Synthesis and mesomorphic properties of calamitic malonates and cyanoacetates tethered to 4-cyanobiphenyls

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Abstract

4-Cyano-1,1′-biphenyl derivatives bearing ω-hydroxyalkyl substituents were reacted with methyl 3-chloro-3-oxopropionate or cyanoacetic acid, giving liquid-crystalline linear malonates and cyanoacetates. These compounds formed monotropic nematic phases at 62 ºC down to ambient temperature upon cooling from the isotropic liquid. The mesomorphic properties were investigated by differential scanning calorimetry, polarizing optical microscopy and X-ray diffraction (WAXS).

Introduction

Nematic liquid crystals display mesophases in which the molecules are oriented along one vector defined by the director axis, but with the molecular arrangement in random positional order [1]. Nematic phases typically display low viscosity [2-4]. Due to the long-range orientational order they reveal anisotropic properties. These features make nematic liquid crystals very attractive materials for electronics [5-8], for the construction of liquid crystal displays [9-11], or as anisotropic conductors [12,13]. Over the past few decades, a huge variety of organic calamitic compounds, which form nematic liquid crystals, have been synthesized and investigated [1,14].

Bulkin et al. were the first to investigate the phase behaviour of metal β-diketonate complexes such as 1 [15] (Scheme 1). Although they were not able to detect any mesophases, their study motivated others to examine the mesomorphic properties of β-diketonates in more detail [16]. Among the first examples of a nematic β-diketonate is the Cu complex 2 described by Haase [17-21]. In contrast to the various diketonato metallo-mesogens only a little information is available about the mesomorphic properties of metal-free diketones. Among the few examples are the nematic compounds 3 [22] and 4 [23,24] (Scheme 1).
The corresponding malonates and cyanoacetates are well known as suitable ligands for strong coordination of main-group and transition metals [25]. Benzylidene derivatives of malonic esters, so called swallow-tailed liquid crystals, were described as forming smectic phases [26]. However, most work on liquid-crystalline malonates has been devoted to C₆₀ fullerene dendrimers [27-31]. Only a few liquid crystalline cyanoacetates have been described so far. The first example, a dihydrazide, was reported by Schubert [32]. Furthermore some calamitic and bent-core mesogens derived from α-cyanocinnamic acid were described in the literature [33,34]. Therefore, we decided to explore the synthesis and mesomorphic properties of malonates and cyanoacetates tethered to calamitic 4-cyanobiphenyl units (Scheme 2).

During the first heating runs all compounds did not show the appearance of any liquid-crystalline phase, but melted without decomposition into isotropic liquids. It was observed that the melting points increased with an increase of the spacer length between 4-cyanobiphenyl and ester groups. Thus, melting points were recorded at 49.1 °C/63.4 °C for the series of 11a/b and at 89.0 °C/93.2 °C for the series of 13a/b, respectively (Table 1). The cyano group is a stronger electron-acceptor than the ester function, and thus the cyanoacetic ester molecules are more polarized than the corresponding malonates. Stronger dipole–dipole interactions for cyano esters led to an increase of their clearing points compared with malonates.

The obtained malonate and cyanoacetic esters 11a,b and 13a,b were subjected to differential scanning calorimetry (DSC) studies (Figure 1, Figure 2, and Table 1).

Results and Discussion
The syntheses of malonate and cyanoacetate derivatives 11, 13 are shown in Scheme 3. Starting from the corresponding diols 6a,b, 6-bromohexan-1-ol (7a) and 10-bromodecan-1-ol (7b) were obtained in moderate yields by bromination with aqueous HBr in toluene [35]. The bromides 7a,b were reacted with 4-cyano-1,1′-biphenyl (8) in acetone in the presence of K₂CO₃ giving compounds 9a,b, bearing C₆₀ or C₁₀-spacers, in 68% and 60% yield, respectively [36-38] after recrystallization from methanol (Scheme 3).

The malonate unit was attached by treatment of the compounds 9a,b with methyl 3-chloro-3-oxopropionate (10) in the presence of pyridine in CH₂Cl₂ to yield the malonates 11a,b in 57% and 65%, respectively, after column chromatography. In a parallel approach, the precursors 9a,b were converted to the corresponding cyanoacetates 13a,b by esterification of cyanoacetic acid (12) in the presence of DMAP and dicyclohexylcarbodiimide in CH₂Cl₂. After chromatography the cyanoacetates 13a,b were isolated as colourless solids in 59% and 41% yield.

