FULL PAPER

Tetra-*tert*-butyltetraoxa[8]circulene and Its Unusual Aggregation Behaviour

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*Dedicated to Professor Jørn B. Christensen on the occasion of his 50th birthday*

We describe the first example of the synthesis of a tetraoxa[8]circulene with only four substituents by means of BF₃·OEt₂ mediated tetramerisation of *tert*-butyl-1,4-benzoquinone. Two of the four regioisomers of tetra-*tert*-butyltetraoxa[8]circulene have been isolated and characterised by single-crystal X-ray analysis. It was found that the tetra-*tert*-butyltetraoxa[8]circulenes aggregate in solution through a cooperative polymerisation mechanism despite functionalisation with bulky *tert*-butyl substituents.

Introduction

Herein, we present our unexpected finding that tetra-*tert*-butyltetraoxa[8]circulene (**1**) aggregates in solution despite fourfold functionalisation with bulky electron-donating *tert*-butyl groups. The aggregation proceeds through a cooperative polymerisation mechanism.[1] It has been shown for a number of large aromatic systems that substitution with *tert*-butyl groups gives high solubility in non-polar solvents, an effect that has been ascribed to the propensity of the bulky substituents to prevent π–π interactions, and thus aggregation.[2] It is noteworthy, that Müllen's hexabenzocoronenes (**2**), Moore's large hexa(phenylacetylene) macrocyles (**3**) substituted with *tert*-butyl groups, and tetra-*tert*-butyl perylene (**4**) have been shown not to aggregate in solution (Scheme 1).[3–5]

Tetraoxa[8]circulene (**5**) is a highly thermally stable heteroaromatic compound that features a central planar eight-membered ring. The crystal packing of the unsubstituted macrocycle (**5**) is dominated by π–π stacking interactions.[6] Erdtman worked with tetraoxa[8]circulenes in the 1930s, but pioneering synthetic and structural work by Högberg and Erdtman in the late 1960s and 1970s led to the first correct structural description of the tetraoxa[8]circulenes.[7–9] Despite the sparsity of reports regarding the synthesis and properties of tetraoxa[8]circulenes, some derivatives have been shown to be liquid crystalline, some have
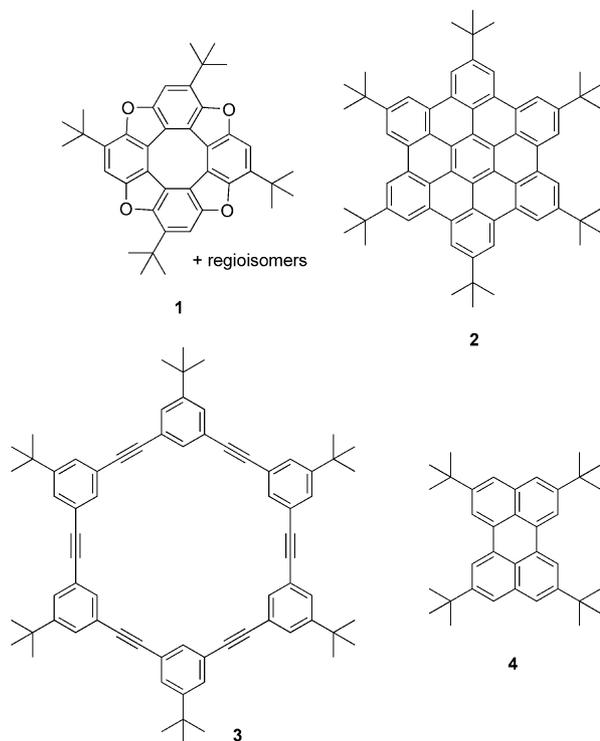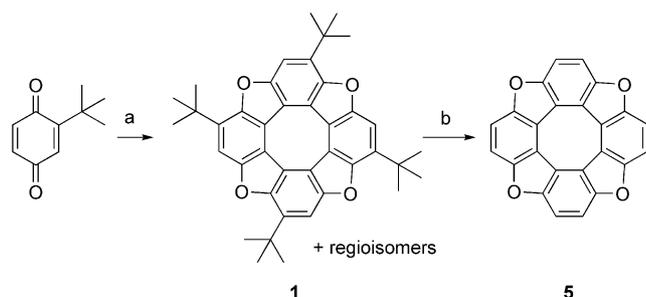

