Chirality

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Spontaneous Mirror-Symmetry Breaking in Isotropic Liquid Phases of Photoisomerizable Achiral Molecules

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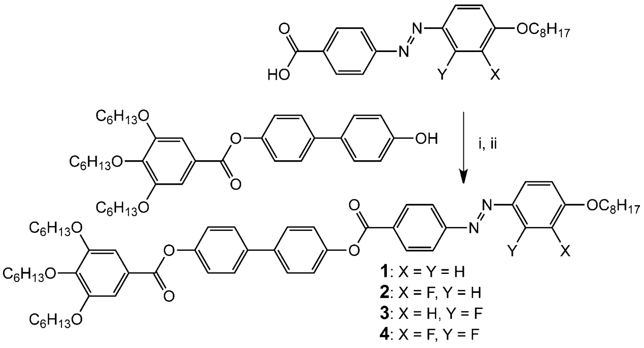
Abstract: *Spontaneous mirror-symmetry breaking is of fundamental importance in science as it contributes to the development of chiral superstructures and new materials and has a major impact on the discussion around the emergence of uniform chirality in biological systems. Herein we report chirality synchronization, leading to spontaneous chiral conglomerate formation in isotropic liquids of achiral and photoisomerizable azobenzene-based rod-like molecules. The position of fluorine substituents at the aromatic core is found to have a significant effect on the stability and the temperature range of these chiral liquids. Moreover, these liquid conglomerates occur in a new phase sequence adjacent to a 3D tetragonal mesophase.*

The observation by Pasteur of chiral conglomerate formation during the crystallization of tartrates marked the birth of stereochemistry.[1] Since then, symmetry breaking in racemic mixtures of chiral molecules and the synchronization of chiral conformers of achiral molecules during crystallization in chiral space groups have been found in numerous cases.[2] Additionally, enantiophobic chirality discrimination between permanently chiral molecules and chirality synchronization of transiently chiral conformers[3] on surfaces[4] and in fibrous aggregates have been well documented.[5] The spontaneous development of chiral conglomerates has also been observed in soft-matter systems, especially in liquid-crystalline (LC) phases of achiral bent-core molecules,[6–9] and this has considerable impact on the problem of the development of uniform chirality in biotic systems.[10] Surprisingly, spontaneous mirror-symmetry breaking was recently found even in isotropic liquids of achiral molecules, which form conglomerates of two immiscible chiral liquids with opposite handedness (labelled here as $\mathrm{Iso}_1^{[*]}$ phases).[11,12] Formation of these liquid conglomerates obviously requires a locally twisted cluster structure of the liquids, providing cooperativity and acting as a template for chirality synchronization of the conformers.[11] However, the few known $\mathrm{Iso}_1^{[*]}$ phases are metastable, with only few exceptions, meaning that they could only be detected on cooling if the formation of the competing crystalline phases is suppressed. Moreover, they were found at high temperatures around 210 °C, where decomposition becomes an issue, thus making their investigation and application difficult.

Herein we report the first chiral liquids formed by photoisomerizable achiral azobenzene-derived compounds **1**–**4** (Scheme 1). These chiral liquids have $\mathrm{Iso}_1^{[*]}$ phases in convenient temperature ranges. These azo-functionalized materials are of special interest because of their photosensitive nature, leading to photoisomerizable chiral liquids which could be addressed by linearly or circularly polarized light and thus used for optical, optoelectronic, and sensing devices.[13–15]



Scheme 1. Synthetic route to polycatenar molecules **1**–**4**. Reagents and conditions: i) $SOCl_2$, DMF, reflux; ii) Et_3N, pyridine, CH_2Cl_2, reflux. DMF = dimethylformamide.

The synthetic pathway to compounds **1**–**4** is shown in Scheme 1. Detailed synthetic procedures and analytical data are reported in the Supporting Information and the transition temperatures are summarized in Table 1.

