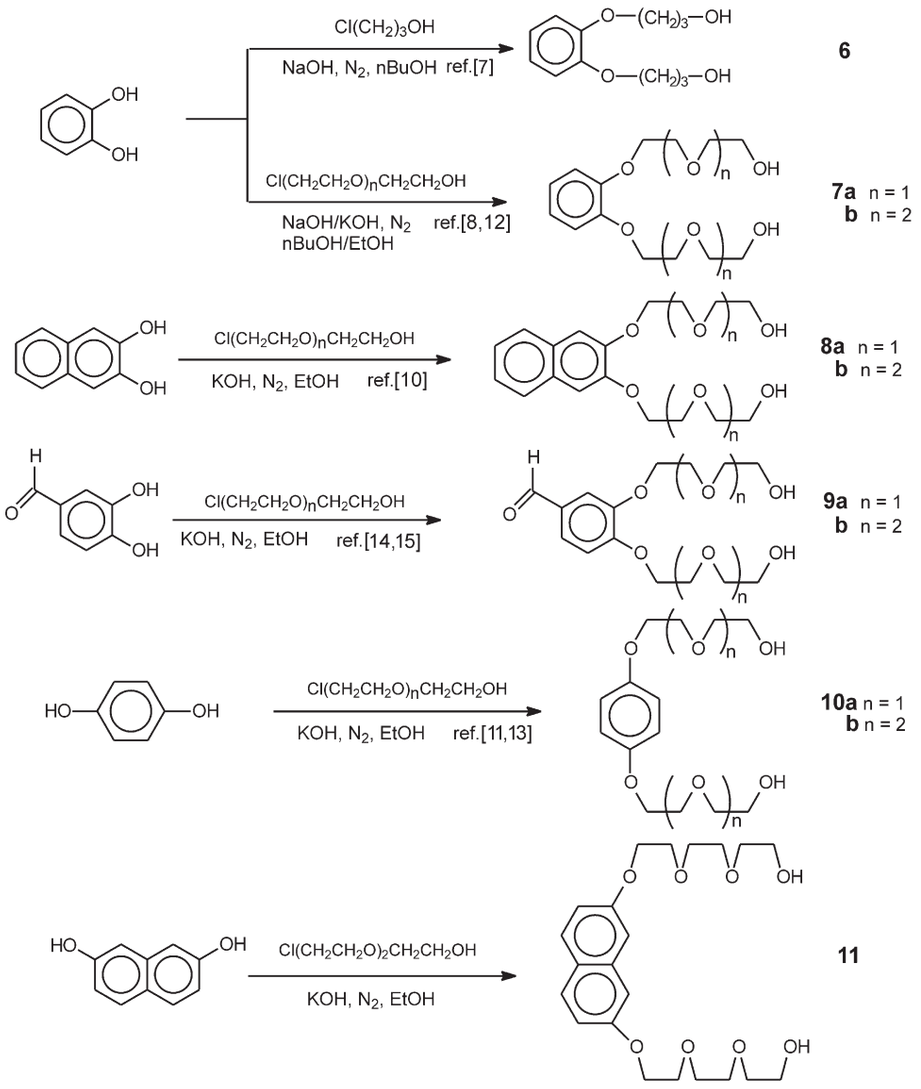
Preparation of Diols

Several diglycols (**6**–**11**) bearing aromatic spacer units were obtained in low to moderate yields (16–50%) from the reaction of phenols or naphthols with the corresponding chloro(ethoxy)$_n$ ethanols according to known procedures [7–15]; diol **11** has not been described previously. All compounds had to be purified with the aid of dry-flash chromatography (see Experimental section) (Scheme 1).

