Cholesteric helix inversion: investigations on the influence of the terminal group on the inversion of the helical pitch in trioxadecalins

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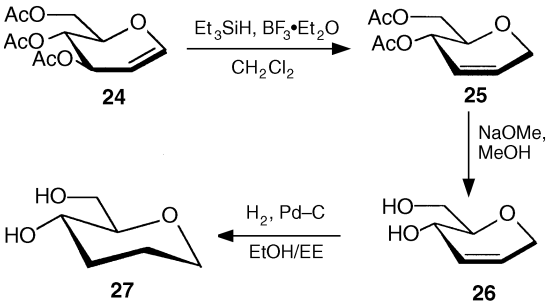
Synthesis and mesogenic properties of new liquid crystals, bearing a chiral trioxadecalin system, are described. As cholesteric helix inversions in trioxadecalin systems bearing a terminal cyano or nitro group have previously been observed, the terminal group has been changed systematically to elucidate its influence on the occurrence of inversions of the helical pitch.

Chirality has become one of the most important and complex topics in liquid crystal research, since molecular asymmetry imparts form chirality to the liquid crystalline phases.[1] Most of the chiral liquid crystals investigated possess only one chiral centre in the flexible side chain.[2] However, the use of carbohydrates enables us to introduce a chiral trioxadecalin ring system directly into the molecular core.[3] In this way it is possible to locate the chirality in that part of the molecule which determines the general mesogenic properties, and many of our compounds show interesting and unusual behaviour. Previously, we reported trioxadecalins with terminal cyano or nitro groups showing a cholesteric helix inversion.[4,5] One of these nitro compounds has presented a nearly double inversion of the helical twist sense, for the first time as far as we are aware.

The aim of this work was to examine the influence of the terminal group on the helix inversion. We synthesized a homologous series of compounds with terminal halogen and pseudo halogen groups, as well as molecules with small non-polar head groups. Also the effect of the position of the chiral trioxadecalin system in the molecule has been examined by synthesizing compounds in which the position of the molecular core was changed.

The diols **12a–c** were synthesized according to the previously described procedure starting from commercially available tri-*O*-acetyl-D-glucal.[3] The diols can easily be combined with aldehyde dimethyl acetals giving the trioxadecalin structure (Scheme 1). The diol **27** (Scheme 2), the starting point for the synthesis of compounds with the trioxadecalin system at a different position to that for compounds **13b–23b** (Scheme 3), was obtained by a modified Ferrier reaction.[6] The dimethyl acetals and the corresponding aldehydes were synthesized using standard methods in the cases where these aldehydes were not commerically available.

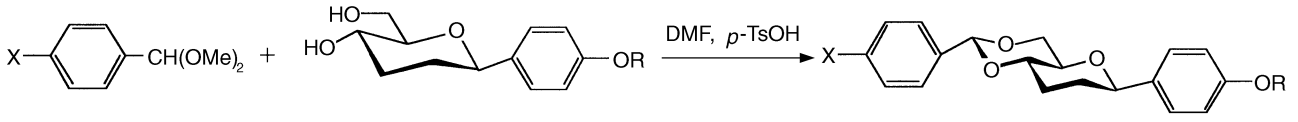


Scheme 2

Experimental

Techniques

TLC was performed on silica gel (Merck GF_{254}), and detection was effected by UV absorbance, and spraying with a solution

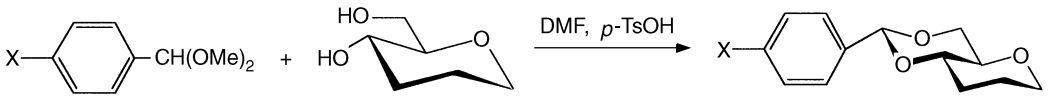


1 X=H
2 X=F
3 X=Cl
4 X=Br
5 X=I
6 X=N_3
7 X=NCS
8 X=Me
9 X=Pr^i
10 X=$Me_3SiC{\equiv}C$
11 X=HC≡C

12a R=C_6H_{13}
b R=C_8H_{17}
c R=$C_{10}H_{21}$

13b X=H, R=C_8H_{17}
14a X=F, R=C_6H_{13}
14b X=F, R=C_8H_{17}
15b X=Cl, R=C_8H_{17}
16a X=Br, R=C_6H_{13}
16b X=Br, R=C_8H_{17}
16c X=Br, R=$C_{10}H_{21}$
17a X=I, R=C_6H_{13}
17b X=I, R=C_8H_{17}
18b X=N_3, R=C_8H_{17}
19b X=NCS, R=C_8H_{17}
20b X=Me, R=C_8H_{17}
21b X=Pr^i, R=C_8H_{17}
22b X=$Me_3SiC{\equiv}C$, R=C_8H_{17}
23b X=HC≡C, R=C_8H_{17}

Scheme 1



28 X=$H_{17}C_8OC_6H_4$
29 X=$H_{17}C_8OC_6H_4CO_2$
30 X=$H_{13}C_6OC_6H_4CO_2$
31 X=$H_{17}C_8OC_6H_4OCO$
32 X=$H_{13}C_6OC_6H_4OCO$

27

33 X=$H_{17}C_8OC_6H_4$
34 X=$H_{17}C_8OC_6H_4CO_2$
35 X=$H_{13}C_6OC_6H_4CO_2$
36 X=$H_{17}C_8OC_6H_4OCO$
37 X=$H_{13}C_6OC_6H_4OCO$

Scheme 3

of ethanol–sulfuric acid (9:1), followed by heating. Column chromatography was performed on silica gel 60 (230–240 mesh, Merck). Optical rotations were recorded using a Perkin-Elmer 241 polarimeter. The NMR spectra (^{1}H: 400 MHz, ^{13}C: 100.6 MHz) were recorded on a Bruker AMX-400 spectrometer with $SiMe_4$ as internal standard (m_c=centred multiplet). *J* values in Hz. An Olympus BH optical polarizing microscope equipped with a Mettler FP 82 hot stage and a Mettler FP 80 cental processor was used to identify thermal transitions and characterize anisotropic textures. For further verification of the textures, a contact preparation with N4 (4-butyl-4′-methoxyazoxybenzene, K 16 N 76 I) was carried out. Analysis by DSC was carried out on a Perkin-Elmer DSC7 instrument using heating and cooling rates of 5 K min^{-1}.

General reaction conditions for the synthesis of the trioxadecalin structure

A flask with 40 mg of the diol, the *para*-substituted benzaldehyde dimethyl acetal (1.2 equiv.) and toluene-*p*-sulfonic acid (monohydrate) (5 mg) in abs. *N*,*N*-dimethylformamide was fitted to a rotatory evaporator. The mixture was heated at reduced pressure (29–33 hPa) in a water-bath of 60 °C, in order to remove the formed methanol, until TLC revealed complete reaction. The solvent was removed *in vacuo* (10 hPa) at a water-bath temperature of 75 °C. The solid residue was washed with saturated aqueous sodium hydrogen carbonate, filtered, washed with water and cold ethanol and then recrystallized from ethanol.