Scheme 1. Structure of tetra-*tert*-butyltetraoxa[8]circulene (**1** + regioisomers with respect to the *tert*-butyl groups), hexa-*tert*-butylbenzocoronene (**2**), hexa-*tert*-butylhexa(phenylacetylene) (**3**) and tetra-*tert*-butylperylene (**4**).

been used as the fluorescent component in organic light-emitting diodes, and others have been shown to form stable radical cation salts.[10,12–13]

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Octaalkyl-substituted tetraoxa[8]circulenes can be prepared from 2,3-dialkyl-1,4-benzoquinones or 1,4-naphthoquinones upon treatment with strong mineral or Lewis acids.[10–11] Here, we show for the first time that a mono-substituted 1,4-benzoquinone may be tetramerised to give a tetraoxa[8]circulene in good yield. This was achieved by treating *tert*-butyl-1,4-benzoquinone with BF$_3$·OEt$_2$ in boiling dichloromethane (CH$_2$Cl$_2$) to yield tetra-*tert*-butyltetraoxa[8]circulene (**1**) in multigram quantities as a mixture of regioisomers with respect to the *tert*-butyl groups (Scheme 2).

Scheme 2. Synthesis of tetra-*tert*-butyltetraoxa[8]circulene (**1**) and the parent tetraoxa[8]circulene (**5**). Reagents and conditions: (a) BF$_3$·OEt$_2$, CH$_2$Cl$_2$, 50%; (b) AlCl$_3$, benzene, 99%.

Compound **1** is highly soluble in organic solvents such as heptane and CH$_2$Cl$_2$, and exhibits green-blue fluorescence. Furthermore, this material provides easy access to the parent tetraoxa[8]circulene by means of a de-*tert*-butylation reaction with AlCl$_3$ in benzene. The overall yield for the parent tetraoxa[8]circulene (**5**) is approximately 50%, which is around 500 times better than the only other published procedure from 1,4-benzoquinone.[7] The mixture of regioisomeric tetra-*tert*-butyltetraoxa[8]circulenes (Scheme 3) was
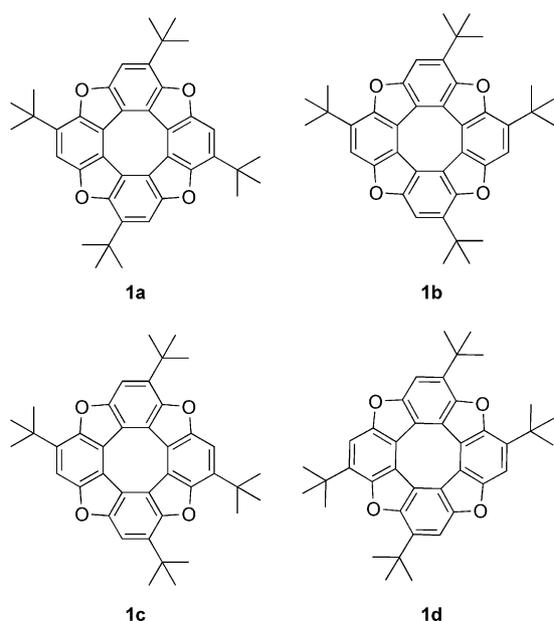
Scheme 3. Structure of the four regioisomers of tetra-*tert*-butyltetraoxa[8]circulene (**1**).

purified using standard column chromatography on silica with heptane as the mobile phase. Using that purification technique, we were able to separate the fourfold symmetrical tetra-*tert*-butyltetraoxa[8]circulene (**1a**) from the other three possible regioisomers. Upon crystallisation of the mixture of the remaining three regioisomers, it was possible to crystallise one of the twofold symmetrical isomers, **1b**, in high purity.