Figure 1, taken as a representative example, shows the differential scanning calorimetry (DSC) curves obtained on heating and cooling of compound **1** (X = Y = H). This compound transforms into a low birefringent tetragonal mesophase (Tet) at $T = 121\,°C$, which melts into an isotropic liquid at $T = 175\,°C$. There are two isotropic liquid phases ($\mathrm{Iso}_1^{[*]}$ and Iso) with a phase transition between them at $T = 189\,°C$ on heating (see Table 1; Figure 1). The achiral liquid

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Table 1: Mesophase types, phase-transition temperatures (T/°C), and transition enthalpies [ΔH/kJ mol^{-1}] of compounds **1**–**4**.[a]

Compd.	Phase sequence
1	Heating: Cr 121 [35.1] Tet 175 [0.7] Iso$_1^{[*]}$ 189 [0.2] Iso Cooling: Iso 185 [0.1] Iso$_1^{[*]}$ 163 [0.3] Tet 76 [33.7] Cr
2	Heating: Cr 137 [45.7] Tet 158 [0.5] Iso$_1^{[*]}$ 169 [< 0.05] Iso Cooling: Iso 162 [< 0.05] Iso$_1^{[*]}$ 150 [0.4] Tet 112 [45.9] Cr
3	Heating: Cr 121 [36.9] SmA 155 [0.3] N 170 [0.2] Iso Cooling: Iso 168 [0.4] N 154 [0.1] SmA 80 [31.3] Cr
4	Heating: Cr 128 [47.6] Iso$_1^{[*]}$ 144 [< 0.05] Iso Cooling: Iso 139 [< 0.05] Iso$_1^{[*]}$ 114 [2.4] Tet 100 [36.4] Cr

[a] Peak temperatures as determined from first heating and first cooling DSC scans with rate 10 K min^{-1}. Abbreviations: Cr = crystalline solid; Tet = tetragonal 3D mesophase; SmA = smectic A phase; N = nematic phase; Iso$_1^{[*]}$ = chiral isotropic conglomerate liquid; Iso = achiral isotropic liquid.

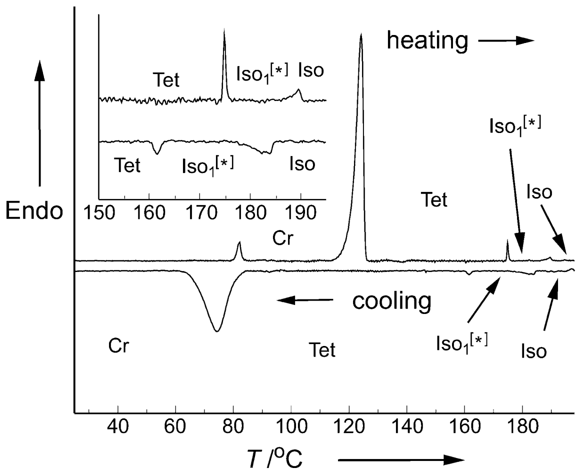

Figure 1. DSC heating and cooling curves (10 K min^{-1}) measured for **1**. Inset: Expanded temperature ranges (150–195 °C) on heating and cooling.

(Iso) as well as the chiral conglomerate liquid (Iso$_1^{[*]}$) appears dark (optically isotropic) between crossed polarizers and both have low viscosity and easily flow under gravity. However, in the temperature range of the Iso$_1^{[*]}$ phase, occurring below 189 °C, uncrossing the polarizers by a small angle (circa 2–5°) in the clockwise or anticlockwise direction leads to the appearance of dark and bright domains. After rotating the analyzer by the same angle in the opposite direction, the dark and bright domains are reversed (Figure 2 a,b). Rotating the sample between crossed polarizers does not lead to any change, indicating that the distinct regions represent optically active domains rotating the plane of polarized light into opposite directions. The Iso$_1^{[*]}$–Iso phase transition is associated with a small enthalpy change of 0.2–0.3 kJ mol^{-1}. The shape of the peak, being relatively sharp at the high-temperature end and having a significant tailing towards the low-temperature side is typically detected for this Iso–Iso$_1^{[*]}$ transition[11,12] (Figure 1, inset).[16]