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-phenyl-8-(4′-octyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (13b)

General reaction conditions using benzaldehyde dimethyl acetal were followed. Yield 16.0 mg (31%); colourless crystals; mp 105.8 °C; $[\alpha]_D^{20}$ +23.8 (*c* 9.87, $CHCl_3$); δ_H ($CDCl_3$) (″=3-phenyl ring; ′=8-octyloxyphenyl ring) 7.51 (dd, 2H, H-2″, H-6″), 7.36 (m_c, 3H, H-3″, H-4″, H-5″), 7.26 (d, 2H, H-2′, H-6′), 6.87 (d, 2H, H-3′, H-5′), 5.60 (s, 1H, H-3), 4.48 (dd, 1H, H-8), 4.32 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.79 (dd, 1H, H-5_{ax}), 3.67 (ddd, 1H, H-1), 3.59 (ddd, 1H, H-6), 2.21 (m_c, 1H, H-10_{eq}), 2.03 (m_c, 1H, H-9_{eq}), 1.86 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.75 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.30 (m_c, 8H, CH_2), 0.89 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 7.5 $^3J_{2'',4'';6'',4''}$ 1.5, $^3J_{2',3';5',6'}$ 8.2, $^3J_{8,9ax}$ 10.2, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.2, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.8; δ_c ($CDCl_3$) 158.8 (C-4′), 137.8 (C-1″), 133.6 (C-1′), 129.0 (C-3″, C-5″), 128.3 (C-4″), 127.2 (C-2′, C-6′), 126.2 (C-2″, C-6″), 114.5 (C-3′, C-5′), 101.8 (C-3), 79.7 (C-8), 78.4 (C-6), 74.1 (C-1), 69.6 (C-5), 68.1 (α-CH_2), 33.1 (C-10), 31.8 (C-9), 29.4, 29.3, 26.1, 22.7 (CH_2), 14.1 (CH_3).

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-(4″-fluorophenyl)-8-(4′-hexyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (14a)

General reaction conditions using 4-fluorobenzaldehyde dimethyl acetal were followed. Yield 41.6 mg (77%); colourless crystals; mp 119.3 °C; $[\alpha]_D^{20}$ +23.3 (*c* 0.91, $CHCl_3$); δ_H ($CDCl_3$) 7.50 (dd, 2H, H-2″, H-6″), 7.26 (d, 2H, H-2′, H′6), 7.05 (dd, 2H, H-3″, H-5″), 6.87 (d, 2H, H-3′, H-5′), 5.58 (s, 1H, H-3), 4.48 (dd, 1H, H-8), 4.30 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.77 (dd, 1H, H-5_{ax}), 3.66 (ddd, 1H, H-1), 3.57 (ddd, 1H, H-6), 2.20 (m_c, 1H, H-10_{eq}), 2.03 (m_c, 1H, H-9_{eq}), 1.85 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.76 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.30 (m_c, 4H, CH_2), 0.89 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.9, $^3J_{3'',F;5'',F}$ 8.8, $^4J_{2'',F;6'',F}$ 5.7, $^3J_{2',3';5',6'}$ 8.7, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.6, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.8; δ_C ($CDCl_3$) 163.1 (C-4″), 158.8 (C-4′), 133.78 (C-1″), 133.5 (C-1′), 128.1 (C-2″, C-6″), 127.2 (C-2′, C-6′), 115.2 (C-3″, C-5″), 114.5 (C-3′, C-5′), 101.1 (C-3), 79.7 (C-8), 78.3 (C-6), 74.0 (C-1), 69.6 (C-5), 68.1 (α-CH_2), 33.0 (C-10), 31.8 (C-9), 29.3, 29.2, 26.0, 22.7 (CH_2), 14.1 (CH_3); $^1J_{4'',F}$ 163.1, $^2J_{3'',F;5'',F}$ 21.6, $^3J_{2'',F;6'',F}$ 8.6, $^4J_{1'',F}$ 3.3.

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-(4″-fluorophenyl)-8-(4′-octyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (14b)

General reaction conditions using 4-fluorobenzaldehyde dimethyl acetal were followed. Yield 40 mg (76%); colourless crystals; mp 113.8 °C; $[\alpha]_D^{20}$ +23.6 (*c* 0.93, $CHCl_3$); δ_H ($CDCl_3$) 7.50 (dd, 2H, H-2″, H-6″), 7.26 (d, 2H, H-2′, H′6), 7.05 (dd, 2H, H-3″, H-5″), 6.87 (d, 2H, H-3′, H-5′), 5.58 (s, 1H, H-3), 4.48 (dd, 1H, H-8), 4.30 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.77 (dd, 1H, H-5_{ax}), 3.66 (ddd, 1H, H-1), 3.57 (ddd, 1H, H-6), 2.20 (m_c, 1H, H-10_{eq}), 2.03 (m_c, 1H, H-9_{eq}), 1.85 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.76 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.30 (m_c 8H, CH_2), 0.89 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.9, $^3J_{3'',F;5'',F}$ 8.8, $^4J_{2'',F;6'',F}$ 5.7, $^3J_{2',3';5',6'}$ 8.7, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.6, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.8; δ_C ($CDCl_3$) 163.1 (C-4″), 158.8 (C-4′), 133.78 (C-1″), 133.5 (C-1′), 128.1 (C-2″, C-6″), 127.2 (C-2′, C-6′), 115.2 (C-3″, C-5″), 114.5 (C-3′, C-5′), 101.1 (C-3), 79.7 (C-8), 78.3 (C-6), 74.0 (C-1), 69.6 (C-5), 68.1 (α-CH_2), 33.0 (C-10), 31.8 (C-9), 29.4, 29.3, 29.2, 26.0, 22.7 (CH_2), 14.1 (CH_3); $^1J_{4'',F}$ 163.1, $^2J_{3'',F;5'',F}$ 21.6, $^3J_{2'',F;6'',F}$ 8.6, $^4J_{1'',F}$ 3.3.

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-(4″-chlorophenyl)-8-(4′-octyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (15b)

General reaction conditions using 4-chlorobenzaldehyde dimethyl acetal were followed. Yield 16.8 mg (31%); colourless crystals; mp 128.8 °C; $[\alpha]_D^{20}$ +25.4 (*c* 0.72, $CHCl_3$); δ_H ($CDCl_3$) 7.45 (d, 2H, H-2″, H-6″), 7.34 (d, 2H, H-3″, H-5″), 7.26 (d, 2H, H-2′, H-6′), 6.87 (d, 2H, H-3′, H-5′), 5.57 (s, 1H, H-3), 4.47 (dd, 1H, H-8), 4.30 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.77 (dd, 1H, H-5_{ax}), 3.66 (ddd, 1H, H-1), 3.57 (ddd, 1H, H-6), 2.20 (m_c, 1H, H-10_{eq}), 2.03 (m_c, 1H, H-9_{eq}), 1.85 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.76 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.30 (m_c, 8H, CH_2), 0.89 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.7, $^3J_{2',3';5',6'}$ 8.7, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.2, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.8; δ_c ($CDCl_3$) 158.8 (C-4′), 136.3 (C-1″), 134.8 (C-4″), 133.4 (C-1′), 128.5 (C-3″, C-5″), 127.7 (C-2″, C-6″), 127.2 (C-2′, C-6′), 114.5 (C-3′, C-5′), 100.9 (C-3), 79.7 (C-8), 78.4 (C-6), 74.0 (C-1), 69.5 (C-5), 68.1 (α-CH_2), 33.0 (C-10), 31.8 (C-9), 29.4, 29.3, 29.2, 26.0, 22.7 (CH_2), 14.1 (CH_3).

