



Solvent-free synthesis of calix[4]resorcinarenes

Brett A. Roberts,^a Gareth W. V. Cave,^a Colin L. Raston^b and Janet L. Scott^{*a}

^a Centre for Green Chemistry, P.O. Box 23, Monash University, 3800, Victoria, Australia.

E-mail: janet.scott@sci.monash.edu.au

^b School of Chemistry, University of Leeds, Leeds, UK LS2 9JT

Received 21st May 2001

First published as an Advance Article on the web 9th October 2001

Calix[4]resorcinarenes may be prepared in high yield and purity by direct reaction of resorcinol and benzaldehyde derivatives in the presence of a catalytic amount of solid acid and at ambient temperature under solvent-free conditions. This represents a viable alternative to traditional solution phase methodology. The solvent-free method measures up well with respect to energy usage, solvent wastes and associated hazards, reaction time and yield. In addition, the relevant benzaldehyde derivatives are prepared in polypropylene glycol, which is readily recycled.

Introduction

Calix[4]resorcinarenes are large cyclic tetramers which have found application as supramolecular tectons¹ and host molecules,² as components in liquid crystals,³ photoresists,⁴ selective membranes,⁵ surface reforming agents,⁶ HPLC stationary phases,⁷ and as ion channel mimics⁸ and metal ion extraction agents.⁹

The synthesis of calix[4]resorcinarenes was first reported in the late 19th century by Baeyer¹⁰ and the most commonly used synthetic methodology is still that of a Brønsted acid-catalysed cyclocondensation between an aldehyde **1** and resorcinol **2** to yield the cyclic tetramer calix[4]resorcinarene **3** achieved by heating the constituents to reflux in a mixture of mineral acid and alcohol. (The Lewis acid catalysed condensation of resorcinol and benzaldehyde has been reported,¹¹ but not widely applied, and other methods utilizing Lewis acids rely on the use of starting materials such as 2,4-dimethoxycinnamates¹² requiring deprotection to yield resorcinarenes with free hydroxy groups.)

The duration of the reaction has been shown to vary from a few hours^{13,14} to several days^{15–18} although Weinelt and Schneider have reported shorter reaction times utilizing dry HCl dissolved in methanol.¹⁹ Large-scale synthesis involves large volumes of solvent and the use of large quantities of acid (usually a 2:2:1 ratio of ethanol, water and concentrated HCl).²⁰ In a previous study on the synthesis of cyclotrimer-arylene (CTV) derivatives²¹ we have shown that the use of ionic liquids or solvent-free methods provide efficient 'greener' protocols for the acid catalysed cyclocondensation reactions used to prepare these large supramolecular tectons. Such processes alleviate the need for large volumes of solvent and

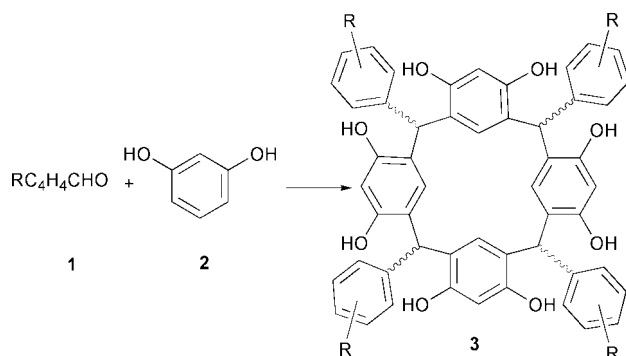
acid, are energy efficient and high yielding and are potentially applicable to starting materials containing acid labile groups.

We now report the synthesis of a number of calix[4]resorcinarenes (including three novel compounds) achieved under solvent-free conditions by the direct reaction of aldehyde and resorcinol in the presence of catalytic quantities of a solid acid. The methodology is simple, high-yielding, energy-efficient and applicable to a variety of aldehyde starting materials. A 'greener' route to the aldehyde starting materials using polypropylene glycol (PPG) as solvent, is also described.

Results and discussion

Reaction of **1** and **2** is achieved by simply grinding together equimolar quantities of starting material in the presence of a catalytic amount of *p*-toluenesulfonic acid. As noted previously,^{21,22} the reaction mixtures are viscous liquids or pastes even where all reagents are solids. The melt phase stiffens within minutes to yield a sticky solid that hardens further on standing. ¹H NMR analysis of this material reveals almost quantitative conversion to product and crude **3** is isolated by simply washing the ground product with water to effect removal of the catalyst. Recrystallisation from hot methanol affords pure material in high yield.