Selected optical properties of **1** are shown in Figure 1, in which the UV/Vis and fluorescence properties are compared with those of octaundecyltetraoxa[8]circulene (**6**).[10] The UV/Vis spectra in solution are very similar, as are the fluorescence spectra of dilute CH$_2$Cl$_2$ solutions. In contrast, the fluorescence spectrum of spin-cast thin films of **1** is significantly different and exhibits broader features. This behaviour is similar to previous observations for **6** when incorporated in organic light-emitting diodes (OLEDs), also by spin-casting.[12] The S$_1$ energy deduced from the spectrum of **1** in solution was approximately 3.0 eV compared with approximately 2.9 eV in the solid state – this observed redshift led us to suspect aggregation behaviour.
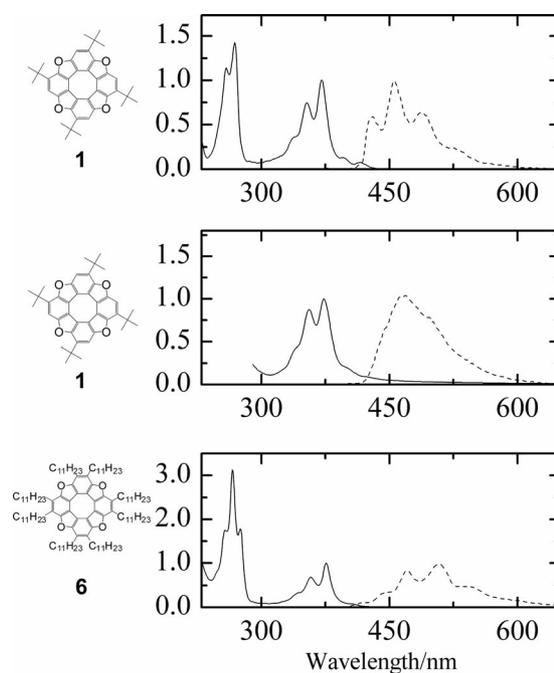

Figure 1. Optical properties: UV/Vis (–) and fluorescence spectra (···) of **1** in CH$_2$Cl$_2$ (top), in a spin-casted thin-film (middle), and of octaundecyltetraoxa[8]circulene (**6**) (bottom) in CH$_2$Cl$_2$ solution.

The electrochemical properties of **1** are very similar to those obtained with **6**. Both oxidations and reductions are reversible under standard conditions in CH$_2$Cl$_2$. For **6**, potentials of –2.18, –1.96 and 1.53 V were found relative to the ferrocene/ferrocenium couple, whereas potentials of –2.28, –1.97 and 1.51 V were found for **1**. This indicates that the two compounds have similar electronic structures.

The optical properties prompted us to study the concentration (Figure 2) and temperature (Figure 3) dependant behaviour of the mixture of regioisomers of **1** in solution, to

validate our hypothesis of aggregation. We observed distinct changes in the UV/Vis spectra upon changing either the temperature or concentration. We also observed that the changes in the concentration dependence did not obey Beer's law (solvent: 1,2-dichloroethane). Initially, we investigated possible aggregation behaviour by dilution experiments in which the UV/Vis spectra were recorded at different concentrations; under these conditions, the extinction coefficient was observed to change by approximately 10% from non-aggregated to the fully aggregated state. The extinction coefficients are plotted in Figure 2 together with the degree of complexation, which was deduced from the extrapolated values of the extinction coefficients.

To establish the thermodynamic parameters of the aggregation, and to gain insight into the structure of the aggregates, we followed the guidelines established by Meijer and co-workers in their recent work on supramolecular polymers.[1b] Analysis of the data (Figure 3) allowed us to conclude that the compound forms a supramolecular polymer that assembles through a cooperative mechanism with binding constants of $K_1 = 3$ M^{-1} and $K_m = 600$ M^{-1}, which gives a value for the cooperativity of 0.005. As the data fits well to a cooperative model, all values of K_m are equal ($K_m = K_2 = K_3 = ...$).