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-(4″-bromophenyl)-8-(4′-hexyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (16a)

General reaction conditions using 4-bromobenzaldehyde dimethyl acetal were followed. Yield 42.1 mg (68%); colourless crystals; mp 144.9 °C; $[\alpha]_D^{20}$ + 23.2 (*c* 0.92, $CHCl_3$); δ_H ($CDCl_3$) 7.50 (d, 2H, H-3″, H-5″), 7.39 (d, 2H, H-2″, H-6″), 7.26 (d, 2H, H-2′, H-6′), 6.87 (d, 2H, H-3′, H-5′), 5.55 (s, 1H, H-3), 4.47 (dd, 1H, H-8), 4.30 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.77 (dd, 1H, H-5_{ax}), 3.65 (ddd, 1H, H-1), 3.57 (ddd, 1H, H-6), 2.21 (m_c, 1H, H-10_{eq}), 2.03 (m_c, 1H, H-9_{eq}), 1.85 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.76 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.33 (m_c, 4H, CH_2), 0.90 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.2, $^3J_{2',3';5',6'}$ 8.5, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.2, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.8; δ_c ($CDCl_3$) 158.8 (C-4′), 136.8 (C-1″), 133.5 (C-1′), 131.4 (C-3″, C-5″), 128.0 (C-2″, C-6″), 127.2 (C-2′, C-6′), 123.1 (C-4″), 114.5 (C-3′, C-5′), 101.0 (C-3), 79.7 (C-8), 78.4 (C-6), 74.0 (C-1), 69.6 (C-5), 68.1 (α-CH_2), 33.0 (C-10), 31.6 (C-9), 29.2, 25.7, 22.6 (CH_2), 14.1 (CH_3).

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-(4″-bromophenyl)-8-(4′-octyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (16b)

General reaction conditions using 4-bromobenzaldehyde dimethyl acetal were followed. Yield 32.0 mg (54%); colourless crystals; mp 132.5 °C; $[\alpha]_D^{20}$ + 23.9 (*c* 0.82, $CHCl_3$); δ_H ($CDCl_3$) 7.50 (d, 2H, H-3″, H-5″), 7.39 (d, 2H, H-2″, H-6″), 7.26 (d, 2H, H-2′, H-6′), 6.87 (d, 2H, H-3′, H-5′), 5.55 (s, 1H, H-3), 4.47 (dd, 1H, H-8), 4.30 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.77 (dd, 1H, H-5_{ax}), 3.65 (ddd, 1H, H-1), 3.57 (ddd, 1H, H-6), 2.21 (m_c, 1H, H-10_{eq}), 2.03 (m_c, 1H, H-9_{eq}), 1.85 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.76 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.33 (m_c, 8H, CH_2), 0.89 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.2, $^3J_{2',3';5',6'}$ 8.5, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.2, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.8; δ_C ($CDCl_3$) 158.8 (C-4′), 136.8 (C-1″), 133.5 (C-1′), 131.4 (C-3″, C-5″), 128.0 (C-2″, C-6″), 127.2 (C-2′, C-6′), 123.1 (C-4″), 114.5 (C-3′, C-5′), 101.0 (C-3), 79.7 (C-8), 78.4 (C-6), 74.0 (C-1), 69.6 (C-5), 68.1 (α-CH_2), 33.0 (C-10), 31.6 (C-9), 29.4, 29.3, 29.2, 26.0, 22.7 (CH_2), 14.1 (CH_3).

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-(4″-bromophenyl)-8-(4′-decyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (16c)

General reaction conditions using 4-bromobenzaldehyde dimethyl acetal were followed. Yield 40.0 mg (69%); colourless crystals; mp 128.0 °C; $[\alpha]_D^{20}$ + 22.2 (*c* 0.89, $CHCl_3$); δ_H ($CDCl_3$) 7.50 (d, 2H, H-3″, H-5″), 7.39 (d, 2H, H-2″, H-6″), 7.26 (d, 2H, H-2′, H-6′), 6.87 (d, 2H, H-3′, H-5′), 5.55 (s, 1H, H-3), 4.47 (dd, 1H, H-8), 4.30 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.77 (dd, 1H, H-5_{ax}), 3.65 (ddd, 1H, H-1), 3.57 (ddd, 1H, H-6), 2.21 (m_c, 1H, H-10_{eq}), 2.03 (m_c, 1H, H-9_{eq}), 1.85 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.76 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.33 (m_c, 12H, CH_2), 0.89 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.2, $^3J_{2',3';5',6'}$ 8.5, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.2, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.8; δ_C ($CDCl_3$) 158.8 (C-4′), 136.8 (C-1″), 133.5 (C-1′), 131.4 (C-3″, C-5″), 128.0 (C-2″, C-6″), 127.2 (C-2′, C-6′), 123.1 (C-4″), 114.5 (C-3′, C-5′), 101.0 (C-3), 79.7 (C-8), 78.4 (C-6), 74.0 (C-1), 69.6 (C-5), 68.1 (α-CH_2), 33.0 (C-10), 31.6 (C-9), 29.6, 29.5, 29.4, 29.3, 29.3, 29.2, 26.0 22.7, (CH_2), 14.1 (CH_3).

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-(4″-iodophenyl)-8-(4′-hexyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (17a)

General reaction conditions using 4-iodobenzaldehyde dimethyl acetal were followed. Yield 37.2 mg (55%); colourless crystals; mp 148.8 °C; $[\alpha]_D^{20}$ + 22.6 (*c* 0.92, $CHCl_3$); δ_H ($CDCl_3$) 7.71 (d, 2H, H-3″, H-5″), 7.25 (d, 4H, H-2″, H-6″, H-2′, H-6′), 6.86 (d, 2H, H-3′, H-5′), 5.54 (s, 1H, H-3), 4.47 (dd, 1H, H-8), 4.30 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.76 (dd, 1H, H-5_{ax}), 3.65 (ddd, 1H, H-1), 3.56 (ddd, 1H, H-6), 2.20 (m_c, 1H, H-10_{eq}), 2.03 (m_c, 1H, H-9_{eq}), 1.85 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.75 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.33 (m_c, 4H, CH_2), 0.90 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.2, $^3J_{2',3';5',6'}$ 8.5, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.9, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.4; δ_C ($CDCl_3$) 158.8 (C-4′), 137.4 (C-3″, C-5″), 133.4 (C-1′), 128.1 (C-2″, C-6″), 127.2 (C-2′, C-6′), 114.5 (C-3′, C-5′), 101.0 (C-3), 94.9 (C-4″), 79.7 (C-8), 78.3 (C-6), 74.0 (C-1), 69.5 (C-5), 68.1 (α-CH_2), 33.0 (C-10), 31.8 (C-9), 29.2, 25.7, 22.6 (CH_2), 14.1 (CH_3).

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-(4″-iodophenyl)-8-(4′-octyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (17b)

General reaction conditions using 4-iodobenzaldehyde dimethyl acetal were followed. Yield 47.8 mg (73%); colourless crystals; mp 134.5 °C; $[\alpha]_D^{20}$ + 20.6 (*c* 0.89, $CHCl_3$); δ_H ($CDCl_3$) 7.71 (d, 2H, H-3″, H-5″), 7.25 (d, 4H, H-2″, H-6″, H-2′, H-6′), 6.86 (d, 2H, H-3′, H-5′), 5.54 (s, 1H, H-3), 4.47 (dd, 1H, H-8), 4.30 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.76 (dd, 1H, H-5_{ax}), 3.65 (ddd, 1H, H-1), 3.56 (ddd, 1H, H-6), 2.20 (m_c, 1H, H-10_{eq}), 2.03 (m_c, 1H, H-9_{eq}), 1.85 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.75 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.30 (m_c, 8H, CH_2), 0.89 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.2, $^3J_{2',3';5',6'}$ 8.5, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.9, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.4; δ_C ($CDCl_3$) 158.8 (C-4′), 137.4 (C-3″, C-5″), 133.4 (C-1′), 128.1 (C-2″, C-6″), 127.2 (C-2′, C-6′), 114.5 (C-3′, C-5′), 101.0 (C-3), 94.9 (C-4″), 79.7 (C-8), 78.3 (C-6), 74.0 (C-1), 69.5 (C-5), 68.1 (α-CH_2), 33.0 (C-10), 31.8 (C-9), 29.4, 29.3, 29.2, 26.04, 22.7 (CH_2), 14.1 (CH_3).