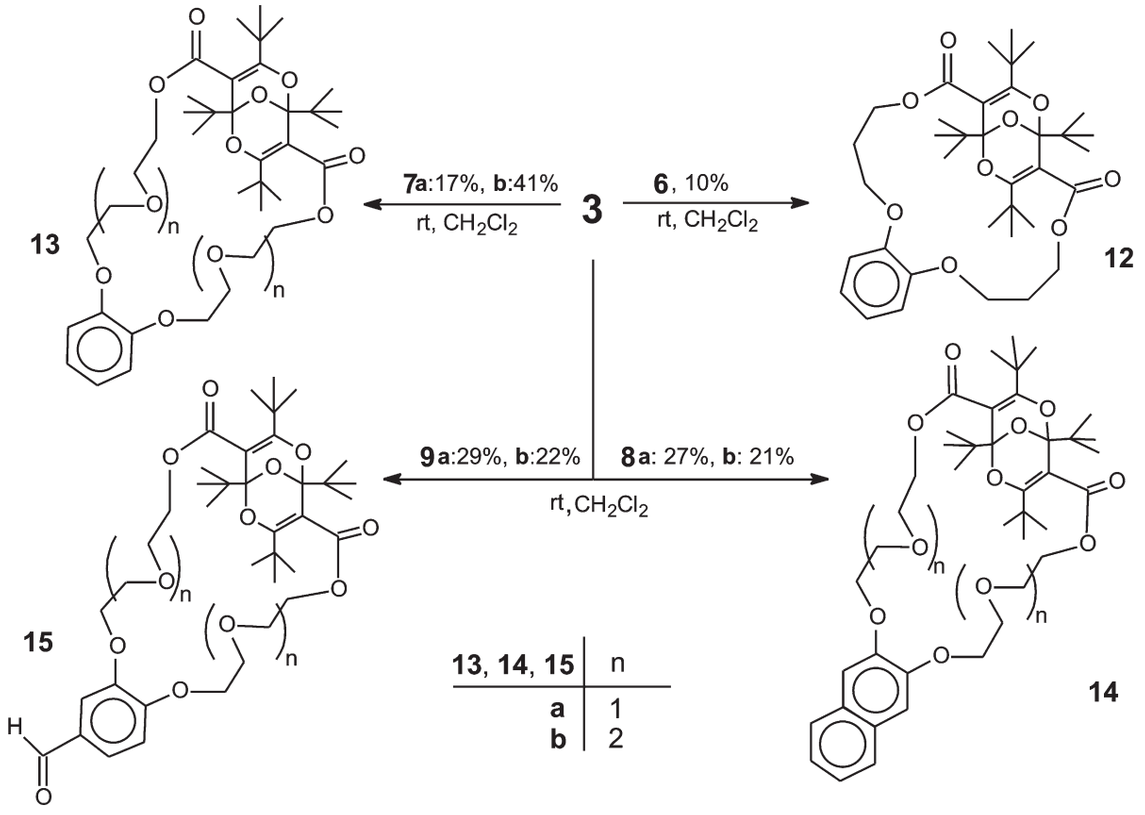
Synthesis of Coronands

Cyclocondensation of diglycols **6**–**11** with 1,3,5,7-tetra-*t*-butyl-2,6,9-trioxabicyclo[3.3.1]nona-3,7-diene -4,8-dicarbonyl chloride (**3**) afforded the corresponding corands **12**–**17** in low to moderate yields (10–50%). The bisacid chloride **3** was prepared from chlorination of the corresponding bisacid with thionyl chloride; the bisacid itself could be obtained via hydrolysis of the dimeric dipivaloylketene [16,17]. Isolation and purification of the target molecules **12**–**17** was achieved with aid of extensive dry-flash chromatography (for details see Experimental section) (Scheme 2).

When bisdiol **10b** was treated with acid chloride **3**, the macrocycle **16** was the minor reaction product. By separating the crude product using dry-flash chromatography the open-chain bisester **18** could be obtained as the main product, although the reaction



SCHEME 1



SCHEME 2

was carried out according to the dilution principle [18], in order to facilitate the intramolecular ring closing process (Scheme 3).

Bisester **18**, containing a bridged bisdioxine system as a spacer unit, may serve as a new podand to generate a much larger macrocycle by cyclocondensation with a further molecule of the bisacid chloride **3**. Actually, the 2:2 corand **20** is obtained in rather low yield (13%), again by utilizing the dilution methodology [18] (Scheme 4).

As an example, corand **17** was also converted into the corresponding tetraoxaadamantane macrocycle **19** by H^+-catalyzed hydrolysis as already demonstrated with several analogues [3,4].

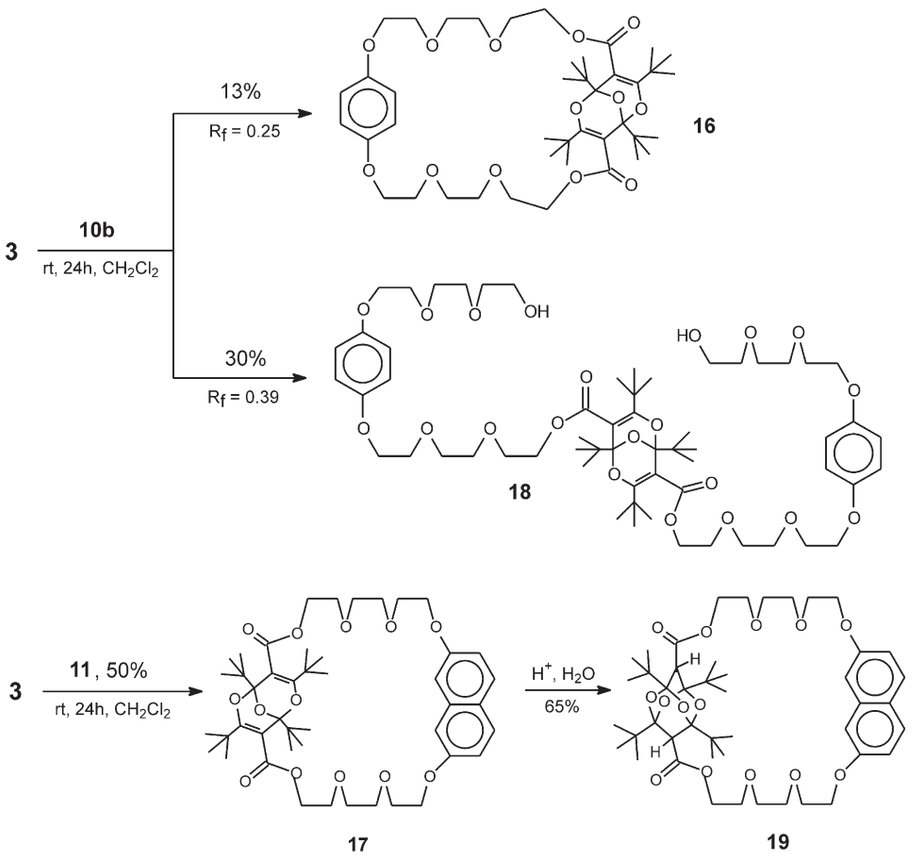
Due to the axial chirality of the building block **3** all 1:1 coronands exist as racemates, while the 2:2 macrocycle **20** should be considered as a mixture of diastereomers, which has been recently established with similar systems [4]. However, since the actual amount of **20** was very low and its host-properties were not very promising (see discussion in "Extraction Experiments" section), no attempts to separate the isomers were made.

Spectroscopic and Analytical Investigations

The polyether diols **6**–**10** have been verified by comparison of their physical data with those already reported (Refs. [7,8,10–15], see also Scheme 1). Elemental analysis and ^{1}H NMR data confirm the molecular structure of **11**.

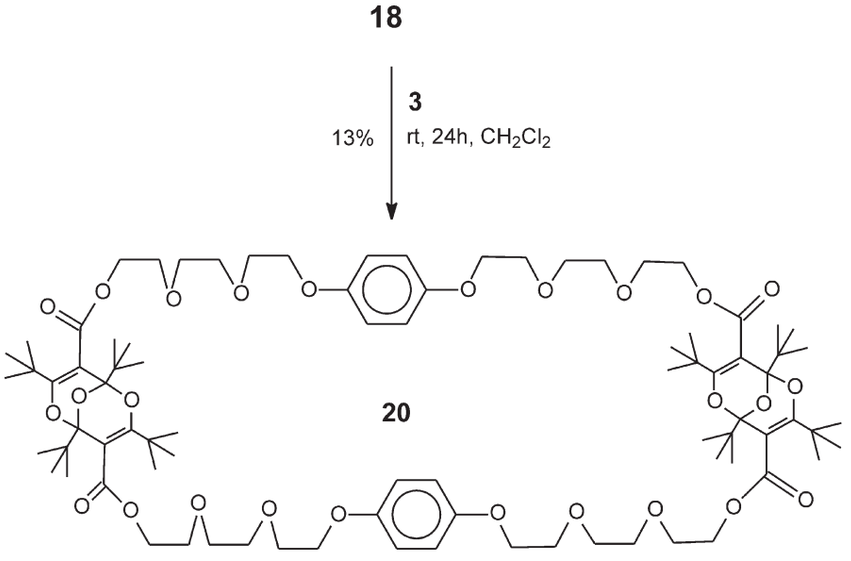
The similarity of all the polyether macrocycles **12**–**17** is clearly demonstrated by their IR spectra, which exhibit characteristic absorption bands at 1720–1715 cm^{-1} (ester carbonyls) and 1630–1620 cm^{-1} (*C*=*C*) and the absence of any OH absorptions. Further structural assignment came from the ^{1}H NMR spectra by comparing the signal intensities of the *t*-butyl groups to the protons of the chain (ethoxy and aromatic) which indicated a 1:1 ratio of the diols **6**–**11** and the bridged bisdioxine unit of **3**. In addition, HMBC [19], HMQC [20] and NOE experiments with selected examples (**13a**,**b**, **16**) allowed the two different *t*-butyl groups at C-3,7 (low field) and C-1,5 (high field) to be distinguished as well as to make an exact assignment of all ring protons, which disclosed a mainly non-crown ether-like conformation of the macrocycle in solution.