The synthesis of the most widely used of the resorcinarenes, *C*-methylcalix[4]resorcinarene, may also be readily achieved by direct reaction of solid resorcinol and liquid acetaldehyde.²³ Unfortunately, this methodology does not give access to resorcinarenes, such as **3f**, that have previously proven difficult to synthesise,¹⁸ indicating that the mechanism of reaction is likely to be no different from that suggested in methods



Scheme 1

Green Context

Calix[4]resorcinarenes have found application in a number of areas including liquid crystals, HPLC stationary phases, metal ion extraction agents and as host molecules. Traditional synthesis involves often very slow reactions and large volumes of solvents. In this paper, a much improved and simplified synthetic procedure is described which is solvent-free, employs a solid acid, and is relatively quick. The high-yielding synthesis of three new, highly functionalised calix[4]resorcinarenes is described. *JHC*

involving dissolution of reagents in a solvent prior to reaction. We would suggest that this is the reaction of two mutually dissolved reagents and thus while 'solvent-free' is still occurring in 'solution'. The only difference being that dissolution is not achieved by addition of an extra (solvent) component but is instead due to mutual miscibility of the reagents.

In comparison to the time scale for most conventional syntheses (several hours to days),^{13–20} the solvent-free reactions described here reach a substantial degree of conversion within minutes. No external heating is required and the grinding method is used to achieve particle size reduction and efficient mixing. High intensity grinding, which is an energy expensive process, is not required as the reaction mixture does not remain dry and powdery but becomes a viscous liquid melt or solution.²² Yields are also often substantially higher using the solvent-free methodology as is indicated in Table 1. Compounds **3c–e** have not, to our knowledge, been previously reported and have been characterised by mass spectrometry, ¹H and ¹³C NMR, microanalysis and X-ray structure elucidation (**3c**).

The aldehydes **1c–e** used in the synthesis of **3c–e** are, in keeping with the environmentally friendly theme, synthesised under conditions that are 'greener' than those conventionally used. Traditional solvents are replaced with polypropylene glycol (PPG), which is a viscous solvent with negligible vapour pressure. 4-Hydroxybenzaldehyde, potassium carbonate and the corresponding bromo- or dibromo-alkane are heated to 60 °C in PPG for 2 h, the aldehyde isolated by distillation and the PPG recycled, obviating the need for lengthy reaction times, extractive work-up and chromatographic purification.²⁴

Calix[4]resorcinarenes commonly occur in two isomeric forms, namely the *cis-cis-cis* (*rccc*) and the *cis-trans-trans* (*rctt*) isomers,¹⁹ which are distinguishable by comparison of ¹H NMR spectra as described by Cram and coworkers.¹⁸ Solution studies indicate the presence of **3d** in the form of the *rccc* isomeric product with *C*_{4v} symmetry, or 'crown' isomer (> 95%),²⁵ as illustrated schematically in Fig. 1(a). The single broad resonance for the aromatic OH, coupled with single resonances for the asymmetric H_a and H_b protons on the resorcinol ring indicate a single environment for the calix[4]resorcinarene in solution. In contrast, compounds **3c** and **3e** indicate a mixture of isomers in solution. These were established as *rccc* (33%) and *rctt* or 'chair' isomer which exhibits *C*_{2h} symmetry²⁵ (66%), based on ¹H NMR integration. The *rctt*

isomer [illustrated schematically in Fig. 1(b)] was identified by two sets of peaks for the OH, H_a and H_b resonances, characteristic of *C*_{2h} symmetry.

Interestingly, compound **3d** alone occurs almost exclusively as the *rccc* isomer, while **3a** and **3b** exhibit the expected mixture of isomers^{18,19} which is reflected in the isomeric distribution of **3c** and **3e**. The predominance of the *rctt* isomer contrasts with molecular modeling calculations,²⁶ which indicate that the *rccc* isomer in the crown conformer is favoured over the *rctt* isomer in the chair conformer (in the absence of solvent effects) by 6.3, 8.5 and 14.4 kcal mol⁻¹ for compounds **3c**, **d** and **e** respectively. Hydrogen bonds between adjacent hydroxy groups on the resorcinol and staggering of the phenyl groups help to stabilise the *rccc* crown conformers, while the *rccc* boat conformer is of similar energy to the *rctt* chair conformer. The distribution of isomers has been attributed to differential solubilities¹⁸ which may also play a role in the solvent-free reactions where differential crystallisation from the melt or liquid phase may occur.