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-(4″-azidophenyl)-8-(4′-octyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (18b)

General reaction conditions using 4-azidobenzaldehyde dimethyl acetal were followed. Yield 37.5 mg (68%); colourless crystals; mp 118.2 °C; $[\alpha]_D^{20}$ + 20.1 (*c* 0.82, $CHCl_3$); δ_H ($CDCl_3$) 7.50 (d, 2H, H-2″, H-6″), 7.02 (d, 2H, H-3″, H-5″), 7.25 (d, 2H, H-2′, H-6′), 6.87 (d, 2H, H-3′, H-5′), 5.57 (s, 1H, H-3), 4.47 (dd, 1H, H-8), 4.30 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.77 (dd, 1H, H-5_{ax}), 3.66 (ddd, 1H, H-1), 3.57 (ddd, 1H, H-6), 2.20 (m_c, 1H, H-10_{eq}), 2.03 (m_c, 1H, H-9_{eq}), 1.85 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.76 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.30 (m_c, 8H, CH_2), 0.88 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.5, $^3J_{2',3';5',6'}$ 8.5, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.2, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.8; δ_C ($CDCl_3$) 158.8 (C-4′), 133.4 (C-1′), 127.8, 118.9 (C-2″, C-3″, C-5″, C-6″), 127.2 (C-2′, C-6′), 114.5 (C-3′, C-5′), 101.2 (C-3), 79.7 (C-8), 78.4 (C-6), 74.0 (C-1), 69.6 (C-5), 68.1 (α-CH_2), 33.1 (C-10), 31.8 (C-9), 29.4, 29.3, 26.0, 22.7 (CH_2), 14.1 (CH_3).

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-(4″-thiocyanatophenyl)-8-(4′-octyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (19b)

General reaction conditions using 4-thiocyanatobenzaldehyde dimethyl acetal were followed. Yield 26.9 mg (47%); colourless crystals; mp 80.7 °C; $[\alpha]_D^{20}$ + 21.6 (*c* 0.21, $CHCl_3$); δ_H ($CDCl_3$) 7.60, 7.53 (d, 2H, H-2″, H-3″) and (d, 2H, H-5″, H-6″), 7.26 (d, 2H, H-2′, H-6′), 6.87 (d, 2H, H-3′, H-5′), 5.60 (s, 1H, H-3), 4.48 (dd, 1H, H-8), 4.31 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.78 (dd, 1H, H-5_{ax}), 3.67 (ddd, 1H, H-1), 3.57 (ddd, 1H,, H-6), 2.21 (m_c, 1H, H-10_{eq}), 2.04 (m_c, 1H, H-9_{eq}), 1.85 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.75 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.30 (m_c, 8H, CH_2), 0.89 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.3, $^3J_{2',3';5',6'}$ 8.7, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.9, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.4; δ_C ($CDCl_3$) 158.8 (C-4′), 139.4, 131.0 (C-4″, C-1″), 133.3 (C-1′), 129.7, 128.2 (C-2″, C-3″, C-5″, C-6″), 125.0 (SCN), 127.2 (C-2′, C-6′), 114.5 (C-3′, C-5′), 100.4 (C-3), 79.7 (C-8), 78.4 (C-6), 73.9 (C-1), 69.6 (C-5), 68.1 (α-CH_2), 33.0 (C-10), 31.8 (C-9), 29.36, 29.25, 29.18, 26.04, 22.66 (CH_2), 14.1 (CH_3).

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-(4″-methylphenyl)-8-(4′-octyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (20b)

General reaction conditions using 4-methylbenzaldehyde dimethyl acetal were followed. Yield 31.8 mg (61%); colourless crystals; mp 118.0 °C; $[\alpha]_D^{20}$ +24.2 (*c* 0.92, $CHCl_3$); δ_H ($CDCl_3$) 7.39 (d, 2H, H-2″, H-6″), 7.26 (d, 2H, H-2′, H-6′), 7.17 (d, 2H, H-3″, H-5″), 6.86 (d, 2H, H-3′, H-5′), 5.57 (s, 1H, H-3), 4.47 (dd, 1H, H-8), 4.30 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.77 (dd, 1H, H-5_{ax}), 3.65 (ddd, 1H, H-1), 3.57 (ddd, 1H, H-5_{eq}), 2.34 (s, 3H, CH_3 Aryl), 2.20 (m_c, 1H, H-10_{eq}), 2.02 (m_c, 1H, H-9_{eq}), 1.85 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.76 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.30 (m_c, 8H, CH_2), 0.89 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.2, $^3J_{2',3';5',6'}$ 8.5, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.2, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.4; δ_C ($CDCl_3$) 158.8 (C-4′), 138.8 (C-4″), 135.0 (C-1″), 133.6 (C-1′), 129.0 (C-3″, C-5″), 127.2 (C-2′, C-6′), 126.1 (C-2″, C-6″), 114.5 (C-3′, C-5′), 101.9 (C-3), 79.7 (C-8), 78.3 (C-6), 74.1 (C-1), 69.6 (C-5), 68.1 (α-CH_2), 33.1 (C-10), 31.8 (C-9), 29.4, 29.3, 29.3, 29.2, 25.1, 22.7 (CH_2), 21.3 (CH_3 Aryl), 14.1 (CH_3).

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-(4″-isopropylphenyl)-8-(4′-octyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (21b)

General reaction conditions using 4-isopropylbenzaldehyde dimethyl acetal were followed. Yield 28.1 mg (51%); colourless crystals; mp 88.3 °C; $[\alpha]_D^{20}$ +18.3 (*c* 1.19, $CHCl_3$); δ_H ($CDCl_3$) 7.43 (d, 2H, H-2″ H-6″), 7.26 (d, 2H, H-2′, H-6′), 7.23 (d, 2H, H-3″, H-5″), 6.86 (d, 2H, H-3′, H-5′), 5.58 (s, 1H, H-3), 4.47 (dd, 1H, H-8), 4.30 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.77 (dd, 1H, H-5_{ax}), 3.66 (ddd, 1H, H-1), 3.58 (ddd, 1H, H-6), 2.90 (sep, 2H, CH Pr^i), 2.20 (m_c, 1H, H-10_{eq}), 2.02 (m_c, 1H, H-9_{eq}), 1.85 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.76 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.30 (m_c, 8H, CH_2), 1.22 (d, 6H, CH_3 Pr^i), 0.89 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.5, $^3J_{2',3';5',6'}$ 8.2, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.2, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.4; δ_C ($CDCl_3$) 158.8 (C-4′), 149.8 (C-4″), 135.3 (C-1″), 133.6 (C-1′), 127.2 (C-2′, C-6′), 126.4 (C-3″, C-5″), 126.1 (C-2″, *c*-6″), 114.5 (C-3′, C-5′), 101.9 (C-3), 79.7 (C-8), 78.3 (C-6), 74.1 (C-1), 69.6 (C-5), 68.1 (α-CH_2), 34.0 (CH Pr^i), 33.1 (C-10), 31.8 (C-9), 29.4, 29.3, 29.3, 29.2, 26.1, 22.7 (CH_2), 23.9 (CH_3 Pr^i), 14.1 (CH_3).