The ^{13}C NMR spectra of **12**, **13a**, **14b** and **15a** exhibit highly characteristic signals at δ 169.6–169.7 (*C*=*O*), 163.1–163.4 (C-3, C-7), 101.9–102.4 (C-4, C-8), 98.0–99.4 (C-1, C-5), 62.0–71.1 (OCH_2), 37.4, 39.4 ($C(Me)_3$) and 24.7, 28.6 ($C(CH_3)_3$). It is interesting to note, that in the spectrum of **15a**, due to loss of symmetry arising from the presence of the aldehyde substituent, some signals are split, in particular the ester



SCHEME 3

carbonyls (δ 169.74, 169.70), and the enolic ring carbon (δ 163.16, 163.06). The ^{1}H NMR spectrum of the tetraoxaadamantyl derivative **19** exhibits a three-line system for the two characteristic C–H protons between 2.82–3.01 ppm [3,4] which collapses to one broad line at 2.90 ppm if warmed above 77°C, thus indicating the presence of rotamers which have also been found with structural analogues [3,4]. The 3:4 ratio of methyl protons compared to oxymethylene protons of podand **18** is established by their signal



SCHEME 4

intensities in the ^{1}H NMR spectrum and the size of the molecule is further corroborated by the mass spectrum (MALDI mode; m/z 1172.0 $[M + Na]^+$). The structural confirmation of the large cavity of macrocycle **20** in particular is based on its mass spectrum (CI mode; m/z 1553.6 $[M + 1]^+$) since the ^{1}H and ^{13}C NMR spectra just confirm the correct ratio of oxymethylene:*t*-butyl:aromatic protons.

Extraction Experiments

The macrocycles **13b**, **14a**, **b** and **15a** were selected and checked for their binding properties towards hard and soft metal cations employing liquid–liquid extraction experiments [5,6]. The determination of the concentrations of the metal ions in both layers was carried out by radiotracer technique [21]. Preliminary studies using Na(I), Cs(I), Ca(II), Ba(II), Ag(I) and Hg(II) salts (1×10^{-4} M) and picric acid (5×10^{-3} M) in aqueous solution as well as chloroform; solutions of the corresponding ligand (**13b**–**15a**, 1×10^{-3} M) showed a slight extractability for Na(I) (0.1%) and a significant extraction efficiency for Hg(II) (1%) under these extraction conditions (shaking time: 30 min at 24°C). The best results with $HgCl_2$ were obtained in the case of **13b** and **14b**, obviously the cavities in **14a** and **15a** are somewhat too small. In order to get more accurate information on the complexation behaviour of Hg(II) ions the relationship of their distribution between the two layers at various concentrations of the ligands **13b** and **14b** was investigated. The extractabilities within the region 5×10^{-4}–5×10^{-3} M were found to be 1–10% and from the ascent of the straight line obtained a clear 1:1 complex between Hg(II) and the ligands **13b**/**14b** became evident (see Fig. 1). There is also a small difference between the two ligands which might be due to a slightly enhanced lipophilicity and rigidity of **14b** coming from the naphthyl spacer compared to the phenyl moiety in **13b**.

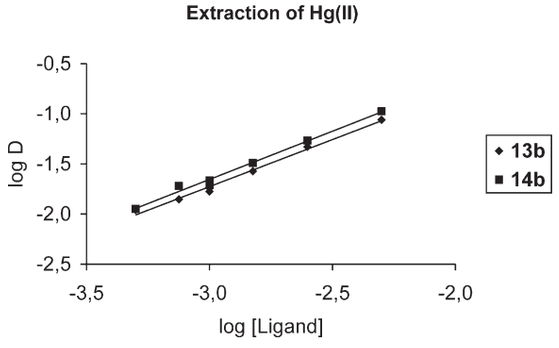


FIGURE 1 Extraction of Hg(II) with **13b** and **14b** in the water–chloroform system. Extraction conditions: $[HgCl_2] = 1 \times 10^{-4}$ M; [picric acid] $= 5 \times 10^{-3}$ M; [ligand] $= 5 \times 10^{-4}$–5×10^{-3} M in $CHCl_3$; shaking time = 30 min; temp = 24°C; $D =$ cHg(org)/cHg(w).