Figure 3. Change in the UV/Vis spectra with temperature in the range from 20 to 80 °C (top) and a magnification of the 390–420 nm region (bottom) showing the isosbetic points.
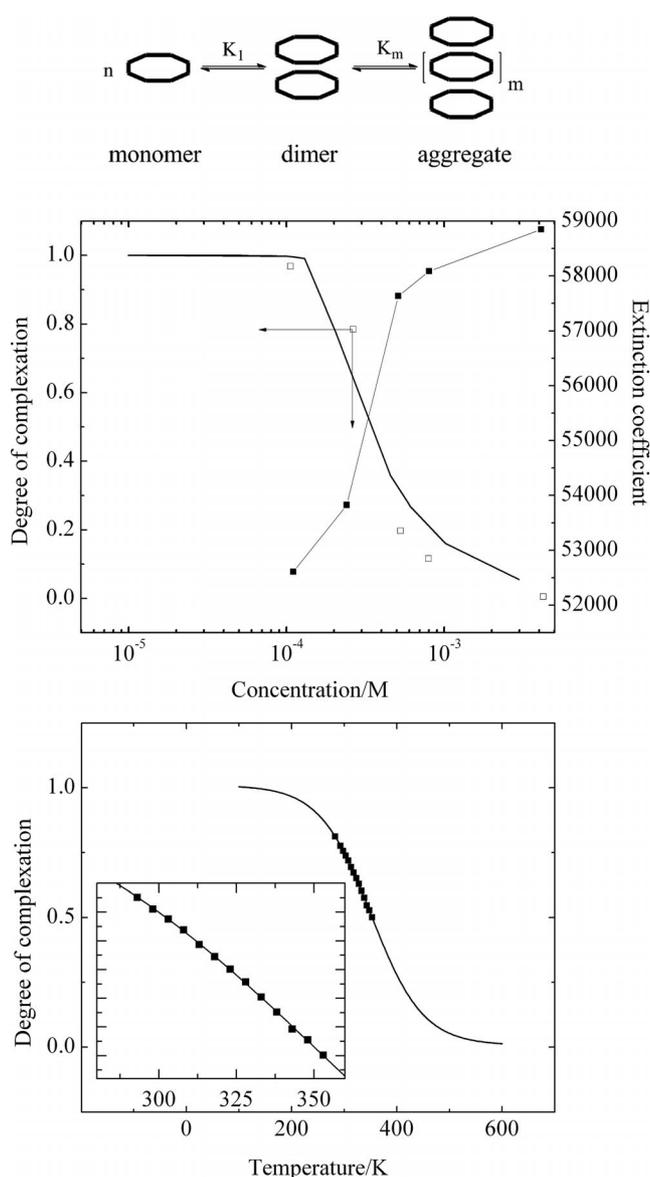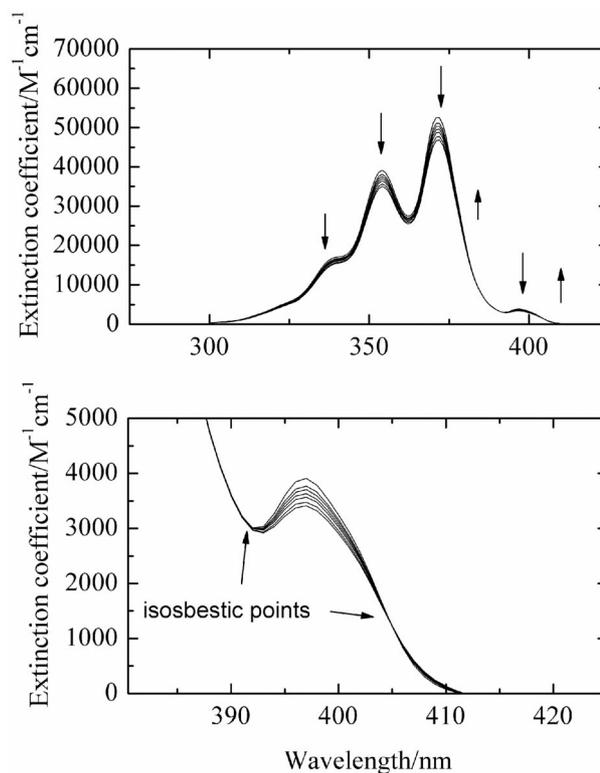

Figure 2. (Top) Schematic illustration of supramolecular dimerisation and aggregate formation. (Middle) Plot of the degree of complexation vs. total concentration, and the fitted graph. (Bottom) Plot of the degree of complexation vs. temperature, and the fitted graph.

To further explore the aggregation behaviour, we also carried out temperature studies. At 20 °C the intensity of the main bands (360 and 370 nm) in the UV/Vis spectrum were more intense than at 80 °C. The behaviour is fully reversible, and clear isosbestic points were observed, which is an indication that only two spectroscopic species were present in solution: the monomer and the aggregates (Figure 3). This observation is highly reproducible both for the mixture of isomers and for the isolated regioisomers (**1a** and **1b**). The spectra obtained were corrected for the temperature dependent change in solvent density.[14] As can be seen from the temperature dependent spectra, isosbestic points can be observed. This supports the notion of molecular aggregation because isosbestic points are unlikely to occur in the case of a simple temperature-induced change in concentration.