The obtained malonate and cyanoacetic esters 11a,b and 13a,b were subjected to differential scanning calorimetry (DSC) studies (Figure 1, Figure 2, and Table 1).

During the first heating runs all compounds did not show the appearance of any liquid-crystalline phase, but melted without decomposition into isotropic liquids. It was observed that the melting points increased with an increase of the spacer length between 4-cyanobiphenyl and ester groups. Thus, melting points were recorded at 49.1 °C/63.4 °C for the series of 11a/11b and at 89.0 °C/93.2 °C for the series of 13a/13b, respectively (Table 1). The cyano group is a stronger electron-acceptor than the ester function, and thus the cyanoacetic ester molecules are more polarized than the corresponding malonates. Stronger dipole–dipole interactions for cyano esters led to an increase of their clearing points compared with malonates.
Scheme 3: Synthesis of malonate and cyanoacetates tethered to 4-cyano-biphenyl moieties.

**Figure 1:** DSC traces of 13a (heating/cooling rate 5 K/min).

**Figure 2:** DSC traces of 11a (heating/cooling rate 10 K/min).
The additional Cr→Cr transitions in the 2nd and 3rd heating curves (Figure 1 and Figure 2) are probably due to equilibration and the presence of keto-enol tautomers. Molecular geometry phase-behaviour relationships in keto-enamine/imino-enol tautomers of ferrocenophanes have been previously studied by Galyametdinov [39]. In the first cooling runs the appearance of nematic mesophases was observed for both series 11a,b and 13a,b. All compounds displayed small transition enthalpies in a range between −0.3 and −0.7 kJ/mol (Table 1) for the transition from the isotropic liquid to the corresponding mesophases. While Cr6-linked compounds displayed monotropic nematic mesophases at temperatures of 21 °C for 11a and 59 °C for 13a, their longer and more flexible C10-linked homologues showed higher transition temperatures at 36 °C for 11b and 62 °C for 13b upon cooling from the isotropic liquid. Due to supercooling, no crystallisation could be observed for compound 11a and, therefore, no mesophase range could be determined. But the second and third heating runs of 11a showed broad recrystallization peaks (Figure 2).

Polarizing optical microscope (POM) studies

POM observations of compounds 11a,b and 13a,b revealed textures typical for nematic phases, only upon cooling from the isotropic liquid (Figure 3 and Figure 4).

**Table 1: Phase-transition temperatures [°C] and enthalpies [kJ/mol] of 11 and 13.**

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*Cr crystalline; N nematic; I isotropic; ● phase was observed; – phase was not observed. Heating and cooling rate: 5 K/min. Heating and cooling rate: 10 K/min. Heating and cooling rate: 1 × 10 K/min. Another crystal-to-crystal transition (87.6 °C, 1.62 kJ/mol) was observed. Another crystal-to-crystal transition (67.7 °C, 1.62 kJ/mol) was observed. Another crystal-to-crystal transition (67.6 °C, 1.86 kJ/mol) was observed. A second crystal-to-crystal transition (78.1 °C, 21.0 kJ/mol) was observed.

**Figure 3:** Schlieren textures of 11a and 11b under crossed polarizers, upon cooling (cooling rate 5 K/min) from the isotropic liquid (magnification 200×): (A) 11a (20 °C), (B) 11a (14 °C), (C) 11b (29 °C).
Schlieren textures with fourfold brushes were observed for compound 13b at the transition from the isotropic liquid into the nematic phase. Quite similar textures were published by Dierking [40,41]. The areas without birefringence in Figure 3 and Figure 4 derive from homeotropic alignment of the molecules.

X-ray diffraction studies
The assignment of the nematic mesophases were exemplarily confirmed by wide-angle X-ray scattering (WAXS) experiments on compound 11a. Representative 2D diffractograms of the crystalline phase, the isotropic phase and the nematic phase are shown in Figure 5.

In the isotropic phase (Figure 5, part B) only a diffuse symmetric halo is observed. The diffraction pattern of 11a at 15 °C (Figure 5, part C) displays a halo split into two diffuse, crescent reflections, which is typical for nematic mesophases [42].