Synthesis of 4-(trimethylsilylethynyl)benzaldehyde dimethyl acetal (10)

Trimethylsilylacetylene (0.6 ml, 4.31 mmol) was added to a solution of 4-iodobenzaldehyde dimethyl acetal **5** (1.0 g, 4.31 mmol), tetrakis(triphenylphosphine)-palladium(0) (258 mg, 0.22 mmol), CuI (172 mg, 0.86 mmol) and butylamine (0.65 ml, 6.46 mmol) in 53 ml abs. toluene at room temp. under nitrogen. The reaction mixture was stirred at room temp. for 28 h and then quenched with water (200 ml). The aqueous layer was extracted with diethyl ether (3 × 70 ml), the combined organic extracts were dried with sodium carbonate and concentrated. The crude residue was purified by column chromatography [light petroleum (bp 60–70 °C)–ethyl acetate 20:1 + 1% triethylamine]. Yield 0.81 g (91%); δ_H ($CDCl_3$) 7.47 (d, 2H, H-3′, H-5′), 7.37 (d, 2H, H-2′, H-6′), 5.38 (s, 1H, CH), 3.30 (s, 6H, OCH_3), 0.25 (s, 9H, $SiMe_3$); $^3J_{Aryl}$ 8.2.

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-[4″-(trimethylsilyethynyl)-phenyl]-8-(4′-octyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]-decane (22b)

General reaction conditions using 4-(trimethylsilyethynyl)benzaldehyde dimethyl acetal were followed. Yield 36.0 mg (58%); colourless crystals; mp 146.1 °C; $[\alpha]_D^{20}$ +21.5 (*c* 0.88, $CHCl_3$); δ_H ($CDCl_3$) 7.47 (d, 2H, H-2″, H-6″), 7.44 (d, 2H, H-3″, H-5″), 7.26 (d, 2H, H-2′, H-6′), 6.87 (d, 2H, H-3′, H-5′), 5.57 (s, 1H, H-3), 4.47 (dd, 1H, H-8), 4.31 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.77 (dd, 1H, H-5_{ax}), 3.65 (ddd, 1H, H-1), 3.57 (ddd, 1H, H-6), 2.20 (m_c, 1H, H-10_{eq}), 2.03 (m_c, 1H, H-9_{eq}), 1.86 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.76 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.30 (m_c, 8H, CH_2), 0.88 (t, 3H, CH_3), 0.25 (s, 9H, $SiMe_3$); $^3J_{2'',3'';5'',6''}$ 8.5, $^3J_{2',3';5',6'}$ 8.7, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.2, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.8; δ_C ($CDCl_3$) 158.8 (C-4′), 137.8 (C-1″), 133.5 (C-1′), 131.9 (C-3″, C-5″), 127.2 (C-2′, C-6′), 126.1 (C-2″, C-6″), 123.8 (C-4″), 114.5 (C-3′, C-5′), 104.9, 94.6 (C-alkyne), 101.2 (C-3), 79.7 (C-8), 78.4 (C-6), 74.0 (C-1), 69.6 (C-5), 68.1 (α-CH_2), 33.1 (C-10), 31.8 (C-9), 29.4, 29.3, 29.2, 26.1, 22.7 (CH_2), 14.1 (CH_3), 0.032 ($SiMe_3$).

Synthesis of 4-ethynylbenzaldehyde dimethyl acetal (11)

Bu_4NF (1.0 M solution in THF, 3.22 ml) was added to a solution of **10** (0.4 g, 1.61 mmol) in 10 ml of abs. THF at room temp. under nitrogen. The reaction mixture was stirred at room temp. over night, and then water (80 ml) was added. The mixture was extracted with diethyl ether (3 × 50 ml), the combined organic extracts dried with sodium carbonate, and concentrated. The crude residue was purified by column chromatography [light petroleum (bp 60–70 °C)–ethyl acetate 5:1]. Yield 0.24 g (85%); δ_H ($CDCl_3$) 7.50 (d, 2H, H-3′, H-5′), 7.41 (d, 2H, H-2′, H-6′), 5.38 (s, 1H, CH), 3.30 (s, 6H, OCH_3), 3.08 (s, 1H, H alkyne); $^3J_{Aryl}$ 8.2.

Synthesis of (1*S*,3*R*,6*R*,8*R*)-3-(4″-ethynylphenyl)-8-(4′-octyloxyphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (23b)

General reaction conditions using 4-ethynylbenzaldehyde dimethyl acetal were followed. Yield 29.5 mg (55%); colourless crystals; mp 114.1 °C; $[\alpha]_D^{20}$ +23.9 (*c* 0.91, $CHCl_3$); δ_H ($CDCl_3$) 7.50 (d, 2H, H-2″, H-6″), 7.47 (d, 2H, H-3″, H-5″), 7.26 (d, 2H, H-2′, H-6′), 6.87 (d, 2H, H-3′, H-5′), 5.59 (s, 1H, H-3), 4.48 (dd, 1H, H-8), 4.31 (dd, 1H, H-5_{eq}), 3.94 (t, 2H, α-CH_2), 3.77 (dd, 1H, H-5_{ax}), 3.66 (ddd, 1H, H-1), 3.57 (ddd, 1H, H-6), 3.07 (s, 1H, H alkyne), 2.20 (m_c, 1H, H-10_{eq}), 2.03 (m_c, 1H, H-9_{eq}), 1.86 (m_c, 2H, H-9_{ax}, H-10_{ax}), 1.76 (q, 2H, β-CH_2), 1.44 (q, 2H, γ-CH_2), 1.30 (m_c, 8H, CH_2), 0.88 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.6, $^3J_{2',3';5',6'}$ 8.9, $^3J_{8,9ax}$ 10.9, $^3J_{8,9eq}$ 2.4, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 10.2, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.8; δ_C ($CDCl_3$) 158.8 (C-4′), 138.2 (C-1″), 133.5 (C-1′), 132.1 (C-3″, C-5″), 127.2 (C-2′, C-6′), 126.2 (C-2″, C-6″), 122.7 (C-4″), 114.5 (C-3′, C-5′), 101.1 (C-3), 83.4 (C alkyne), 79.7 (C-8), 78.4 (C-6), 77.5 (C alkyne), 74.0 (C-1), 69.6 (C-5), 68.1 (α-CH_2), 33.0 (C-10), 31.8 (C-9), 29.4, 29.3, 29.2, 26.1, 22.7 (CH_2), 14.1 (CH_3).

Synthesis of 4-octyloxybiphenyl-4′-carbaldehyde dimethyl acetal (12)

A solution of 4-octyloxyphenylboronic acid (2.75 g, 11 mmol) in 20 ml ethanol was added to a stirred mixture of 4-bromobenzaldehyde (1.96 g, 8.5 mmol) and tetrakis(triphenylphosphine)-palladium(0) (0.326 g, 0.28 mmol) in 15 ml benzene and aqueous sodium carbonate (2 M, 15 ml) at room temp. under nitrogen. The stirred mixture was heated at the temperature of reflux for 23 h. Then water was added, the product was extracted with light petroleum (bp 60–70 °C), the combined organic extracts dried with sodium carbonate and the solvent removed *in vacuo*. The crude residue was purified by repeated recrystallization from methanol. Yield 2.43 g (80%); colourless crystals; mp 49.4 °C; δ_H ($CDCl_3$) 7.55 (d, 2H, H-2″, H-6″), 7.52 (d, 2H, H-3″, H-5″), 7.48 (d, 2H, H-2′, H-6′), 6.96 (d, 2H, H-3′, H-5′), 5.42 (s, 1H, CH), 3.99 (t, 2H, α-CH_2), 3.36 (s, 6H, OCH_3), 1.80 (q, 2H, β-CH_2), 1.47 (q, 2H, γ-CH_2), 1.31 (m_c, 8H, -CH_2), 0.89 (t, 3H, -CH_3); $^3J_{Aryl''}$ 8.8, $^3J_{Aryl'}$ 8.5.