Altering the reaction time did not lead to an increase in the formation of the *C*_{4v} isomer for compounds **3c** and **3e**. Despite heating the starting materials to 85 °C for 5 h, the ratio of the *C*_{4v} isomer never exceeded 33%. However, when the reaction mixture containing compound **3e** was left to stand for an extended period of time, before work-up, solution studies indicate the presence of only the *rctt* isomer. This conversion can be compared to a study by Cram and coworkers¹⁸ on the reaction of resorcinol with 4-methoxybenzaldehyde, that revealed that an increase in reaction time led to an increase in the formation of the *C*_{2h} isomer.

Single crystal diffraction studies on compound **3c**,† indicates that the *rctt* calix[4]resorcinarene crystallises in the form of the chair isomer with *C*_{2h} symmetry. This confirms assignment of isomers from NMR data. Compared with the more common crown isomer, there are only a few examples of structurally characterised chair isomers.^{15,18,27,28} Compound **3c** crystallises in the space group *PI* with one molecule of the calix[4]resorcinarene and two molecules each of DMF and acetone in the unit cell. The asymmetric unit comprises one half of the resorcinarene with associated, hydrogen-bonded solvent molecules, illustrated in Fig. 2, and the remainder of the resorcinarene is generated through a crystallographic inversion centre. The axial position of the phenyl groups deriving from the benzaldehyde, which are bonded in a *cis-trans-trans* fashion (*rctt* configuration), and chair conformation of the macrocycle is illustrated in Fig. 3. All resorcinol hydroxy groups form hydrogen bonds. These include OH...O H-bonds with acceptor carbonyl oxygen atoms of the included solvent molecules, a long OH...O H-bond with a resorcinarene molecule translated 1 unit cell along *a* and an OH...Ar interaction directed towards the aromatic ring of the aldehyde moiety of a neighbouring resorcinarene, as indicated in Fig. 3. Individual 'tapes' of H-

Table 1 Yields and isomeric distribution for compounds **3a–f**

Compound	1 (R)	Yield 3 (%) ^a	<i>rccc</i> : <i>rctt</i>
a	H ¹⁹	90(90, ¹⁹ 83 ¹⁸)	1:2 (lit. 1:2) ¹⁹
b	<i>o</i> -OH ¹⁸	81(78) ¹⁸	1:2 (lit. 1:2) ¹⁸
c	<i>p</i> -O(CH ₂) ₃ CH ₃	96	1:2
d	<i>p</i> -O(CH ₂) ₇ CH ₃	80	95:5
e	<i>p</i> -O(CH ₂) ₄ Br	92	1:2 → 0:100 ^b
f	<i>p</i> -NO ₂	0	—

^a Mixture of isomers. Yield determined post reaction and washing but prior to recrystallisation. Product losses are largely due to difficulties in transferring small quantities of glassy products from a mortar and pestle, thus, yields of larger scale reactions would be expected to be significantly improved. ^b Dependent on extent of reaction time.

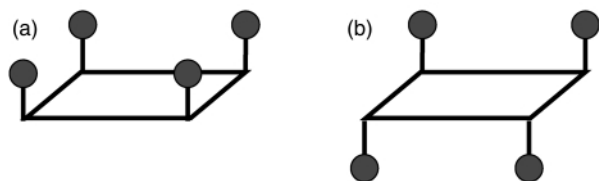


Fig. 1 Schematic of *rccc* and *rctt* isomers.

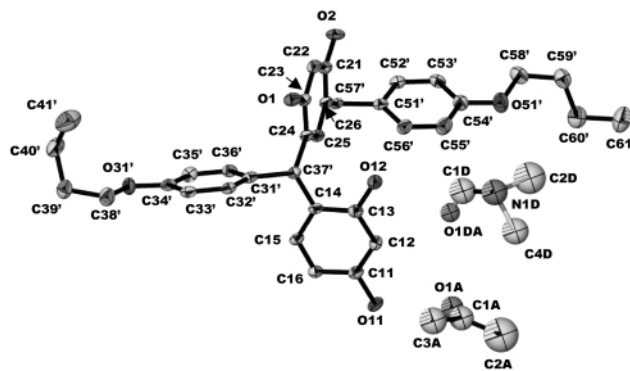


Fig. 2 ORTEP diagram of **3c** with thermal ellipsoids plotted at the 50% probability level. Alternative positions for the disordered solvent molecules are omitted for clarity.