Complexation Studies

NMR-titration experiments in general are versatile tools to investigate and calculate complexation constants in host–guest interactions [22–24]. Compounds **13a**,**b**, **14a**,**b** and **15b** were selected as ligands and subjected to such investigations using inorganic (sodium thiocyanate, mercury thiocyanate) as well as organic (benzylammonium chloride, phenylglycine methyl ester hexafluorophosphate) guests. The experimental procedure followed the methodology described in Ref. [23], with the ligands dissolved in d_6-acetone, $CDCl_3$ or DMSO-d_6, and addition of increasing amounts of the corresponding guest with constant monitoring of the chemical shift values of the protons affected. As expected from the extraction experiments, titration of **14b** with increasing amounts of Hg(II)thiocyanate in d_6-acetone solution showed significant shift differences of $\Delta\delta = 0.018 - 0.031$ ppm for OCH_2 protons at 3.92, 3.97, 4.28 and 4.54 ppm. Unfortunately, due to the limited solubility of the Hg(II) salt in acetone the complete shape of the titration curve could not be observed which made an exact calculation of the binding constant impossible. However, when this titration was repeated in DMSO-d_6 the shift differences became significantly smaller $\Delta\delta = 0.001 - 0.005$ ppm, but nevertheless a weak binding constant ($K_b = 3.1 \pm 1.5$ l mol^{-1}) could be obtained [23]. Titration of **13a** with sodium thiocyanate, **14a** with phenylglycine methyl ester hexafluorophosphate and **15b** with benzylammonium chloride did not exhibit any significant change in the chemical shift values. A chemical shift difference of $\Delta\delta = 0.008$ ppm for multiplets of the OCH_2 protons at 4.1001–4.1789 as well as 4.4335–4.5325 ppm, found with equimolar amounts of macrocycle **13b** and sodium thiocyanate, indicated a very small but nevertheless observable host–guest interaction. Corand **14b** when treated with phenylglycine methyl ester hexafluorophosphate, prepared *in situ* from reaction of phenylglycine methyl ester hydrochloride and lithium hexafluorophosphate [25], did not show any interaction with the organic guest molecule (no change of the δ-values of the phenylglycine protons). However, a $\Delta\delta$ value of 0.012–0.016 ppm for the naphthyl protons in the *ortho*-position to the two naphthol oxygens (s, $\delta = 7.12$ ppm) as well as the vicinal CH_2 protons attached (t, $\delta = 4.25$ ppm) could suggest an interaction of the small Li(I) ion with that limited part of the macrocycle which is located opposite to the space-demanding bulky *t*-butyl groups of the bridged bisdioxine spacer.

CONCLUSION

In order to improve the potential host-abilities of the macrocyclic system of variable sizes containing chiral

bridged bisdioxines as well as tetraoxaadamantanes as unusual spacer molecules [4], several aromatic units were inserted into the macrocyclic chain to afford the new systems **13**–**17**, **19** and **20**. This resulted in slightly increased complexation properties towards metal ions compared to similar systems [4]. This is ascribed to an enhanced rigidity of the macrocycles in general. In particular, ligands **13b** and **14b** are capable of binding and extracting Hg(II) as a 1:1 complex from aqueous into the organic phase.

EXPERIMENTAL

General

Melting points are uncorrected. ^{1}H NMR spectra were recorded at 360 and 500 MHz; ^{13}C NMR spectra at 90 MHz, respectively, in $CDCl_3$ unless otherwise noted. Chemical shifts are reported in ppm (δ) relative to TMS. IR spectra were determined as potassium bromide pellets. Mass spectral data were obtained either by using the MALDI technique (for **18**) or the CI mode (for **20**). Dry-flash column chromatography was performed using silica gel (5–40 μm, Merck 60H). Analytical thin-layer chromatography was carried out on precoated silicagel aluminum plates containing a fluorescent indicator (GF-254 Merck) or by spraying with vanilline/sulfurous acid and warming up.

Materials

Dipivaloylmethane and oxalyl dichloride were purchased from Aldrich Chemicals and used without further purification, bisacid chloride **3** was prepared according to the literature [2], the diphenols and dinaphthols as well as the corresponding chloro(ethoxy)$_n$ethanols as starting materials for the preparation of the diols **6**–**11** were commercially available. The stationary phase (silica gel 60H, Merck) and all solvents used as eluents in dry-flash chromatography (DFC) were purchased in high p.a. quality (evaporation residue $>0.0003\%$).

1,2-Bis(3-hydroxypropoxy)benzene (**6**) was prepared exactly following Ref. [7].

Preparation of the Diols 7–10. General Procedure

The following general procedure was applied with adaption from the literature [7–15]: potassium hydroxide (40 mmol) and the corresponding diphenol, or dinaphthol derivative (20 mmol) were dissolved in dry ethanol with slight warming under nitrogen. In case of **7a** the solvent was *n*-butanol and sodium hydroxide was used as base. 2-(2-Chloroethoxy)ethanol or 2-[2-(chloroethoxy)ethoxy]ethanol, respectively, dissolved in dry ethanol (10 ml), were added drop by drop with stirring and the whole reaction mixture was refluxed for 2 d. Then the solvent was evaporated, the residue dissolved in chloroform (20 ml) and washed three times with water (20 ml each). The organic layer was dried over sodium sulfate and after evaporation, the crude residue was separated and purified with aid of dry-column flash chromatography [26]. Details are presented in Table I.

2,7-Di-(8-hydroxy-3,6-dioxaoctyloxy)naphthalene (**11**). 2,7-Dihydroxynaphthalene (3.2 g, 20 mmol) and powdered potassium hydroxide (2.25 g, 40 mmol) were suspended in dry ether (25 ml) and refluxed under nitrogen. A solution of 2-[2-(chloroethoxy) ethoxy]ethanol (5.61 g, 45 mmol) in dry ethanol (10 ml) was added slowly (30 min) drop by drop. The reaction mixture was then refluxed for 2 d, evaporated and the crude residue dissolved in chloroform (20 ml). The chloroform solution was extracted with water three times and dried over sodium sulfate. After evaporation the product was separated and purified by dry-column flash chromatography (eluent ethyl acetate:MeOH = 9 : 1, $R_F = 0.25$) to afford 3.35 g (40%) of **11** as a clear oil. ^{1}H NMR ($CDCl_3$): δ 2.80 (sb, 2H, OH), 3.62 (t, $J =$ 5.3 Hz, 4H, OCH_2), 3.75 (m, 12H, OCH_2), 3.97 (t, $J =$ 5.3 Hz, 4H, OCH_2), 4.22 (t, $J = 5.3$ Hz, 4H, OCH_2), 7.02 (d, $J = 9$ Hz, 2H, aromat), 7.08 (s, 2H, aromat), 7.56 (d, $J = 9$ Hz, 2H, aromat). Anal. Calcd for $C_{22}H_{32}O_8$: C, 62.25; H, 7.60. Found: C, 62.36; H, 7.60.