Synthesis of (1*S*,3*R*,6*R*)-2-(4″-octyloxybiphenyl)-2,4,7-trioxabicyclo[4.4.0]decane (33)

General reaction conditions using 4-octyloxybiphenyl-4′-carbaldehyde diemthyl acetal were followed. The product was

purified by column chromatography [light petroleum (bp 60–70 °C)–ethyl acetate 10:1]. Yield 75.4 mg (49%); colourless crystals; mp 122.9 °C; $[\alpha]_D^{20}$ −4.8 (*c* 1.01, $CHCl_3$); δ_H ($CDCl_3$) 7.53 (s, 4H, H-2′, H-3′, H-5′, H-6′), 7.49 (d, 2H, H-2″, H-6″), 6.95 (d, 2H, H-3″, H-5″), 5.60 (s, 1H, H-3), 4.26 (dd, 1H, H-5_{eq}), 3.92–4.02 (m, 3H, α-CH_2, H-8_{eq}), 3.70 (dd, 1H, H-5_{ax}), 3.58 (ddd, 1H, H-1), 3.51 (ddd, 1H, H-8_{ax}), 3.36 (ddd, 1H, H-6), 2.13 (m_c, 1H, H-10_{eq}), 1.74–1.92 (m, 4H, H-9_{ax}, H-9_{eq}, β-CH_2), 1.68 (dddd, 1H, H-10_{ax}), 1.47 (q, 2H, γ-CH_2), 1.35 (m_c, 8H, CH_2), 0.89 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.7, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 11.5, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.4, $^2J_{8ax,8eq}$ 11.6, $^3J_{8ax,9ax}$ 11.6, $^3J_{8ax,9eq}$ 3.4, $^2J_{10ax,10eq}$ 11.6, $^3J_{10ax,9ax}$ 11.6, $^3J_{10ax,9eq}$ 4.4; δ_C ($CDCl_3$) 158.9 (C-4″), 141.6 (C-4′), 136.1 (C-1′), 133.2 C-1″), 128.2 (C-2″, 6″), 126.7, 126.5 (C-2′, C-3′, C-5′, C-6′), 114.8 (C-3″, C-5″), 101.7 (C-3), 78.6 (C-1), 74.2 (C-6), 69.4 (C-5), 68.1 (C-8), 31.8 (CH_2), 29.4, 29.3, 29.3 (C-9, CH_2), 28.9 (C-10), 26.1, 25.6, 22.7 (CH_2), 14.1 (CH_3).

Synthesis of (1*S*,3*R*,6*R*)-3-[4′-(4″-octyloxybenzoyloxy)-phenyl]-2,4,7-trioxabicyclo[4.4.0]decane (34)

General reaction conditions using 4-(4-octyloxybenzoyloxy) benzaldehyde dimethyl acetal were followed. Yield 136.0 mg (65%); colourless crystals; mp 126.9 °C; $[\alpha]_D^{20}$ −4.3 (*c* 1.08, $CHCl_3$); δ_H ($CDCl_3$) 8.12 (d, 2H, H-2″, H-6″), 7.54 (d, 2H, H-2′, H-6′), 7.20 (d, 2H, H-3′, H-5′), 6.96 (d, 2H, H-3″, H-5″), 5.59 (s, 1H, H-3), 4.26 (dd, 1H, H-5_{eq}), 4.04 (t, 2H, α-CH_2), 3.95 (ddd, 1H, H-8_{eq}), 3.70 (dd, 1H, H-5_{ax}), 3.57 (ddd, 1H, H-1), 3.51 (ddd, 1H, H-8_{ax}), 3.35 (ddd, 1H, H-6), 2.13 (m_c, 1H, H-10_{eq}), 1.74–1.92 (m, 4H, H-9_{ax}, H-9_{eq}, β-CH_2), 1.67 (dddd, 1H, H-10_{ax}), 1.47 (q, 2H, γ-CH_2), 1.32 (m_c, 8H, CH_2), 0.89 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.9, $^3J_{2',3';5',6'}$ 8.7, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^2J_{8ax,8eq}$ 11.5, $^3J_{8eq,9ax}$ 4.8, $^3J_{8eq,9eq}$ 3.4, $^2J_{10ax,10eq}$ 11.6, $^3J_{10ax,9ax}$ 11.6, $^3J_{10ax,9eq}$ 4.2; δ_C ($CDCl_3$) 164.7 (C-4″), 163.6 (C=O), 151.5 (C-4′), 135.2 (C-1′), 132.3 (C-2″, C-6″), 127.4 (C-2′, C-6′), 121.6, 121.5 (C-3′, C-5′, C-1″), 114.3 (C-3″, C-5″), 101.2 (C-3), 78.6 (C-1), 74.1 (C-6), 69.4 (C-5), 68.3, 68.1 (C-8, α-CH_2), 29.1 (C-9), 28.8 (C-10), 31.8, 29.3, 29.2, 26.0, 25.6, 22.7 (CH_2), 14.0 (CH_3).

Synthesis of (1*S*,3*R*,6*R*)-3-[4′-(4″-hexyloxybenzoyloxy]-phenyl)-2,4,7-trioxabicyclo[4.4.0]decane (35)

General reaction conditions using 4-(4-hexyloxybenzoyloxy) benzaldehyde dimethyl acetal were followed. Yield 73.9 mg (49%); colourless crystals; mp 146.6 °C; $[\alpha]_D^{20}$ −4.8 (*c* 1.01 $CHCl_3$); δ_H ($CDCl_3$) 8.12 (d, 2H, H-2″, H-6″), 7.54 (d, 2H, H-2′, H-6′), 7.20 (d, 2H, H-3′, H-5′), 6.96 (d, 2H, H-3″, H-5″), 5.59 (s, 1H, H-3), 4.26 (dd, 1H, H-5_{eq}), 4.04 (t, 2H, α-CH_2), 3.95 (ddd, 1H, H-8_{eq}), 3.70 (dd, 1H, H-5_{ax}), 3.57 (ddd, 1H, H-1), 3.51 (ddd, 1H, H-8_{ax}), 3.35 (ddd, 1H, H-6), 2.13 (m_c, 1H, H-10_{eq}), 1.74–1.92 (m, 4H, H-9_{ax}, H-9_{eq}, β-CH_2), 1.67 (dddd, 1H, H-10_{ax}), 1.48 (q, 2H, γ-CH_2), 1.35 (m_c, 4H, CH_2), 0.92 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.9, $^3J_{2',3';5',6'}$ 8.7, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^2J_{8ax,8eq}$ 11.5, $^3J_{8eq,9ax}$ 4.8, $^3J_{8eq,9eq}$ 1.7, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 11.5, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.8, $^3J_{8ax,9ax}$ 11.6, $^3J_{8ax,9eq}$ 3.4, $^2J_{10ax,10eq}$ 11.6, $^3J_{10ax,9ax}$ 11.6, $^3J_{10ax,9eq}$ 4.2; δ_C ($CDCl_3$) 164.7 (C-4″), 163.6 (C=O), 151.5 (C-4′), 135.2 (C-1′), 132.3 (C-2″, C-6″), 127.4 (C-2′, C-6′), 121.6, 121.5 (C-3′, C-5′, C-1″), 114.3 (C-3″, C-5″), 101.2 (C-3), 78.6 (C-1), 74.1 (C-6), 69.4 (C-5), 68.3, 68.1 (C-8, α-CH_2), 29.1 (C-9), 28.8 (C-10), 31.6, 25.7, 25.6, 22.6 (CH_2), 14.0 (CH_3).