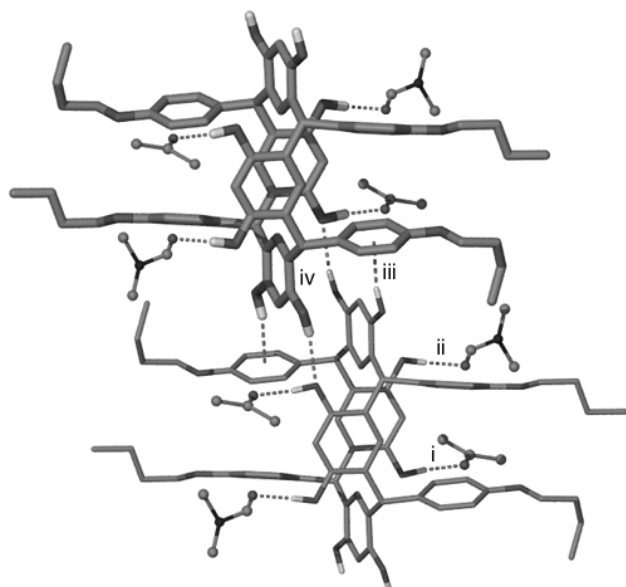


Fig. 3 Molecular structure of **3c** derived from single crystal structure data. Two molecules of **3c** are shown with four DMF and four acetone molecules (disordered positions omitted for clarity). Hydrogen bonds are shown as dotted lines.

	Unique H-bond geometries		
	O...O/Å	H...O/Å	OHO°
(i) O11–H11O...O1A	2.752(6)	1.79(2)	171(5)
(ii) O12–H12O...O1D	2.868(4)	1.72(3)	166(6)
(iii) O11–H11O...centroid(Ar) ^b	3.177(3)	2.23(3)	165(6)
(iv) O1–H1O...O11 ^a	3.032(5)	2.22(5)	142(6)

$$a = x + 1, y, z. \quad b = 2 - x, 2 - y, 1 - z.$$

bonded **3c** and solvent molecules propagate in the [100] direction as illustrated in Fig. 4.

In conclusion, we have shown a simple, solvent-free, energy efficient, clean pathway for the synthesis of three new, highly functionalised calix[4]resorcinarenes. This method also demonstrates a cost-effective alternative to commercially available products. The extended alkyl chain in the *para* position, offers

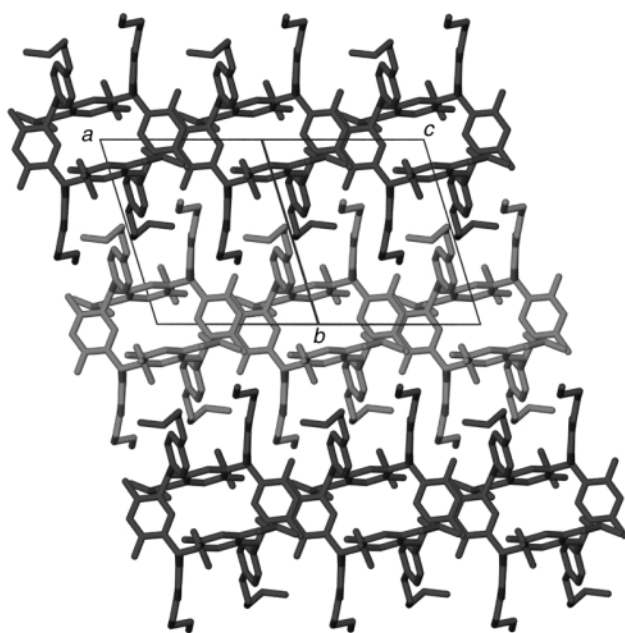


Fig. 4 Packing diagram of **3c** viewed perpendicular to (101) showing 'tapes' of hydrogen bonded calix[4]resorcinarene molecules and H-bonded occluded solvent.

enormous potential for further binding through both covalent and non-covalent interactions and is an area of further study.