Reaction of Bisacid Chloride 3 with Diols 6–10b. General Procedure

A solution of the corresponding diols (**6**–**9**, 0.32 mmol) in dry dichloromethane (3 ml) was

TABLE I Isolation and physical data of **7**–**10**

Compound [Ref.]	Solvents	R_F value	Yield (%)	Physical data
7a [12]	Ethyl acetate:MeOH 10:1	0.25	25	Oil
7b [8]	Ethyl acetate:MeOH 5:1	0.40	40	Oil
8a [10]	Ethyl acetate:MeOH 50:3	0.16	16	Solid; mp: 60–61°C
8b [10]	Ethyl acetate:MeOH 10:3	0.29	29	Oil
9a [14]	Ethyl acetate:MeOH 50:7	0.17	18	Oil
9b [15]	Ethyl acetate:MeOH 50:7	0.13	20	Oil
10b [11]	Ethyl acetate:MeOH 20:1	0.20	60	Solid; mp: 49–50°C
10a [13]	Ethyl acetate:MeOH 40:1	0.20	35	Oil

TABLE II Isolation and physical data of macrocycles **12**–**15**

Compound	Eluents*	R_F value	mp (°C)	Yield (%)
12	(a) PE:EE 20:1	0.25		
	(b) CH_2Cl_2:MeOH 10:1	0.79	198–199	10
13a	PE:EE 5:1	0.26	119–120	41
13b	PE:EE 5:2	0.25	109–111	17
14a	PE:EE 50:9	0.18	210–211	27
14b	PE:EE 5:2	0.20	120–122	21
15a	PE:EE 5:2	0.17	154–156	29
15b	PE:EE 4:3	0.24	130–132	22
16	PE:EE 5:2	0.25	74–75	13

*PE: petrol ether (40–60°C); EE: ethyl acetate.

added slowly drop by drop with stirring to freshly prepared bisacid chloride **3** (150 mg, 0.32 mmol) [2], dissolved in dry dichloromethane (3 ml). The reaction mixture was allowed to stand overnight (12–15 h) at rt. After evaporation the crude residue was immediately subjected to dry-column flash chromatography. Details and physical data are presented in Table II.

4,8-[Phenylene-1,2-bis(1-oxo-2,6-dioxahexano)]-1,3,5,7-tetra-t-butyl-2,6,9-trioxabicyclo[3.3.1]nona-3,7-diene (**12**). IR (KBr) ν/cm^{-1} 3020–2840 (CH), 1720 (*C*=*O*), 1620 (*C*=*C*); ^{1}H NMR ($CDCl_3$) δ 1.07 (s, 18H, *t*-Bu), 1.16 (s, 18H, *t*-Bu), 2.10–2.24 (m, 4H, CH_2), 3.60–4.27 (m, 6H, OCH_2), 3.55–3.72 (m, 2H, OCH_2), 6.80–6.98 (m, 4H, Ar–H); ^{13}C NMR ($CDCl_3$) δ 24.79, 28.62 (C(*C*H$_3$)$_3$), 28.73 (CH_2), 37.56, 39.49 (*C*(Me)$_3$), 62.88, 69.28 (OCH_2), 99.39 (C-1/C-5), 101.92 (C-4/C-8), 117.75, 122.35 (CH-aromat), 149.59 (C–O, Ar–O), 163.41 (C-3/C-7), 169.69 (*C*=*O*). Anal. Calcd for $C_{36}H_{52}O_9$: C, 68.76; H, 8.34. Found: C, 68.45; H, 8.52.

4,8-[Phenylene-1,2-bis(1-oxo-2,5,8-trioxaoctano)]-1,3,5,7-tetra-t-butyl-2,6,9-trioxa[3.3.1]nona-3,7-diene (**13a**). IR (KBr) ν/cm^{-1} 3020–2860 (CH), 1715 (*C*=*O*), 1625 (*C*=*C*); ^{1}H NMR ($CDCl_3$) δ 1.06 (s, 18H, *t*-Bu), 1.21 (s, 18H, *t*-Bu), 3.73–3.92 (m, 10H, OCH_2), 4.02–4.22 (m, 4H, OCH_2), 4.52–4.66 (m, 2H, OCH_2), 6.92 (s, 4H, Ar–H); ^{13}C NMR ($CDCl_3$) δ 24.59, 28.70 (C(*C*H$_3$)$_3$), 37.44, 39.47 (*C*(Me)$_3$), 64.43, 68.91, 69.29, 70.07 (OCH_2), 98.05 (C-1/C-5), 102.23 (C-4/C-8), 116.04, 122.05 (CH–Ar), 149.28 (Ar–O), 163.17 (C-3/C-7), 169.76 (*C*=*O*). Anal. Calcd for $C_{38}H_{56}O_{11}$: C, 66.26; H, 8.19. Found: C, 66.48; H, 8.23.

4,8-[Phenylene-1,2-bis(1-oxo-2,5,8,11-tetraoxaundecano)]-1,3,5,7-tetra-t-butyl-2,6,9-trioxabicyclo[3.3.1]nona-3,7-diene (**13b**). IR (KBr) ν/cm^{-1} 3020–2840 (CH), 1715 (*C*=*O*), 1620, 1595 (*C*=*C*); ^{1}H NMR ($CDCl_3$) δ 1.04 (s, 18H, *t*-Bu), 1.22 (s, 18H, *t*-Bu), 3.57–3.89 (m, 16H, OCH_2), 3.89–3.97 (m, 2H, $COOCH_b$), 4.11–4.16 (m, 4H, Ar–OCH_2), 4.48–4.56 (m, 2H, $COOCH_a$), 6.90 (s, 4H, Ar–H). Anal. Calcd for $C_{42}H_{64}O_{13}$: C, 64.93; H, 8.30. Found: C, 65.08; H, 8.34.

4,8-[Naphthylene-2,3-bis(1-oxo-2,5,8-trioxaoctano)]-1,3,5,7-tetra-t-butyl-2,6,9-trioxabicyclo[3.3.1]nona-3,7-diene (**14a**). IR (KBr) ν/cm^{-1} 3020–2840 (CH), 1715 (*C*=*O*), 1620 (*C*=*C*); ^{1}H NMR ($CDCl_3$) δ 1.05 (s, 18H, *t*-Bu), 1.20 (s, 18H, *t*-Bu), 3.79–3.97 (m, 8H, OCH_2 + 2H, $COOCH_b$), 4.25 (t, 4H, OCH_2), 4.55–4.72 (m, 2H, $COOCH_a$), 7.15 (s, 2H, Ar–H), 7.33 (m, 2H, Ar–H), 7.68 (m, 2H, Ar–H). Anal. Calcd for $C_{42}H_{58}O_{11}$: C, 68.27; H, 7.91. Found: C, 68.18; H, 7.96.