Conclusion
The mesogenic 4-cyano-1,1'-biphenyl group can be attached to either a malonate or a cyanoacetic ester scaffold by means of simple reaction sequences and with the aid of cheap chemical precursors. Linked ester molecules 11a,b and 13a,b have a distinct linear shape and easily form monotropic mesophases at ambient temperature upon cooling from the isotropic liquid. Following POM and X-ray studies, nematic mesophases could be assigned to all the described compounds 11a,b and 13a,b.

Experimental
General information
All reactions were carried out under a nitrogen atmosphere with Schlenk-type glassware. Solvents were dried and distilled under nitrogen prior to use. Flash chromatography was performed on silica gel, with grain size 40–63 μm (Macherey-Nagel).

The following instruments were used for physical characterization of the compounds. Elemental analyses: Carlo Erba Strumentazione Elemental Analyzer, Modell 1106. NMR: Bruker ARX-500 (1H, 500 MHz; 13C, 125 MHz). Assignments of the resonances are supported by 2D experiments and chemical shift calculations. 1H and 13C NMR spectra were referenced to an internal Me4Si (TMS) standard. IR: Bruker 22 FT-IR spectrometer with a golden-gate single-reflection diamond ATR system. MS: Bruker Daltonics mikro-TOF-Q (ESIMS). Differ-
6-[(4'-cyano-[1,1'-biphenyl]-4-yl)oxy]hexyl methyl malonate (11a)

Pyridine (150 mg, 1.69 mmol) and then methyl 3-chloro-3-oxopropionate (10) (114 mg, 0.84 mmol) were added over 10 min at 0 °C under a N2 atmosphere to a solution of 4’-((6-hydroxyhexyl)oxy)-[1,1'-biphenyl]-4-carbonitrile (9a) (500 mg, 1.69 mmol) in abs. CH2Cl2 (5 mL). The reaction mixture was stirred at 0 °C for 1 h, then for 2 h at rt. The reaction was quenched with 1 N H2SO4 (3 mL). The aqueous layer was extracted with CH2Cl2 (3 × 5 mL). The combined organic layers were washed with brine (40 mL), dried over MgSO4 and evaporated under reduced pressure. The crude product was purified by column chromatography on silica gel (hexanes/EtOAc 20:1) to give 11a as a colourless solid (188 mg, 0.48 mmol, 65%). Mp 63.4 °C; found: C, 71.82; H, 7.37; N, 3.10; Anal. calcd for C25H22NO5: C, 71.82; H, 7.37; N, 3.10; found: C, 71.66; H, 7.34; N, 3.03; Rf 0.68 (hexanes/EtOAc 2:1).

6-[(4'-cyano-[1,1'-biphenyl]-4-yl)oxy]hexyl 2-cyanoacetate (13a)

To a solution of 4’-((6-hydroxyhexyl)oxy)-[1,1'-biphenyl]-4-carbonitrile (9a) (100 mg, 338 μmol) in abs. CH2Cl2 (2.5 mL) were added sequentially a solution of cyanoacetic acid (12) (32 mg, 376 μmol) in EtOAc (0.4 mL), a solution of DMAP (12 mg, 98 μmol) in abs. CH2Cl2 (0.8 mL) and then at 0 °C a solution of dicyclohexylcarbodiimide (37 mg, 187 μmol) in abs. CH2Cl2 (2.5 mL). The reaction mixture was stirred at rt for 7.5 h, then evaporated under vacuum. The crude product was purified by column chromatography on silica gel (hexanes/EtOAc 12:1) to give 13a as a colourless solid (72 mg, 190 μmol, 59%). Mp 89.0 °C; found: C, 71.82; H, 7.37; N, 3.10; Anal. calcd for C25H22NO5: C, 71.82; H, 7.37; N, 3.10; found: C, 71.66; H, 7.34; N, 3.03; Rf 0.68 (hexanes/EtOAc 2:1).