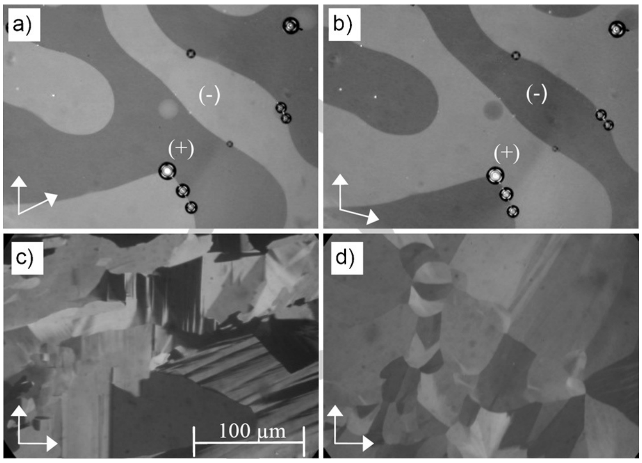

Figure 2. Textures of compounds **1** and **4** between nontreated glass substrates (thickness ≈ 25 µm). a) Compound **1** in the Iso$_1^{[*]}$ phase at $T = 180$ °C after rotating one polarizer by circa 5° from the crossed position in the anticlockwise and b) in the clockwise direction. Dark and bright domains are evident, indicating the presence of a conglomerate of domains with opposite chirality. The conglomerate textures observed for these isotropic liquids were found to be independent of the used substrates, also in homeotropic and planar cells, as long as any contamination with traces of chirality is strictly excluded; in this case unequal areas or only one sign of handedness would be formed. c) Tet phase of compound **1** at $T = 160$ °C. d) Tet phase of compound **4** at $T = 113$ °C.[21] The direction of the polarizers is indicated by arrows. See Figure S12 for a color version of this figure.

On cooling, the liquid–liquid transition between the achiral Iso phase and the chiral conglomerate liquid (Iso$_1^{[*]}$) takes place at $T = 185$ °C, and upon further cooling a mesophase is formed at $T = 163$ °C, indicated by the rapid growth of a low birefringent mosaic-like texture (see Figure 2 c). This mesophase is highly viscous and does not flow even under medium mechanical stress, which is indicative of a mesophase with a 3D lattice. The formation of this phase from the adjacent Iso$_1^{[*]}$ phase is associated with a small transition enthalpy of only $\Delta H \approx 0.3$ kJ mol^{-1} (Table 1). Despite the solid-like crystalline optical appearance, XRD investigations show a completely diffuse wide-angle scattering with a maximum at $d = 0.45$ nm, not very distinct from that in the Iso phases, thus confirming that the individual molecules have no fixed positions (Figure 3 a, inset).

There are numerous sharp reflections in the small-angle range (Figure 3 b; Table S1 in the Supporting Information) which can be indexed to a tetragonal 3D lattice (Tet). In previous work tetragonal mesophases were observed as birefringent LC phases, often accompanying bicontinuous cubic phases of rod-like molecules.[17–19] A tetragonal phase was also reported for bent-shaped molecules.[20] There are different subtypes of tetragonal phases with distinct lattice types, but the structures and the reasons for their formation have not been well understood. Unfortunately, the exact symmetry of the lattice could not be determined from powder XRD patterns and the oriented diffractions could not be achieved at the current stage. The highest symmetry that fits the diffraction pattern is $P4/mmm$, though a $P4_222$ lattice could also be possible. The lattice parameters ($a = 13.9$ and $c = 18.9$ nm) are much larger than the molecular length ($L_{\text{mol}} = 4.9$ nm in the most stretched conformation with all-*trans* alkyl chains) and indicate a complex structure of this