Experimental

¹H (300 MHz) and ¹³C (75 MHz) were recorded on a Bruker DPX 300 instrument in ppm (δ) and referenced to TMS. Melting points were recorded on an Electrothermal digital melting point apparatus and are uncorrected. Molecular modeling calculations were carried out using the Discover minimisation package of the MSI Insight II molecular modeling program²⁶ with standard CVFF forcefields and the structure minimised using the conjugate gradients algorithm with a convergence criterion of the average derivative being <0.001 kcal mol⁻¹. Single crystal diffraction data were collected on an Enraf-Nonius Kappa CCD at 123 K using graphite monochromated Mo-K α radiation ($\lambda = 0.71073$ Å, $1^\circ \varphi$ and ω scans). The structure was solved by direct methods using the program SHELXS-97²⁹ and refined by full matrix least-squares refinement on F^2 using the programs SHELXL-97³⁰ and Xseed.³¹ Non-hydrogen atoms of the calix[4]resorcinarene were refined anisotropically whilst those of the DMF and acetone solvent molecules were refined isotropically. The solvent molecules show evidence of disorder and three positions for the DMF methyl groups, each with 66% occupancy, are modeled (*sof* = 0.667). The DMF carbonyl oxygen is also disordered over two positions (70 and 30% occupancy). All hydrogen atoms, except those of the hydroxy groups, were inserted at geometrically determined positions. Hydroxy hydrogen atoms (all of which are involved in hydrogen bonds) were identified in electron density difference maps and refined with simple bond length restraints.

Synthesis

All commercially available reagents were purchased from Aldrich and used as supplied, unless stated otherwise. Aldehydes **1c–e** could also be prepared by reaction in polypropylene glycol and the synthesis of **1d**, the only benzaldehyde derivative not readily available from commercial sources, is described below.

1d: 1-Bromooctane (1.58 g, 8.20 mmol) was added to a stirred slurry of 4-hydroxybenzaldehyde (1 g, 8.20 mmol) and anhydrous potassium carbonate (1.13 g, 8.20 mmol) in polypropylene glycol (average M_n ca. 425, 5 cm³). The reaction mixture was heated (60 °C, 2 h) in a round-bottomed flask equipped with an air condenser. The pure product was isolated by vacuum distillation (125 °C, 0.5 mmHg). Yield 98% (1.88 g, 8.02 mmol). δ_H (300 MHz, 298 K, CDCl₃) 0.83 (3H, t, ³*J* 7.0 Hz, CH₃), 1.25 (10H, m, chain), 1.73 (2H, m, OCH₂CH₂), 3.95 (2H, t, ³*J* 6.5 Hz, OCH₂), 6.89 (2H, AA'XX', Ar), 7.72 (2H, AA'XX', Ar), 9.80 (1H, s, aldehyde).

The PPG was recycled by filtering it through a sintered funnel (porosity 1) under reduced pressure and the experiment was repeated three times using the original sample of PPG (yields 98, 97 and 97% consecutively). The PPG was observed to gradually change from colourless to yellow during the four batch processes.

3a–e: In a typical synthesis a 1:1 mixture of the starting aldehyde and resorcinol (0.5 to 1.0 g scale), along with a catalytic amount of *p*-toluenesulfonic acid (ca. 5%) were added together in a mortar and pestle and ground vigorously. Within seconds a viscous paste forms which hardens on further grinding. The paste was left to stand for up to 1 h, during which time it solidified to yield a red solid. The solid was reground,

washed with water to remove any acid, filtered and the pure product recrystallised with hot methanol.

Characterisation

3c: Yield 96%, mp > 250 °C (decomp.) ESI-MS (70 eV) [M]⁺ (calc: *m/z* 1081.3, found 1081.5). Microanalysis: some of the resorcinarene products have a propensity to form solvates which (due to variable desorption of occluded solvent molecules) renders microanalysis results irreproducible and these are therefore not included.