4,8-[Naphthylene-2,3-bis(1-oxo-2,5,8,11-tetraoxaundecano)]-1,3,5,7-tetra-t-butyl-2,6,9-trioxabicyclo[3.3.1]nona-3,7-diene (**14b**). IR (KBr) ν/cm^{-1} 3020–2840 (CH), 1715 (*C*=*O*), 1620 (*C*=*C*); ^{1}H NMR ($CDCl_3$) δ 1.06 (s, 18H, *t*-Bu), 1.22 (s, 18H, *t*-Bu), 3.58–4.00 (m, 16H, OCH_2 + 2H, $COOCH_b$), 4.25 (t, 4H, OCH_2), 4.50–4.62 (m, 2H, $COOCH_a$), 7.11 (s, 2H, Ar–H), 7.32 (m, 2H, Ar–H), 7.67 (m, 2H, Ar–H); ^{13}C NMR ($CDCl_3$) δ 24.63, 28.70 (C(*C*H$_3$)$_3$), 37.45, 39.45 (*C*(Me)$_3$), 63.91, 68.92, 69.02, 69.79, 70.50, 71.13 (OCH_2), 98.14 (C-1/C-5), 102.39 (C-4/C-8), 108.08, 124.23, 126.30 (CH–Ar), 129.32 (Ar–C), 149.02 (Ar–O), 163.31 (C-3/C-7), 169.63 (*C*=*O*). Anal. Calcd for $C_{46}H_{66}O_{13}$: C, 66.81; H, 8.04. Found: C, 66.97; H, 8.03.

4,8-[4-Formylphenylene-1,2-bis(1-oxo-2,5,8-trioxaoctano)]-1,3,5,7-tetra-t-butyl-2,6,9-trioxabicyclo[3.3.1]nona-3,7-diene (**15a**). IR (KBr) ν/cm^{-1} 3020–2840 (CH), 1715, 1695 (*C*=*O*), 1620, 1600, 1585 (*C*=*C*); ^{1}H NMR ($CDCl_3$) δ 1.02 (s, 18H, *t*-Bu), 1.20 (s, 18H, *t*-Bu), 3.71–3.93 (m, 10H, OCH_2), 4.12–4.29 (m, 4H, OCH_2), 4.50–4.66 (m, 2H, OCH_2), 6.99 (d, J = 8 Hz, 1H, Ar–H), 7.40 (s, 1H, Ar–H), 7.48 (d, J = 8 Hz, 1H, Ar–H); ^{13}C NMR ($CDCl_3$) δ 24.58, 28.68 (C(*C*H$_3$)$_3$), 37.43, 39.48 (*C*(Me)$_3$), 63.68, 64.35, 64.38, 68.51, 68.97, 69.09, 69.61, 69.68 (OCH_2), 98.01 (C-1/C-5), 102.17, 102.25 (C-4/C-8), 112.64, 113.18 (Ar–CH), 130.48 (Ar–C), 149.2, 154.42 (Ar–O), 163.07, 163.16 (C-3/C-7), 169.70, 169.74 (ester *C*=*O*), 190.77 (*C*=*O*). Anal. Calcd for $C_{39}H_{56}O_{12}$: C, 65.34; H, 7.87. Found: C, 65.59; H, 8.07.

4,8-[4-Formylphenylene-1,2-bis(1-oxo-2,5,8,11-tetraoxaundecano)]-1,3,5,7-tetra-t-butyl-2,6,9-trioxabicyclo[3.3.1]nona-3,7-diene (**15b**). IR (KBr) ν/cm^{-1} 3020–2800 (CH), 1715, 1690 (*C*=*O*), 1620, 1600, 1590 (*C*=*C*); ^{1}H NMR ($CDCl_3$) δ 1.06 (s, 18H, t-Bu), 1.22 (s, 18H, t-Bu), 3.53–4.00 (m, 18H, OCH_2), 4.15–4.30 (m, 4H, OCH_2), 4.45–4.60 (m, 2H, OCH_2), 6.95 (d, J = 8 Hz, 1H, Ar–H), 7.41 (s, 1H, Ar–H), 7.46 (d, J = 8 Hz, 1H, Ar–H), 9.62 (s, 1H). Anal. Calcd for $C_{43}H_{64}O_{14}$: C, 64.16; H, 8.01. Found: C, 64.04; H, 8.20.

4,8-[Phenylene-1,4-bis(1-oxo-2,5,8,11-tetraoxaundecano)]-1,3,5,7-tetra-t-butyl-2,6,9-trioxabicyclo[3.3.1]-nona-3,7-diene (**16**). IR (KBr) ν/cm^{-1} 3020–2780 (CH), 1720 (*C*=*O*), 1620 (*C*=*C*); ^{1}H NMR ($CDCl_3$) δ 1.06 (s, 18H, *t*-Bu), 1.11 (s, 18H, *t*-Bu), 3.53–3.71 (m, 12H, OCH_2), 3.79–3.85 (m, 4H, OCH_2), 4.11–4.16 (m, 8H, $COOCH_2$ + Ar–OCH_2), 6.87 (s, 4H, Ar–H). Anal. Calcd for $C_{42}H_{64}O_{13}$: C, 64.93; H, 8.30. Found: C, 64.96; H, 8.62.