We observed similar, but less pronounced, aggregation behaviour for the isolated isomers (**1a** and **1b**). The values obtained suggest that the initial dimerisation of two molecules is not particularly favoured, whereas subsequent aggregate formation is more pronounced.

Several equilibrium constants have been reported for the aggregation of larger aromatic structures in which aggregation follows both the isodesmic and the cooperative model. A schematic illustration is shown in Figure 4 for selected molecules (for the cooperative model, the equilibrium constants plotted are for aggregate formation).
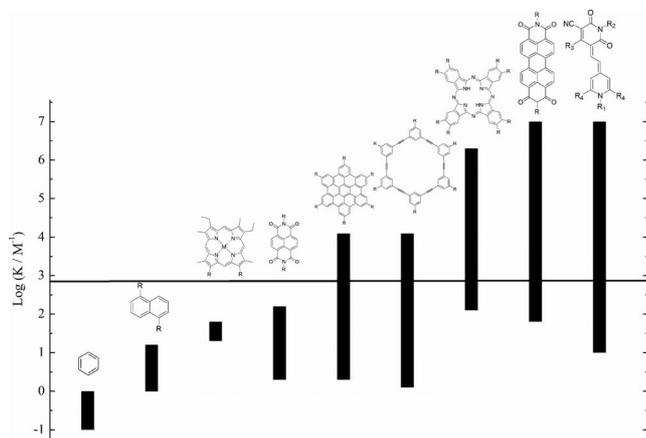

Figure 4. Aggregation constants for a number of large aromatic compounds with different substituents. The gray line is that for **1**.

The equilibrium constant for the formation of circulene aggregates is comparable to larger aromatic structures such as phenylacetylenes. The substituents on the macrocycles can alter the aggregation properties, as has been shown in a series of perylene bisimides.[16] A change of more than an order of magnitude has been observed for the equilibrium constant when going from an unsubstituted perylene bisimide to one substituted with *tert*-butyl groups. We speculate that the mechanism of aggregation observed for tetra-*tert*-butyltetraoxa[8]circulene is not driven by π–π interactions but, instead, by CH–π interactions. This is supported by the packing pattern observed in the X-ray crystal structure of **1a** (see Figure 6 below).

We proceeded to solve the single-crystal X-ray structures of the isolated regioisomers **1a** and **1b** (Figure 5),[17] and observed completely different crystal packing patterns for the two regioisomers. In the fourfold symmetrical structure of **1a**, there was no evidence of π–π stacking in the crystal lattice, because the space-filling nature of the *tert*-butyl groups prevents this. Conversely, in the crystal lattice of the twofold symmetrical structure of **1b**, distinct π–π stacking phenomena were observed (Figure 6). The two closest tetraoxa[8]circulenes in **1b** do not π–π stack in a completely co-planar manner, but the distance between the aromatic cores are consistent with the roughly 3.5 Å separation expected for π–π stacked systems.[15] The *tert*-butyl groups of two closest neighbouring tetraoxa[8]circulenes in **1b** are twisted roughly 45° with respect to each other, allowing

enough space for the two π-systems to approach each other. It seems that the aggregation behaviour of these structures can be probed by the use of a non-regular pattern of *tert*-butyl substituents.
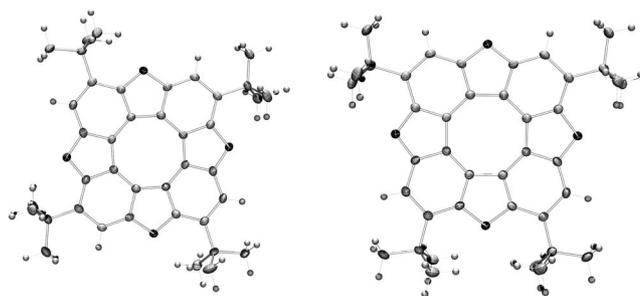