δ_{H} (300 MHz, 298 K, acetone-*d*₆) C_{2h} isomer: 0.98 (12H, t, ³*J* 5.3 Hz, CH₃), 1.50 (8H, m, CH₂), 1.75 (8H, m, CH₂), 3.97 (8H, t, ³*J* 6.4 Hz, OCH₂), 5.67 (4H, s, CH), 5.93 (2H, s, ArH *meta* to OH, equatorial), 6.26 (2H, s, ArH *ortho* to OH, axial), 6.41 (2H, s, ArH *ortho* to OH, equatorial), 6.51 (10H, s, ArH, *meta* to OH, axial and AA'XX' ArH *ortho* to O-alkyl), 6.67 (8H, AA'XX' ArH *meta* to O-alkyl), 7.11 (4H, s, ArOH), 7.55 (4H, s, ArOH).

C_{4v} isomer: 0.98 (12H, t, ³*J* 5.3 Hz, CH₃), 1.50 (8H, m, CH₂), 1.75 (8H, m, ³*J* 6.4 Hz, CH₂), 4.00 (8H, t, OCH₂), 5.73 (4H, s, CH), 6.30 (4H, s, ArH *ortho* to OH), 6.43 (4H, s, ArH, *meta* to OH), 6.62 (8H, m, AA'XX' ArH *ortho* to O-alkyl), 6.75 (8H, m, AA'XX' ArH *meta* to O-alkyl), 7.32 (8H, s, ArOH). δ_{C} (75.0 MHz, 298 K, acetone-*d*₆) 14.2, 18.8, 20.0, 29.1, 32.4, 42.9, 57.7, 68.1, 103.2, 114.2, 114.4, 122.7, 122.9, 131.0, 132.3, 136.3, 137.5, 154.0, 154.2, 157.7, 158.9 (signals for both isomers combined due to overlap of signals).

Crystals of **3c** suitable for X-ray analysis were grown by slow diffusion of hexane into a solution of the calix[4]resorcinarene in acetone–DMF (95:5). The crystals produced in this manner were small but all attempts to achieve good quality single crystals by other methods of crystallization such as slow evaporation of solvent or slow cooling proved fruitless, yielding only microcrystalline powders or oils. The small crystals obtained did not diffract strongly and long exposure times were required leading to higher than desirable levels of diffuse scattering.

3d: Yield 80%, mp > 260 °C (decomp.), ESI-MS (125 eV) [M]⁺ (calc: *m/z* 1305.7, found: 1305.8). Microanalysis: calc. (found) C, 77.27 (76.31); H, 8.03 (8.19)%.

δ_{H} (300 MHz, 298 K, acetone-*d*₆) C_{4v} isomer: 0.88 (12H, m, CH₃), 1.25 (32H, m, CH₂), 1.53 (8H, m, CH₂), 1.81 (8H, m, CH₂), 3.98 (8H, m, OCH₂), 5.74 (4H, s, CH), 6.25 (4H, s, ArH *ortho* to OH), 6.39 (4H, s, ArH, *meta* to OH), 6.61 (8H, AA'XX' ArH *ortho* to O-alkyl), 6.77 (8H, AA'XX' ArH *meta* to O-alkyl), 7.31 (8H, s, ArOH). δ_{C} (75.0 MHz, 298 K, acetone-*d*₆) 14.7, 23.7, 27.4, 29.4–31.3, 68.87, 103.8, 114.7, 122.8, 131.1, 132.7, 146.2, 154.5, 158.2.

3e: Yield 92%, mp > 200 °C (decomp.), ESI-MS (100 eV) [M + Na]⁺ (calc: *m/z* 1419.8, found: 1419.1). Microanalysis: calc. (found) C, 58.65 (58.39); H, 5.13 (5.13)%.

δ_{H} (300 MHz, 298 K, acetone-*d*₆) C_{2h} isomer: 1.95 (8H, m, CH₂), 2.13 (8H, m, CH₂), 3.65 (8H, m, CH₂Br), 3.96 (8H, m, OCH₂), 5.68 (4H, s, CH), 5.91 (4H, s, ArH *meta* to OH, equatorial), 6.33 (4H, s, ArH *ortho* to OH, axial), 6.44 (4H, s, ArH, *ortho* to OH, equatorial), 6.52 (12H, s, ArH *meta* to OH, axial and AA'XX' ArH *ortho* to O-alkyl), 6.77 (8H, AA'XX' ArH *meta* to O-alkyl), 7.15 (4H, s, ArOH), 7.53 (4H, s, ArOH).