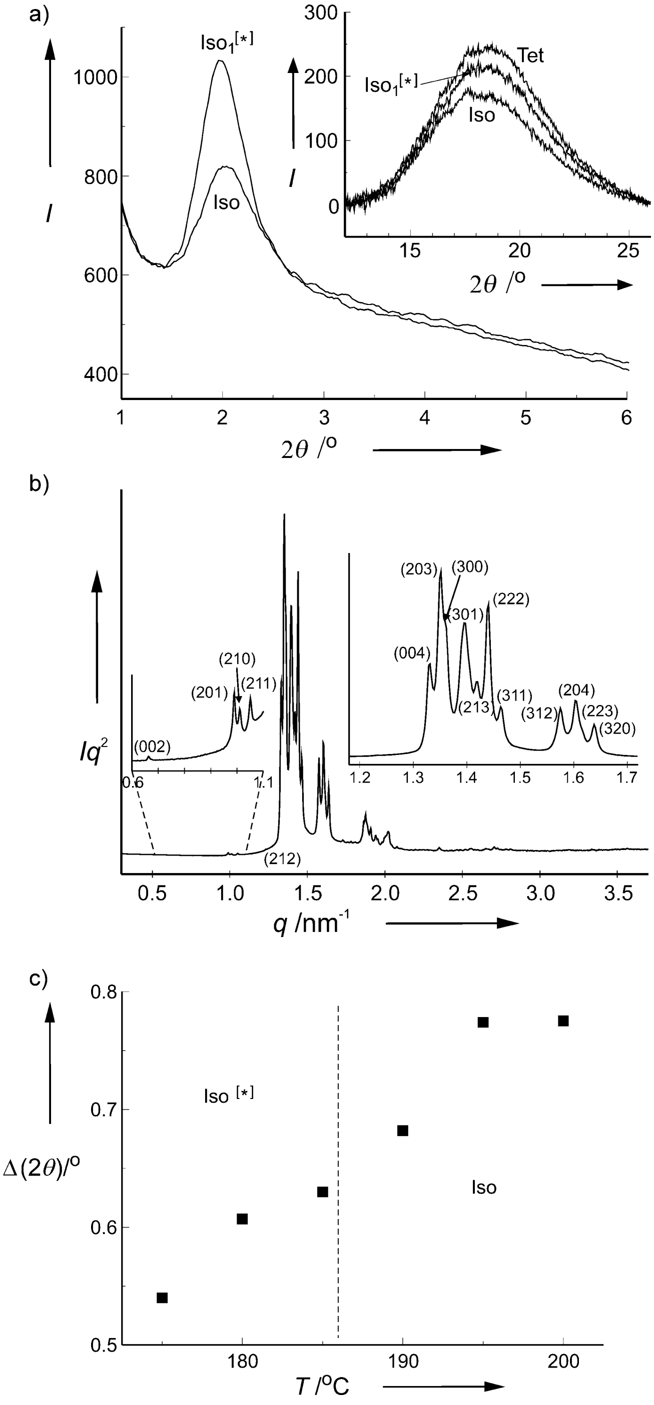

Figure 3. XRD data of compound **1**: a) small-angle and wide-angle (inset) XRD diffractograms at different temperatures for the Iso phase at $T=195\,°C$, Iso$_1^{[*]}$ phase at $T=180\,°C$, and Tet phase at $T=170\,°C$; b) SAXS diffractogram of the Tet phase at $T=160\,°C$ with indexation; and c) full width at half maximum (FWHM) of the small-angle scatterings ($\Delta(2\theta)$; fitted using Lorentzian line shapes) depending on temperature as observed in the isotropic liquid phases.

mesophase with about 2500 molecules per unit cell (see the Supporting Information). There is no indication of chirality in the Tet phases of compounds **1**, **2**, and **4** but this could probably be hidden under the birefringence and thus might not be detectable by optical methods.[21]

Modification of the parent structure **1** by introducing one lateral fluorine substituent (X = F, compound **2**) on the terminal benzene ring next to the alkoxy chain does not change the phase sequence, but reduces the range of the Tet phase and narrows the Iso$_1^{[*]}$ range (see Table 1). A further reduction of the transition temperatures was achieved by introducing two fluorine atoms (X = Y = F, compound **4**; see Table 1 and Figure 2d). Changing the position of the single fluorine atom from X to Y (X = H, Y = F, compound **3**) results in a completely different behavior, where the Tet and Iso$_1^{[*]}$ phases are removed and replaced by lamellar (SmA) and nematic (N) LC phases (Figure S11). In compound **3** the larger F atom (compared to H) in the 2-position (Y = F) is pointing to the center of the molecule. This slightly reduces the imbalance of interfacial area between rigid cores and alkyl-chain periphery, thus leading to decreased interface curvature and the formation of SmA and N phases.