Figure 5. X-ray crystal structures of the regioisomers **1a** (left) and **1b** (right).
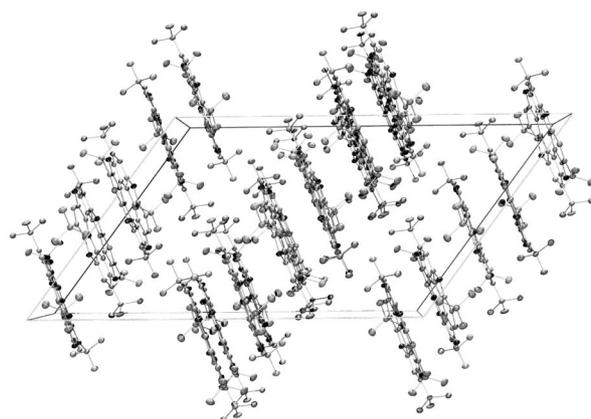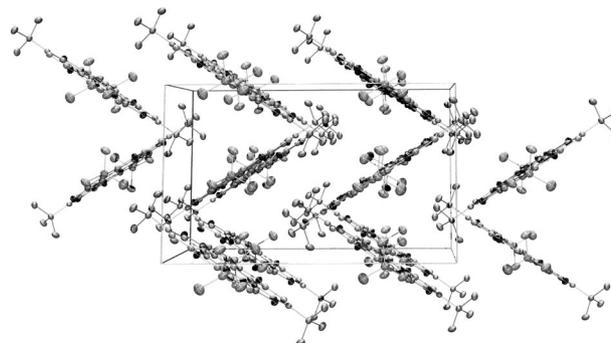

Figure 6. Crystal packing in the X-ray crystal structures of the regioisomers **1a** (top) and **1b** (bottom).

Conclusions

We have devised a high-yielding synthesis of the parent tetraoxa[8]circulene (**5**) from the highly soluble tetra-*tert*-butyltetraoxa[8]circulene (**1**), and have demonstrated that **1** aggregates in solution through a cooperative mechanism. This aggregation behaviour is unusual and we believe it is a consequence of the non-regular *tert*-butyl substitution pattern on the tetraoxa[8]circulene. Future efforts in this

field will explore other tetra-hetero-[8]circulenes, and examine their optical, electrochemical and solution-state aggregation behaviour.

Experimental Section

General Methods: NMR spectra were measured with a 500 MHz instrument from Bruker. All chemical shift values in the ^{1}H and ^{13}C NMR spectra are referenced to the solvent (δH = 7.26 ppm; δC = 77.00 ppm). Thin-layer chromatography (TLC) was carried out on commercially available precoated plates (silica 60) with fluorescence indicator. Melting points were measured with a Büchi B-140 apparatus and are uncorrected. Elemental analyses were performed with a Thermoquest 112 series apparatus. MALDI-TOF mass spectra were recorded with a Bruker spectrometer in the positive ion mode by using dithranol as the matrix. Column chromatography was performed on Merck Kieselgel 60 (0.015–0.040 mm) by using the DCVC technique or on Merck Kieselgel 60 (0.040–0.063 mm) for flash chromatography.

Synthetic Procedures

Tetra-*tert*-butyltetraoxa[8]circulene (1): To a solution of *tert*-butylbenzoquinone (1.0 g, mmol) in CH_2Cl_2 (25 mL), was added $BF_3\cdot OEt_2$ (10 mL). The reaction mixture was heated to reflux for 24 h, cooled to room temperature and poured into aqueous HCl (2 M, 50 mL). The phases were separated and the aqueous phase was extracted with CH_2Cl_2 (2 × 50 mL). The organic extracts were combined, dried (Na$_2$SO$_4$), filtered through paper and concentrated in vacuo. The crude material was purified by dry column vacuum chromatography (heptane/EtOAc) on silica to yield the title compound as a mixture of regioisomers as a pale-yellow solid; yield 0.445 g, 50 %.

By careful chromatography on silica, using heptane as the eluent, the fourfold symmetrical tetra-*tert*-butyltetraoxa[8]circulene (**1a**) was isolated; crystallization from heptane gave X-ray quality crystals. Crystallization of the remaining mixture of regioisomers from CH_2Cl_2 gave the twofold symmetrical tetra-*tert*-butyltetraoxa[8]-circulene (**1b**) as a very pure and crystalline material. These crystals were also of X-ray quality.