C_{4v} isomer: 1.95 (8H, m, CH₂), 2.13 (8H, m, CH₂), 3.67 (8H, m, CH₂Br), 4.00 (8H, m, OCH₂), 5.77 (4H, s, CH), 6.25 (4H, s, ArH *ortho* to OH), 6.39 (4H, s, ArH, *meta* to OH), 6.67 (8H, AA'XX' ArH *ortho* to O-alkyl), 6.70 (8H, AA'XX' ArH *meta* to O-alkyl), 7.34 (8H, s, ArOH). δ_{C} (75.0 MHz, 298 K, acetone-*d*₆) 29.4, 35.1, 42.7, 43.3, 68.0, 103.6, 103.8, 114.7, 114.825, 122.9, 123.2, 131.2, 131.5, 132.6, 133.3, 137.0, 138.2, 154.4,

154.5, 157.9, 158.0 (signals for both isomers combined due to overlap of signals).

References

† Crystal data for **3c**: C₈₀H₉₈N₂O₁₆ (C₆₈H₇₀O₁₂·2C₃H₈NO·2C₃H₆O), *M_r* = 1343.60, triclinic, space group *P*1, *a* = 11.2391(2), *b* = 12.8890(2), *c* = 14.4780(4) Å, α = 90.734(1), β = 110.956(1), γ = 112.210(1)°, *V* = 1786.48(6) Å³, *Z* = 1, μ (Mo-K α) = 0.086 mm⁻¹. Of 30522 reflections measured, 8752 were unique (*R*_{int} = 0.0984) with 3850 with *I* > 2 σ (*I*), *R* indices [*I* > 2 σ (*I*): *R*₁ = 0.0979, *wR*₂ = 0.2273, GOF on *F*² = 0.938 for 428 refined parameters and 6 restraints (bond lengths associated with OH groups and disordered solvent).

CCDC reference number 168122. See <http://www.rsc.org/suppdata/gc/b1/b104430n/> for crystallographic data in CIF or other electronic format.