Synthesis of (1*S*,3*R*,6*R*)-3-[4′-(4″-octyloxyphenyloxy-carbonyl)phenyl]-2,4,7-trioxabicyclo[4.4.0]decane (36)

General reaction conditions using 4-(4-octyloxyphenyloxycarbonyl)benzaldehyde dimethyl acetal were followed. The product was purified by column chromatography [light petroleum (bp 60–70 °C)–ethyl acetate 5:1]. Yield 75.5 mg (62%); colourless crystals; mp 106.7 °C; $[\alpha]_D^{20}$ −10.9 (*c* = 1.04, $CHCl_3$); δ_H ($CDCl_3$) 8.18 (d, 2H, H-3′, H-5′), 7.63 (d, 2H, H-2′, H-6′), 7.11 (d, 2H, H-2″, H-6″), 6.92 (d, 2H, H-3″, H-5″), 5.63 (s, 1H, H-3), 4.28 (dd, 1H, H-5_{eq}), 3.96 (m, 3H, α-CH_2, H-8_{eq}), 3.71 (dd, 1H, H-5_{ax}), 3.59 (ddd, 1H, H-1), 3.51 (ddd, 1H, H-8_{ax}), 3.36 (ddd, 1H, H-6), 2.15 (m_c, 1H, H-10_{eq}), 1.74–1.93 (m, 4H, H-9_{ax}, H-9_{eq}, β-CH_2), 1.69 (dddd, 1H, H-10_{ax}), 1.46 (q, 2H, γ-CH_2), 1.31 (m_c, 8H, CH_2), 0.89 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.9, $^3J_{2',3';5',6'}$ 8.5, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 11.5, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.8, $^2J_{8ax,8eq}$ 11.6, $^3J_{8ax,9ax}$ 11.6, $^3J_{8ax,9eq}$ 3.4, $^2J_{10ax,10eq}$ 11.6, $^3J_{10ax,9ax}$ 11.6, $^3J_{10ax,9eq}$ 4.4; δ_C ($CDCl_3$) 165.3 (C=O), 156.9 (C-4″), 144.2 (C-1″), 142.8 (C-1′), 130.2 (C-3′, C-5′), 130.1 (C-4′), 126.4 (C-2′, C-6′), 122.4 (C-2″, C-6″), 115.1 (C-3″, C-5″), 100.9 (C-3), 78.7 (C-1), 74.0 (C-6), 69.5 (C-5), 68.5 (C-8), 68.1 (α-CH_2), 31.8 (CH_2), 29.3 (C-9), 28.8 (C-10), 29.4, 29.3, 26.1, 25.6, 22.7 (CH_2), 14.1 (CH_3).

Synthesis of (1*S*,3*R*,6*R*)-3-[4′-(4″-hexyloxyphenyloxy-carbonyl)phenyl]-2,4,7-trioxabicyclo[4.4.0]decane (37)

General reaction conditions using 4-(4-hexyloxyphenyloxycarbonyl)benzaldehyde dimethyl acetal were followed. Yield 25.2 mg (15%); colourless crystals; mp 122.5 °C; $[\alpha]_D^{20}$ −10.3 (*c* 1.01, $CHCl_3$); δ_H ($CDCl_3$) 8.18 (d, 2H, H-3′, H-5′), 7.63 (d, 2H, H-2′, H-6′), 7.11 (d, 2H, H-2″, H-6″), 6.92 (d, 2H, H-3″, H-5″), 5.63 (s, 1H, H-3), 4.28 (dd, 1H, H-5_{eq}), 3.96 (m, 3H, α-CH_2, H-8_{eq}), 3.71 (dd, 1H, H-5_{ax}), 3.59 (ddd, 1H, H-1), 3.51 (ddd, 1H, H-8_{ax}), 3.36 (ddd, 1H, H-6), 2.15 (m_c, 1H, H-10_{eq}), 1.74–1.93 (m, 4H, H-9_{ax}, H-9_{eq}, β-CH_2), 1.69 (dddd, 1H, H-10_{ax}), 1.47 (q, 2H, γ-CH_2), 1.35 (m_c, 4H, CH_2), 0.91 (t, 3H, CH_3); $^3J_{2'',3'';5'',6''}$ 8.9, $^3J_{2',3';5',6'}$ 8.5, $^2J_{5eq,5ax}$ 10.2, $^3J_{5eq,6}$ 4.8, $^3J_{5ax,6}$ 10.2, $^3J_{1,10ax}$ 11.5, $^3J_{1,6}$ 8.9, $^3J_{1,10eq}$ 4.8, $^2J_{8ax,8eq}$ 11.6, $^3J_{8ax,9ax}$ 11.6, $^3J_{8ax,9eq}$ 3.4, $^2J_{10ax,10eq}$ 11.6, $^3J_{10ax,9ax}$ 11.6, $^3J_{10ax,9eq}$ 4.4 Hz; δ_C ($CDCl_3$) 165.3 (C=O), 156.9 (C-4″), 144.2 (C-1″), 142.8 (C-1′), 130.2 (C-3′, C-5′), 130.1 (C-4′), 126.4 (C-2′, C-6′), 122.4 (C-2″, C-6″), 115.1 (C-3″, C-5″), 100.9 (C-3), 78.7 (C-1), 74.0 (C-6), 69.5 (C-5), 68.5 (C-8), 68.1 (α-CH_2), 31.6 (CH_2), 29.3 (C-9), 28.8 (C-10), 25.7, 25.6, 22.6 (CH_2), 14.1 (CH_3).

Results and Discussion

We first synthesized a series of compounds with a halogen or pseudo halogen head group, while the length of the terminal alkoxy chain was kept constant (Table 1). In the case of the fluorine compound **14b** we could observe a change of the helical pitch with increasing temperature, but the clearing point of 125.0 °C is too low to observe the complete inversion. The same holds true for the iodo compound **17b** and the thiocyanato compound **19b**, but in these cases, a strong concentration-dependent inversion of the helical pitch in contact with N4 was observed [sequence of textures in the contact area: cholesteric (Grandjean texture), nematic (schlieren texture), cholesteric (fan texture), nematic (schlieren texture). Since the unwinding of the helix was mainly a function of the concentration and a smectic A phase could not be observed, an unwinding of the helix as a pretransitional effect of a transition to a smectic A phase can be excluded as reason for this inversion effect.]. In addition compound **19b** shows a crystal–crystal interconversion to a crystalline phase resembling a soft crystal.

The compounds with chloro **15b**, bromo **16b** and azido **18b** terminal groups exhibited a helix inversion in the pure form, with inversion temperatures lying close togther at *ca.* 130 °C.

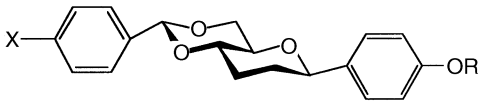
To elucidate the influence of volume effects, we synthesized **20b** and **21b** with a terminal methyl and isopropyl group. Neither compound **20b** nor **21b** showed an inversion of the helical pitch, and while the methyl compound still displayed a cholesteric phase besides a monotropic smectic A phase, we could only observe a smectic A phase in the case of a broad terminal isopropyl group.

Table 1 Data for compounds **13b–23b**

no.	X	recryst.[a] /°C	Cr/°C	S_A/°C	Ch/°C	T_i/°C	C
13b	H		105.8	—	61.4		
14b	F	48.0	113.8	—	125.0	>130.0	*b*
15b	Cl	89.0	128.8	—	143.0	127.0	
16b	Br		132.5	—	140.1	132.0	Tm_2 119.0 °C
17b	I	91.0	134.5	—	132.2		*c*
18b	N_3	83.0	118.2	—	145.2	123.0	
19b	NCS		80.7	—	97.0		*c,d*
20b	Me		118.0	95.9	136.1	—	
21b	Pr^i	20.0	88.3	121.1	—	—	Tm_2 85.0 °C Tm_3 79.0 °C
22b	$Me_3SiC{\equiv}C$	106.0	146.1	157.2	—	—	
23b	$HC{\equiv}C$	62.0	114.1	—	153.1	96.5	Tm_2 104.0 °C

[a]Abbreviations: recryst. = recrystallization; Cr = crystallization; Ch = cholesteric; S_A = smectic A; T_i = inversion temperature; Tm_x = melting points of additional crystalline modifications. [b]The inversion temperature is an extrapolated value. [c]Concentration-dependent helix inversion in contact with N4. [d]Cr_2 65.0 Cr_1 80.7 Ch 97.0 decomp., Cr_1 = soft crystals.