Characterization (1a): ^{1}H NMR (CDCl$_3$, 500 MHz): δ = 7.68 (s, 4 H), 1.70 (s, 36 H) ppm. ^{13}C NMR (CDCl$_3$, 125 MHz): δ = 153.4, 151.9, 136.1, 117.0, 114.6, 107.2, 35.4, 30.2 ppm. MS (MALDI-TOF): m/z = 584.74 [M]$^+$. C$_{40}$H$_{40}$O$_4$ (584): calcd. C 82.16, H 10.94; found C 82.23, H 11.10.

Characterization (1b): ^{1}H NMR (CDCl$_3$, 500 MHz): δ = 7.71 (s, 2 H), 7.60 (s, 2 H), 1.75 (s, 18 H), 1.70 (s, 18 H) ppm. ^{13}C NMR (CDCl$_3$, 125 MHz): δ = 153.8, 153.5, 152.0, 151.5, 135.8, 135.5, 116.9, 116.8, 114.9, 114.8, 107.8, 107.2, 35.4, 35.3, 30.3, 30.2 ppm. MS (MALDI-TOF): m/z = 360.33 [M]$^+$. C$_{40}$H$_{40}$O$_4$ (584): calcd. C 82.16, H 10.94; found C 82.37, H 10.90.

Tetraoxa[8]circulene (5): To a solution of tetra-*tert*-butyltetraoxa[8]-circulene (**1**; 0.50 g, 0.86 mmol) in benzene (20 mL), was added anhydrous AlCl$_3$ (200 mg) and the reaction mixture was stirred overnight at room temperature. The solid material was isolated by means of centrifugation and washed with aqueous HCl (2 M, 10 mL) and then water (2 × 10 mL), EtOH (10 mL), and finally Et$_2$O (10 mL) before drying under vacuum. The resulting highly pure pale-yellow solid product could be further purified by sublimation to give the title compound as a yellow powder; yield 0.300 g, 99 %. Needles could be obtained by crystallisation from CS$_2$, but significant loss of yield was observed.

Characterization of 5: MS (MALDI-TOF): m/z = 360 [M]$^+$. C$_{24}$H$_8$O$_4$ (360): calcd. C 80.00, H 2.24; found C 79.92, H 2.42.

[1] a) T. F. A. de Greff, M. M. J. Smulders, M. Wolffs, A. P. H. J. Schenning, R. P. Sijbesma, E. W. Meijer, *Chem. Rev.* **2009**, *109*, 5687–5754; b) M. M. J. Smulders, M. M. L. Nieuwenhuizen, T. F. A. de Greff, P. van der Schoot, A. P. H. J. Schenning, W. Meijer, *Chem. Eur. J.* **2010**, *16*, 362–367.

[2] F. Würtner, T. E. Kaiser, C. R. Saha-Möller, *Angew. Chem. Int. Ed.* **2011**, *50*, 3376–3411.

[3] M. Kastler, W. Pisula, D. Wasserfallen, T. Pakula, K. Müllen, *J. Am. Chem. Soc.* **2005**, *127*, 4286–4296.

[4] a) J. Zhang, J. S. Moore, *J. Am. Chem. Soc.* **1992**, *114*, 9701–9702; b) A. S. Shetty, J. Zhang, J. S. Moore, *J. Am. Chem. Soc.* **1996**, *118*, 1019–1027; c) D. Zhao, J. S. Moore, *Chem. Commun.* **2003**, 807–818.

[5] a) A. Bohnen, K.-H. Koch, W. Lüttke, K. Müllen, *Angew. Chem.* **1990**, *102*, 548; *Angew. Chem. Int. Ed. Engl.* **1990**, *29*, 525–527; b) U. Scherf, K. Müllen, *Synthesis* **1992**, 23–38; c) S. Schrader, K. H. Koch, A. Mathy, C. Bubech, K. Müllen, G. Wegner, *Synth. Met.* **1991**, 3223–3226; d) A. D. Schlüter, *Adv. Mater.* **1991**, *3*, 282–291.

[6] J. E. Berg, H. Erdtman, H.-E. Högberg, B. Karlsson, A. M. Pilotti, A. C. Söderholm, *Tetrahedron Lett.* **1977**, *18*, 1831–1834.