4,8-[Naphthylene-2,7-bis(1-oxo-2,5,8,11-tetraoxaundecano)]-1,3,5,7-tetra-t-butyl-2,6,9-trioxabicyclo[3.3.1]-nona-3,7-diene (**17**). Bisacid chloride **3** (150 mg, 0.32 mmol) was dissolved in dry acetonitrile (4 ml) and warmed up to 60°C to obtain a clear solution. Then diol **11** (140 mg, 0.32 mmol), dissolved in acetonitrile (3 ml) was slowly added drop by drop with stirring (30 min). The reaction mixture was cooled to rt and stirred for 24 h. In order to complete the reaction, a small amount of bisacid chloride **3** (30 mg, 0.06 mmol) was again added and stirring continued for an additional 24 h. Then the reaction mixture was evaporated and the crude oily residue subjected to dry-column flash chromatography (eluent: *n*-hexane:ethyl acetate 7:3) to provide 130 mg (50%) of **17** as an viscous oil. IR (KBr) ν/cm^{-1} 3060–2800 (CH), 1720 (*C*=*O*), 1620 (*C*=*C*); ^{1}H NMR ($CDCl_3$) δ 1.02 (s, 18H, *t*-Bu), 1.20 (s,18H, *t*-Bu), 3.55–3.80 (m, 12H, OCH_2), 3.90 (t, $J = 4.5$ Hz, 4H, OCH_2), 4.0–4.35 (m, 8H, OCH_2), 7.0 (d, $J = 9$ Hz, 2H, Ar–H), 7.12 (s, 2H, Ar–H), 7.65 (d, $J = 9$ Hz, 2H, Ar–H); ^{13}C NMR ($CDCl_3$) δ 24.64, 28.66 (C(*C*H_3)$_3$), 37.46, 39.47 (*C*(Me)$_3$), 63.75, 67.38, 68.61, 69.80, 70.62 (OCH_2), 97.98 (C-1/C-5), 102.46 (C-4/C-8), 106.65, 116.51, 129.1 (Ar–CH), 124.49, 135.75 (Ar–C), 157.37 (Ar–O), 163.28 (C-3/C-7), 169.14 (*C*=*O*). Anal. Calcd for $C_{46}H_{66}O_{13}$: C, 66.81; H, 8.04. Found: C, 66.63; H, 8.27.

9,10-[Naphthylene-2,7-bis(1-oxo-2,5,8,11-tetraoxaundecano)]-1,3,5,7-tetra-t-butyl-2,4,6,8-tetraoxaadamantane **(19)**. Corand **17** (170 mg, 20 mmol) was dissolved in dichloromethane (2 ml) and acetic acid (2 ml). After addition of conc. hydrochloric acid (170 mg) the flask was closed and the reaction mixture stirred for 12 h at rt. Then on opening the flask the dichloromethane was allowed to escape and the remaining liquids were removed by evaporation, followed by lyophilization at the vacuum line (10^{-3} mbar). The so-formed crude solid crystallized by triturating with *n*-hexane to afford white crystals 113 mg (65%); mp 187°C. ^{1}H NMR ($CDCl_3$) δ 0.95, 1.0, 1.10 (3s, 36H, *t*-Bu), 2.92, 2.94, 2.98 (3s, 2H, collapsed to 1 broad signal at 2.95 above 77°C, 2H, CH), 3.75–4.35 (m, 24H, OCH_2), 7,01 (m, 4H, Ar–H), 7.72 (d, $J = 7.9$ Hz, 2H, Ar–H). Anal. Calcd for $C_{46}H_{68}O_{14}$: C, 65.40; H, 8.05. Found: C, 65.50; H, 8.21.

1,1′-(1,3,5,7-Tetra-t-butyl-2,6,9-trioxabicyclo[3.3.1]-nona-3,7-diene-4,8-yl)-11,11′[benzene-di-(2,5,8,11-tetraoxaundecan)]-1,1′-dione (**18**). Diol **11** (900 mg, 2.4 mmol), dissolved in dry dichloromethane (2.5 ml) was added to a solution of bisacid chloride **3** (280 mg, 0.59 mmol) in dichloromethane (1.5 ml) with stirring. After 24 h at rt, the solvent was evaporated and the crude product separated and purified with the aid of dry-column flash chromatography (eluent: petrol ether (40–60°C):ethyl acetate: MeOH 20:20:8, $R_F = 0.39$); yield 200 mg (30%). ^{1}H NMR ($CDCl_3$) δ 1.03 (s, 18H, t-Bu), 1.18 (s, 18H, t-Bu), 2.54 (sb, 2H, OH), 3.60 (m, 8H, OCH_2), 3.69 (m, 24H, OCH_2), 3.82 (m, 8H, OCH_2), 4.06 (m, 8H, OCH_2), 6.82 (s, 8H, Ar–H); MS (MALDI) $m/z = 1172.0$ ($M + Na^+$), 1170.9 $(M + H_2O)^+$. Anal. Calcd for $C_{60}H_{94}O_{21}$x H_2O: C, 61.54; H, 8.37. Found: C, 61.31; H, 8.26.

1,1′, 1″, 1‴-Bis (1,3,5,7-tetra-t-butyl-2,6,9-trioxabicyclo[3.3.1]nona-3,7-diene-4,8-diyl)-11,11′-[benzene-di (2,5,8,11-tetraoxaundecane)-1,1′-dione (***20***). Podand **18** (110 mg, 0.1 mmol), dissolved in dry dichloromethane (5 ml) was added drop by drop to a solution of bisacid chloride **3** in dry dichloromethane (3 ml) with stirring. The reaction mixture was kept at rt for 24 h. Then the solvent was evaporated and the residue subjected to dry-column flash chromatography (eluent: petrol ether (40–60°C):ethyl acetate 3:2; R_F value = 20) finally affording 20 mg (13%) of pure **20**, mp 121–123°C. ^{1}H NMR ($CDCl_3$) δ 1.037 (s, 36H, t-Bu), 1.198 (s, 36H, t-Bu), 3.69 (m, 24H, OCH_2), 3.81 (m, 8H, OCH_2), 4.06 (m, 12H, OCH_2), 4.30 (m, 4H, OCH_2), 6.81 (s, 8H, Ar–H); ^{13}C NMR ($CDCl_3$) δ 24.64, 28.71 (C(*C*H_3)$_3$), 37.47, 39.48 (*C*(Me)$_3$), 63.76, 68.06, 68.61, 69.93, 70.51, 70.71 (OCH_2), 98.08 (C-1/C-5), 102.43 (C-4/C-8), 115.56 (Ar–CH), 153.10 (Ar–O), 162.92 (C-3/C-7), 169.26 (*C*=*O*); MS (CI-mode) m/z 1553.6 ($M + H^+$). Anal. Calcd for $C_{84}H_{128}O_{26}$: C, 64.95; H, 8.24. Found: C, 65.44; H, 8.24.

Extraction Experiments

Extraction was performed at 24°C in microcentrifuge tubes (2 ml) by mechanically shaking 0.5 ml each of the organic and aqueous phases for 30 min, which was sufficient to reach the extraction equilibrium. All samples were then centrifuged and the concentration of metal ions in both layers was determined radiometrically [21] by measuring the gamma radiation of Na-22, Cs-137, Sr-85, Ba-133, Ag-110m, Zn-65 and Hg-203 in a NaJ(Tl) scintillation counter (Cobra II, Canberra-Packard) and the beta radiation of Ca-45 in a liquid scintillation counter (Tricarb 2500, Canberra-Packard).