Table 2 Data for compounds **14a,b**, **16a–c** and **17a,b**



no.	X	OR	recryst. /°C	Cr/°C	Ch/°C	T_i/°C	C
16a	Br	OC_6H_{13}		144.9	151.7	110.0	
16b	Br	OC_8H_{17}		132.5	140.1	132.0	Tm_2 119.0 °C
16c	Br	$OC_{10}H_{21}$	70.0	128.0	136.5	>137.0	*a*
14a	F	OC_6H_{13}		119.3	135.2	124.0	
14b	F	OC_8H_{17}	48.0	113.8	125.0	>130.0	*a*
17a	I	OC_6H_{13}	99.0	148.8	137.5		*b*
17b	I	OC_8H_{17}	91.0	134.5	132.2		*b*

[a]The inversion temperature is an extrapolated value. [b]Concentration-dependent helix inversion in contact with N4.

Examining the synthesized trioxadecalin molecules discussed so far, it seemed that a polar terminal group might be necessary for the occurrence of a helix inversion. To verify this idea, we synthesized **23b** with an ethynyl head group, which we expected not to exhibit an inversion, in contrast to the same compound with a terminal cyano group. Contrary to our assumption, compound **23b** exhibited a pitch inversion at a temperature of 96.5 °C, indicating that the reasons for the occurrence of the cholesteric helix inversions have to be more complex than our simple supposition.

Moreover, we observed a second crystal modification of compound **23b**. The frequently observed polymorphism of crystal forms of the compounds synthesized in this work reflects the different stacking possibilities and may be the polymorphism of orientation possibilities. Unfortunately, we could not obtain crystals suitable for X-ray diffraction to elucidate the stacking possibilities.

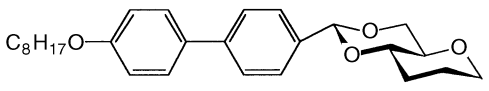
Compound **22b** with a trimethylsilylethynyl head group showed, as well as compound **21b**, only a smectic A phase indicating that this phase might be stabilized by a broad terminal group. A broad terminal group changes the molecular shape towards a cylinder; if the width of the terminal group is comparable to the width of the core, and favours therefore smectic phases.

If the terminal groups are arranged in order of increasing clearing temperature of the cholesteric phase and in consideration of the already described nitro, cyano and methoxy compounds, the following series is obtained: H < SCN < F < I < Me < Br < Cl < N_3 < NO_2 < OMe < ethynyl < CN.

To examine the effect of the length of the alkoxy chains we synthesized the bromo compounds **16a** and **16c** with a hexyloxy and a dexyloxy chain instead of the octyloxy chain of **16b.** The shortening of the alkoxy chain by two CH_2 groups led to a decrease of the inversion temperature by 22.0 °C and to an increase of the clearing temperature by 11.6 °C (Table 2). In the case of **16c**, with the extended chain, only a change of the helical pitch with increasing temperature could still be observed, since **16c** cleared at 136.5 °C before reaching the inversion point.

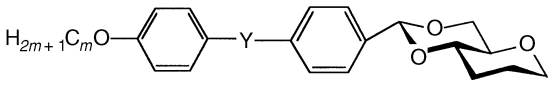
Since the shortening of the alkoxy chain led to a distinct decrease of the inversion temperature, it seemed to be interesting to synthesize the compounds analogous to **14b** and **17b**, but with a hexyloxy instead of an octyloxy chain, since in the

Table 3 Data for compound **33**



no.	Cr/°C	Ch/°C	C
33	122.9	96.0	N at T_C, Tm_2 100.6 °C

Table 4 Data for compounds **34**–**37**



no.	m	Y	recryst. /°C	Cr/°C	Ch/°C	C
34	8	C(O)-O		126.9	90.1	*a*
35	6	C(O)-O		146.6	96.6	*a*
36	8	O-C(O)	72.0	106.7	87.5	*a*, Tm_2 99.8 °C, Tm_3 91.7 °C
37	6	O-C(O)	57.0	122.5	90.9	*a*, Tm_2?, Tm_3?

[a]Concentration dependent helix inversion in contact with N4.

case of the latter only a change of the helical pitch could be observed because of the low clearing temperatures. The shortening of the alkoxy chain, in case of **14b**, indeed led to a sufficient drop of the inversion temperature, so that the pitch inversion was observed, while **17b** still showed only an inversion in contact with N4.

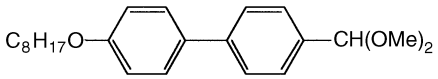
With the results obtained so far, it seems that the chiral trioxadecalin structure in the centre of the molecule is responsible for the occurrence of the cholesteric helix inversion, but at the same time an unsymmetrical substitution pattern is necessary: that is X must not be an alkoxy or alkyl chain and further X must not have a broad structure, since otherwise a smectic A phase will be stabilized, preventing the observation of the helix inversion.

In all the compounds discussed so far which show cholesteric helix inversion, the trioxadecalin structure was located in the centre of the molecule. The molecules **33**–**37** were synthesized to elucidate whether this is a necessary requirement.

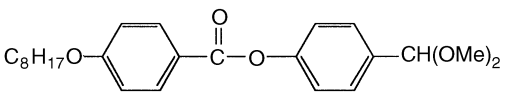
Compound **33** exhibited a monotropic cholesteric phase (fan texture at low temperatures) with a strong temperature-dependent helical pitch being just nematic (schlieren texture) at the clearing temperature of 96.0 °C (Table 3).

The introduction of a carboxy linkage between the two phenyl rings in **33** effects, almost independently from the orientation of the linkage, a small decrease in the clearing temperature (Table 4). All these compounds display cholesteric phases with a fan texture without visible changes of the texture with temperature. However, all of them show a concentration dependent helix inversion in contact with N4.

It is noteworthy that some of our dimethyl acetals used for the synthesis of the decalin system also showed mesogenic properties. The separation of the biphenyl system through a carboxy linkage effected in this case a decrease of the clearing point of the monotropic smectic A phase by 20 °C.



K 49.4 S_A 43.4 I, Tm_2 43.8



K 58.2 S_A 23.8 I, Tm_2 54.5

Conclusions

The space filling of the terminal groups is not the reason for the helix inversion since chloro and bromo compounds **15b** and **16a,b** exhibited an inversion whereas the methyl compound **20b** did not.

The polarity of the terminal group can be excluded as the cyano compound as well as compound **23b** with its ethynyl head group show an inversion of the helical pitch at a comparable temperature.

The chiral trioxadecalin structure does not need to be located directly in the centre of the molecule, since compounds **33**–**37** with a terminal decalin system also display helix inversions in contact with N4.

The concentration dependence of the helical pitch is stronger in most cases than the temperature dependence [the cholesteric phase in the contact preparation (fan texture) shows selective reflection and has a short helical pitch. The absolute change of the helical pitch going from the area in the contact preparation with a cholesteric phase to the area with a nematic phase is large, while the helical pitch is great and hence the absolute change quite low in the case of the compounds with *e.g.* a terminal nitro group[5] which show a helix inversion in the pure form on heating].

Orientation effects of the molecular axis being defined by the chiral molecular core[7] seem to be the reason for these inversion effects. Because of the different flexibility of the molecular core and the wing groups the direction of the mean molecular axis changes slightly with temperature, leading to a change of the effective chirality, which is a function of the mean molecular axis.

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