[7] For early reports describing work towards tetraoxa[8]circulenes, see: a) H. G. H. Erdtman, *Proc. R. Soc. London, Ser. A.* **1933**, *143*, 191–222; b) H. G. H. Erdtman, *Proc. R. Soc. London, Ser. A.* **1933**, *143*, 228–241.

[8] For the first correct description of a tetraoxa[8]circulene, see: H. Erdtman, H.-E. Högberg, *Chem. Commun.* **1968**, 773–774.

[9] a) H. Erdtman, H.-E. Högberg, *Tetrahedron Lett.* **1970**, *11*, 3389–3392; b) H.-E. Högberg, *Acta Chem. Scand.* **1972**, 309–316; c) R. Buchan, O. C. Musgrave, *J. Chem. Soc., Perkin Trans. 1* **1980**, 90–92; d) H.-E. Högberg, *Acta Chem. Scand.* **1973**, 2591–2596; e) H. Erdtman, H.-E. Högberg, *Tetrahedron* **1979**, *35*, 535–540.

[10] a) J. Eskildsen, T. Reenberg, J. B. Christensen, *Eur. J. Org. Chem.* **2000**, *8*, 1637–3640; b) J. Eskildsen, P. Hammershøj, T. K. Reenberg, U. Larsen, M. Pittelkow, S. M. Leth, R. Peck, J. B. Christensen, *Asian Chem. Lett.* **2007**, *11*, 211–218.

[11] H.-E. Högberg, *Acta Chem. Scand.* **1972**, *26*, 2752–2758.

[12] C. B. Nielsen, T. Brock-Nannestad, T. K. Reenberg, P. Hammershøj, J. B. Christensen, J. W. Stouwdam, M. Pittelkow, *Chem. Eur. J.* **2010**, *16*, 13030–13034.

[13] R. Rathore, S. H. Abdelwahed, *Tetrahedron Lett.* **2004**, *45*, 5267–5270.

[14] A. Valtz, C. Coquelet, G. Boukais-Belaribi, A. Dahmani, F. B. Belaribi, *J. Chem. Eng. Data* **2011**, *56*, 1629–1657.

[15] Z. Chen, *π-Stacks Based on Self-Assembled Perylene Bisimides: Structural, Optical, and Electronic Properties*, PhD Thesis, University of Würzburg, **2006**.

[16] Crystal data for **1a**: C$_{40}$H$_{40}$O$_4$; M = 584.72; monoclinic; a = 17.005(4) Å, b = 18.234(3) Å, c = 11.472(2) Å, α = 90.00°, β = 103.306(17)°, γ = 90.00°; V = 3461.6(12) Å^3; T = 122(1) K; space group $C2/c$; Z = 4; μ(Mo-K_α) = 0.071 mm^{-1}; 47267 reflections measured, 4002 independent reflections (R_{int} = 0.0896). The final R_1 values were 0.0571 [$I > 2\sigma(I)$]. The final $wR(F^2)$ values were 0.1138 [$I > 2\sigma(I)$]. The final R_1 values were 0.0897 (all data). The final $wR(F^2)$ values were 0.1233 (all data). The goodness of fit on F^2 was 1.040. CCDC-822561.

Crystal data for **1b**: $C_{40}H_{40}O_4$; M = 584.72; monoclinic; $a =$ 28.916(3) Å, $b =$ 14.382(2) Å, $c =$ 18.402(3) Å, $a =$ 90.00°, $\beta =$ 126.58(2)°, $\gamma =$ 90.00°; $V =$ 6145.3(20) Å³; $T =$ 122(1) K; space group $C2/c$; $Z = 8$; μ(Mo-K_α) = 0.080 mm⁻¹; 103649 reflections measured, 5404 independent reflections ($R_{int} =$ 0.1223). The final R_1 values were 0.0472 [$I > 2\sigma(I)$]. The final $wR(F^2)$ values were 0.0910 [$I > 2\sigma(I)$]. The final R_1 values were 0.0836 (all data). The final $wR(F^2)$ values were 0.1073 (all data). The goodness of fit on F^2 was 1.109. CCDC-822562. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

[17] C. A. Hunter, J. K. M. Sanders, *J. Am. Chem. Soc.* **1990**, *112*, 5525–5534.