In contrast, the F substituent at the peripheral 3-position (that is, X = F) contributes to an increase in the interface curvature[22] and thus favors the Tet and Iso$_1^{[*]}$ phases for compound **2** and for the disubstituted compound **4**, which has F substituents in both the 2- and 3-positions (X = Y = F; Table 1). Compound **4** behaves similar to the nonsubstituted compound **1**, but forms the Iso$_1^{[*]}$ phase at much lower temperature and in a wider temperature region. Thus, fluorination provides a tool for tailoring mirror-symmetry breaking in liquids.

XRD investigation of the Iso phases was performed for compound **1**. As shown in Figure 3a, in both Iso phases there is a diffuse small-angle scattering. The position of the maximum of the small-angle scattering is at $d=4.3$–4.4 nm, corresponding approximately to the molecular length ($d/L_{\mathrm{mol}}=0.87$–0.90). This indicates that the Iso$_1^{[*]}$ phase has a cybotactic structure. The cybotactic clusters appear to have a helical or a twisted lamellar local structure acting as a template for helical molecular packing with synchronization of chiral conformations. The full width at half maximum of the small-angle scattering changes continuously without a visible step at the Iso–Iso$_1^{[*]}$ transition, indicating a continuous growth of the size of the cybotactic clusters with decreasing temperature, being in the range of 28 nm at the transition (see Figure 3c). With growing cluster size on decreasing temperature, chiral fluctuations in the achiral Iso phase increase and become long-range at the phase transition. By chirality synchronization of molecular conformations, a denser packing is achieved, giving rise to the detected enthalpic gain. Helical conformations result from the twist of the COO groups in the phenylbenzoate units[6c] and probably also from the twist of the biphenyl core. As the liquid state is retained, conformational disorder and molecular motions are partly retained at the transition and thus the overall entropic penalty of this process is decreased. Therefore, the enthalpic gain of chirality synchronization can exceed the entropic penalty of demixing of the enantiomorphic conformers of these relatively large molecules.[11,23,24] At the Iso$_1^{[*]}$–Tet transition the local clusters fuse to a long-range 3D structure forming the tetragonal lattice.

Figure 4 shows the UV/Vis spectra of compound **1** in chloroform solution. For the freshly prepared sample an

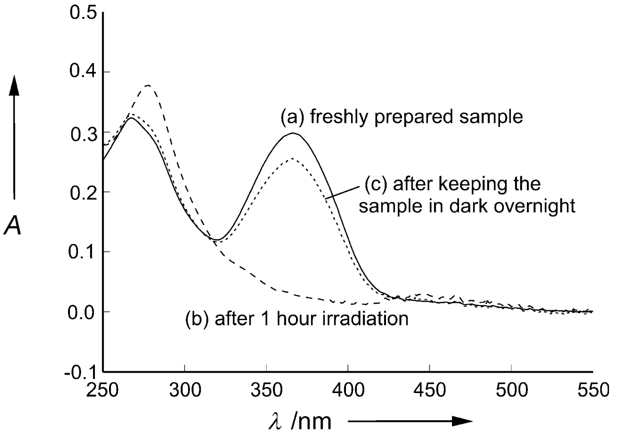

Figure 4. UV/Vis spectra of compound **1** dissolved in chloroform at 25 °C.

absorption band maximum was detected at $\lambda = 367$ nm as a result of a π–π^* transition (solid line).[25] After irradiation for one hour with UV light ($\lambda = 365$ nm), the absorption band at 367 nm disappeared (dashed line),[26] indicating that the *trans* isomer has completely transformed to the less stable *cis* isomer. After keeping the solution in the dark overnight, thermal relaxation to the *trans* isomer was nearly complete (dotted line).

In summary, we report the first azobenzene-based polycatenar compounds showing spontaneous breaking of mirror symmetry by chirality synchronization in the isotropic liquid state. Structural modifications by fluorination of the molecular core lead to compounds with lower transition temperatures and broaden the temperature ranges of the corresponding symmetry broken fluids. The photosensitive azobenzene unit may render this class of compounds suitable for potential applications in chirality switching and phase modulation by interaction with light.[27]

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