10-[(4’-cyano-[1,1'-biphenyl]-4-yl)oxy]decyl methyl malonate (11b)

The ester 11b was obtained by the same procedure as described above for 11a from 4’-(10-hydroxyhexyl)oxy)-[1,1'-biphenyl]-4-carbonitrile (9b) (560 mg, 1.60 mmol), methyl 3-chloro-3-oxopropionate (10) (109 mg, 0.80 mmol) and pyridine (126 mg, 1.60 mmol) in abs. CH2Cl2 (5 mL). The crude product was purified by column chromatography on silica gel (gradient: hexanes/EtOAc 20:1, then 15:1) to give 11b as a colourless solid (240 mg, 0.53 mmol, 65%). Mp 63.4 °C; 1H NMR (500 MHz, CDCl3) δ 1.31–1.35 (m, 10H, 6-H, 7-H, 8-H, 9-H, 10-H), 1.44–1.50 (m, 2H, 11-H), 1.61–1.67 (m, 2H, 5-H), 1.77–1.83 (m, 2H, 12-H), 3.38 (s, 2H, 2-H), 3.75 (s, 3H, OCH3), 4.00 (t, J = 6.5 Hz, 2H, 13-H), 4.14 (t, J = 6.8 Hz, 2H, 4-H), 6.98–6.99 (m, 2H, 2’-H), 7.51–7.53 (m, 2H, 3’-H), 7.63–7.64 (m, 2H, 6’-H), 7.68–7.69 (m, 2H, 7’-H) ppm; 13C NMR (125 MHz, CDCl3) δ 25.7 (C-6), 25.8 (C-7), 28.4 (C-5), 29.0 (C-8), 41.4 (C-2), 52.5 (OCH3), 65.6 (C-4), 67.8 (C-9), 110.0 (C-’8’), 115.0 (C-’2’), 119.1 (CN), 127.0 (C-’6’), 128.3 (C-’3’), 131.3 (C-’5’), 132.6 (C-’7’), 145.2 (C-’4’), 159.6 (C-’1’), 162.9 (C-3) ppm; ATR–FTIR: 2927 (m), 2854 (w), 2225 (m), 1746 (m), 1603 (m), 1494 (m), 1383 (m), 1249 (s), 1180 (s), 1103 (s), 1014 (w), 903 (m), 723 (s); IR: 2927 (m), 2854 (w), 1746 (m), 1603 (m), 1494 (m), 1383 (m), 1249 (s), 1180 (s), 1103 (s), 1014 (w), 903 (m), 723 (s); ESIMS (m/z): 472.2 [M + Na]+, 452.2 [M + H]+; Anal. calcd for C25H22NO5: C, 71.82; H, 7.37; N, 3.10; found: C, 71.66; H, 7.34; N, 3.03; Rf 0.56 (hexanes/EtOAc 2:1).
as a colourless solid (57 mg, 140 μmol, 41%). Mp 93.2 °C; 1H NMR (500 MHz, CDCl3) δ 1.32–1.36 (m, 10H, 6-H, 7-H, 8-H, 9-H, 10-H), 1.44–1.50 (m, 2H, 11-H), 1.65–1.71 (m, 2H, 5-H), 1.78–1.83 (m, 2H, 12-H), 3.44 (s, 2H, 2-H), 4.00 (t, J = 6.5 Hz, 2H, 13-H), 4.20 (t, J = 6.9 Hz, 2H, 4-H), 6.98–6.99 (m, 2H, 2'-H), 7.51–7.53 (m, 2H, 3'-H), 7.63–7.64 (m, 2H, 6'-H), 7.68–7.69 (m, 2H, 7'-H) ppm; 13C NMR (125 MHz, CDCl3) δ 24.7 (C-2), 25.6 (C-6), 26.0 (C-11), 28.3 (C-5), 29.11 (C-12), 29.21, 29.32, 29.36, 29.40 (C-7, C-8, C-9, C-10), 67.1 (C-4), 68.1 (C-13), 110.0 (C-8'), 113.0 (C-1), 115.0 (C-2'), 119.1 (CN), 127.0 (C-6'), 128.3 (C-3'), 131.3 (C-5'), 132.5 (C-7'), 145.2 (C-4'), 159.7 (C-1'), 162.9 (C-3) ppm; ATR–FTIR ν: 2928 (m), 2955 (w), 2225 (w), 1747 (m), 1603 (m), 1494 (m), 1250 (m), 1180 (m), 903 (s), 725 (s); ESIMS (m/z): 457 [M + K]+, 441.2 [M + Na]+, 436.2, 419.2 [M + H]+; Anal. calc. for C25H30N2O6: C, 74.61; H, 7.22; N, 6.69; found: C, 74.04; H, 7.18; N, 6.54; Rf 0.58 (hexanes/EtOAc 2:1).

Supporting Information

Supporting Information File 1
Full experimental procedures and DSC traces of 11b and 13b. [http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-8-40-S1.pdf]

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