^{1}H NMR Titration Experiments

^{1}H NMR titration experiments were performed to determine the values of the complexation constants K_b. The experimental procedure followed the methodology described by Sterk *et al.* [23,27,28],

the ligand (*e.g.* **14b**, 0.5 mg, 6.04×10^{-4} mmol) was dissolved in d_6-acetone (0.7 ml) and increasing amounts of *e.g.* Hg(II)SCN (4.5 mg, 0.014 mmol) dissolved in d_6-acetone (0.6 ml), were added step by step (7 additions, 50 or 100 µl each) with permanent control of the chemical shift values of the OCH_2 groups at 4.24 ppm, which were affected most by the complexation process. Again, from the titration of **14b** (0.5 mg, 6.04×10^{-4} mmol) dissolved in DMSO-d_6 (0.5 ml), with Hg(II)SCN (10.7 mg, 0.337×10^{-1} mmol) dissolved in DMSO-d_6 (0.2 ml), a K_b value of 3.1 ± 1.5 l mol^{-1} was then calculated according to the equation: $K_b = C_C/[(C_{Itot} - C_C) \times (C_{Ltot} \cdot C_C)]$ (C_C = concentration of the complex, C_{Itot} = total concentration of the metal ion, C_{Ltot} = total concentration of the ligand). Due to the very small shift differences involved (0.001–0.005 ppm) this titration was repeated twice, thus the K_b value given represents an average value of all three runs.

References

[1] Kappe, C. O.; Färber, G.; Wentrup, C.; Kollenz, G. *Tetrahedron Lett.* **1992**, *33*, 4553.
[2] Kappe, C. O.; Kollenz, G.; Fabian, W. M. F.; Wentrup, C.; Färber, G. *J. Org. Chem.* **1993**, *58*, 3361.
[3] Heilmayer, W.; Dalvi, T. S.; Kappe, C. O.; Wentrup, C.; Gruber, K.; Sterk, H.; Kollenz, G. *Chem. Commun.* **1995**, 797.
[4] Wallfisch, B. C.; Egger, T.; Heilmayer, W.; Kappe, C. O.; Wentrup, C.; Gloe, K.; Belaj, F.; Klintschar, G.; Kollenz, G. *Supramol. Chem.* **2002**, *14*, 383.
[5] Gloe, K.; Muehl, P.; Beger, J. *Z. Chem.* **1988**, *28*, 1.
[6] Moyer, B. A. In *Comprehensive Supramolecular Chemistry*; Lehn, J. M., Atwood, J. L., Davis, J. E., McNicol, D. D., Vögtle, F., Eds.; Pergamon Press: Oxford, 1996; Vol. 1, pp 377–416.
[7] Chen, C. S.; Wang, S. J.; Wu, S. C. *Org. Prep. Proc. Int. (OPPI Briefs)* **1981**, 350.
[8] Shinkai, S.; Inuzuka, K.; Miyazaki, O.; Manabe, O. *J. Am. Chem. Soc.* **1985**, *107*, 3950.
[9] Cordova, E.; Bissell, R. A.; Spencer, N.; Ashton, P. R.; Stoddart, J. F.; Kaifer, A. E. *J. Org. Chem.* **1993**, *58*, 6550.
[10] Czech, B.; Czech, A.; Bartsch, R. A. *J. Heterocycl. Chem.* **1984**, 341.
[11] Anelli, P. L.; Ashton, P. R.; Spencer, N.; Slawin, A. M. Z.; Stoddart, J. F.; Williams, D. J. *Angew. Chem.* **1991**, *103*, 1052.
[12] Dale, J.; Kristianson, P. O. *Acta Chem. Scand.* **1972**, *26*, 1471.
[13] Anelli, P. L.; Ashton, P. R.; Ballardini, R.; Balzani, V.; Delgado, M.; Gandolfi, M. T.; Goodnow, T. T.; Kaifer, A. E.; Philip, D.; Pietraszkiewicz, M.; Prodi, L.; Reddington, M. V.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Vicent, C.; Williams, D. J. *J. Am. Chem. Soc.* **1992**, *14*, 193.
[14] Cantrill, S. J.; Youn, G. J.; Stoddart, J. F.; Williams, D. J. *J. Org. Chem.* **2001**, *66*, 6857.
[15] Boden, N.; Bushby, R. J.; Donovan, K.; Liu, Qu.; Lu, Z.; Kreouzis, T.; Wood, A. J. *Liq. Cryst.* **2001**, *28*, 1739.
[16] Kappe, C. O.; Evans, R. A.; Kennard, C. H. L.; Wentrup, C. *J. Am. Chem. Soc.* **1991**, *113*, 4234.
[17] Kappe, C. O.; Färber, G.; Wentrup, C.; Kollenz, G. *J. Org. Chem.* **1992**, *57*, 7078.
[18] Knops, P.; Sendhoff, N.; Vögtle, F. *Top. Curr. Chem.* **1991**, *161*, 3.
[19] Bax, A.; Summers, F. *J. Am. Chem. Soc.* **1986**, *108*, 2093.
[20] Lerner, H.; Bax, A. *J. Magn. Reson.* **1986**, *69*, 375.
[21] Gloe, K.; Muehl, P. *Isotopenpraxis* **1983**, *19*, 257.
[22] Steed, J. W.; Atwood, J. L. In *Supramolecular Chemistry*; Steed, J. W., Atwood, J. L., Eds.; John Wiley & Sons: England, 2000; p 16.
[23] Geringer, M.; Sterk, H. *Magn. Reson. Chem.* **1989**, *27*, 1148.
[24] Wang, T.; Bradshaw, J. S.; Izatt, R. M. *J. Heterocycl. Chem.* **1994**, *31*, 1097, Review.
[25] Joly, J. P.; Nazhaoui, M.; Dumont, B. *Bull. Soc. Chim. Fr.* **1994**, *131*, 369.
[26] Harwood, L. M. *Aldrichimica Acta* **1985**, *18*, 25.
[27] Geringer, M.; Sterk, H. *Spectrosc. Lett.* **1992**, *25*, 619.
[28] Geringer, M.; Dworczak, R.; Sterk, H. *J. Mol. Liq.* **1991**, *50*, 21.