- 1 L. R. MacGillivray and J. L. Atwood, *J. Solid State Chem.*, 2000, **152**, 199; L. R. MacGillivray, P. R. Diamente, J. L. Reid and J. A. Ripmeester, *Chem. Commun.*, 2000, 359; R. G. Harrison, N. K. Dalley and A. Y. Nazarenko, *Chem. Commun.*, 2000, 1387.
- 2 G. M. Martinez, C. R. Teran, O. A. Tlapanco, A. Toscano and R. Cruz-Almanza, *Fullerene Sci. Technol.*, 2000, **8**, 475; F. C. Tucci, A. R. Renslo, D. M. Rudkevich and J. Rebek, *Angew. Chem., Int. Ed.*, 2000, **39**, 1076.
- 3 K. Yonetake, T. Nakayama and M. Ueda, *J. Mater. Chem.*, 2001, **11**, 761.
- 4 H. Ito, T. Nakayama and M. Ueda, *US Pat.*, US 6093517, 2000; O. Haba, K. Haga, M. Ueda, O. Morikawa and H. Konishi, *Chem. Mater.*, 1999, **11**, 427; T. Nakayama, D. Takahashi, K. Takeshi and M. Ueda, *J. Photopolym. Sci. Technol.*, 1999, **12**, 347.
- 5 N. Tbeur, T. Rhallou, M. Hlaibi, D. Langevin, M. Metayer and J.-F. Verchere, *Carbohydr. Res.*, 2000, **329**, 409; O. Pietraszkiewicz, M. Kozbial and M. Pietraszkiewicz, *Pol. J. Chem.*, 1998, **72**, 886.
- 6 K. Ichimura, E. Kurita and M. Ueda, *Eur. Pat.*, EP 671220, 1995.
- 7 O. Pietraszkiewicz and M. Pietraszkiewicz, *J. Inclusion Phenom. Macrocycl. Chem.*, 1999, **35**, 261.
- 8 N. Yoshino, A. Satake and Y. Kobuke, *Angew. Chem., Int. Ed.*, 2001, **40**, 457.
- 9 E. Gaunert, H. Barnier, L. Nicod, A. Favre-Reguillon, J. Foos, A. Guy, C. Bardot and M. Lemaire, *Sep. Sci. Technol.*, 1997, **32**, 2309; L. S. Kuznetsova, A. R. Mustafina, A. Y. Ziganshina and E. K. Kazakova, *J. Inclusion. Phenom. Macrocycl. Chem.*, 2001, 65.
- 10 A. Baeyer, *Ber. Dtsch. Chem. Ges.*, 1872, **5**, 25; A. Baeyer, *Ber. Dtsche. Chem. Ges.*, 1872, **5**, 280.
- 11 O. I. Pieroni, N. M. Rodriguez, B. M. Vuano and M. C. Cabaleiro, *J. Chem. Res. (S)*, 1994, 188.
- 12 B. Botta, M. C. Di Giovanni, G. D. Monache, M. C. De Rosa, E. Gacs-Baitz, M. Botta, F. Corelli, A. Tafi, A. Santini, E. Benedetti, C. Pedone and D. Misi, *J. Org. Chem.*, 1994, **59**, 1532; B. Botta, P. Iacomacci, C. Di Giovanni, G. D. Monache, E. Gacs-Baitz, M. Botta, A. Tafi, F. Corelli and D. Misi, *J. Org. Chem.*, 1992, **57**, 3259.
- 13 A. G. S. Högberg, *J. Org. Chem.*, 1980, **45**, 4498.
- 14 T. Haino, D. M. Rudkevich, A. Shivanyuk, K. Rissanen and J. Rebek, Jr., *Chem.-Eur. J.*, 2000, **6**, 3797.
- 15 K. N. Rose, M. J. Hardie, J. L. Atwood and C. L. Raston, *J. Supramol. Chem.*, 2001, **1**, 35.
- 16 T. Gerkenmeier, W. Iwanek, C. Agena, R. Fröhlich, S. Kotila, C. Näther and J. Mattay, *Eur. J. Org. Chem.*, 1999, 2257.
- 17 J. B. Niederl and H. J. Vogel, *J. Am. Chem. Soc.*, 1940, **62**, 2512.
- 18 L. M. Tunstad, J. A. Tucker, E. Dalcanale, J. Weiser, J. A. Bryant, J. C. Sherman, R. C. Helgeson, C. B. Knobler and D. J. Cram, *J. Org. Chem.*, 1989, **54**, 1305.
- 19 F. Weinelt and H.-J. Schneider, *J. Org. Chem.*, 1991, **56**, 5527.
- 20 D. J. Cram and J. M. Cram, *Container Molecules and Their Guests*, Royal Society of Chemistry, Cambridge, 1994, p. 89.
- 21 J. L. Scott, D. R. MacFarlane, C. L. Raston and C. M. Teoh, *Green Chem.*, 2000, 123.
- 22 G. Rothenberg, A. P. Downie, C. L. Raston and J. L. Scott, *J. Am. Chem. Soc.*, 2001, **123**, 8701.
- 23 G. W. V. Cave, M. J. Hardie, B. A. Roberts and C. L. Raston, *Eur. J. Org. Chem.*, 2001, 3227.
- 24 M.-A. Guillevic, M. E. Light, S. J. Coles, T. Gelbrich, M. B. Hursthouse and D. W. Bruce, *J. Chem. Soc., Dalton Trans.*, 2000, 1437.
- 25 Nomenclature used by P. Timmerman, W. Verboom and D. N. Reinhoudt, *Tetrahedron*, 1996, **52**, 2663 and references therein.
- 26 BIOSYM MSI, San Diego, CA, USA, 2000.

- 27 A. Shivanyuk, E. F. Paulus, V. Böhmer and W. Vogt, *Angew. Chem., Int. Ed.*, 1997, **36**, 1301.
- 28 K. J. Palmer, R. Y. Wong, L. Jurd and K. Stevens, *Acta Crystallogr., Sect. B*, 1976, **32**, 847; G. Zahn, K. Müller and G. Mann, *Z. Kristallogr.*, 1994, **209**, 473; O. Middel, W. Verboom, R. Hulst, H. Kooijman, A. L. Spek and D. N. Reinhoudt, *J. Org. Chem.*, 1998, **63**, 8259; G. Rumboldt, V. Böhmer, B. Botta and E. F. Paulus, *J. Org. Chem.*, 1998, **63**, 9618.
- 29 G. M. Sheldrick, SHELXS-97, University of Gottingen, 1990.
- 30 G. M. Sheldrick, SHELXL-97, University of Gottingen, 1997.
- 31 L. J. Barbour, X-Seed—a graphical interface to the SHELX program suite, University of Missouri, 1999.