Light-driven molecular motors and switches

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Chapter 7
Light-Controlled Supramolecular Helicity of a Polymeric Liquid Crystalline Phase

Control over the preferred helical sense of a poly(n-hexyl isocyanate) using a single light-driven molecular motor that is covalently attached at the polymer’s terminus has been accomplished in solution via a combination of photochemical and thermal isomerizations. In this chapter, it is reported that after redesigning the photochromic unit to a thermally bi-stable chiroptical molecular switch, the chiral induction to the polymer’s backbone is significantly improved and the handedness of the helical polymer is addressable by irradiation with two different wavelengths of light. Moreover, the transmission of the chiral information, via the macromolecular level of the polyisocyanate, further to the supramolecular level of a lyotropic cholesteric liquid crystalline phase consisting of these stiff, rod-like polymers, is demonstrated. This allows the magnitude and sign of the supramolecular helical pitch of the liquid crystal film to be fully controlled by light.*

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7.1 Introduction

Liquid crystals (LCs) are particularly interesting materials with respect to the amplification of chiral information, due to their sensitivity to small molecular perturbations. Controlling the magnitude and sign of the supramolecular chiral organization of a cholesteric LC has been shown to be possible in the case of low molecular weight LCs. For instance, this has been demonstrated via the addition of bi-stable molecular switches as dopants to the LC material, as these switches can alter their shape in reaction to external stimuli (for instance light or heat), resulting in a change in the interactions between the dopants and the LC host molecules. Aggregation of rigid rod-like polymers, e.g. the polyisocyanates described in the previous chapter, in a sufficiently concentrated solution also leads to the formation of a LC phase. External control of the helical organization of these polymeric LCs has been demonstrated by adjusting the magnitude of the helical pitch using photo-switchable units introduced in the polymer’s side chains. With the system described in Chapter 6, it is possible to control the preferred macromolecular helical handedness using a photo-switch attached at the polymer’s terminus. It is expected that the supramolecular helicity of an LC matrix formed by these functionalized polymers is also controllable by the photo-switch attached to the polymer.

The system described in Chapter 6 suffered from a few drawbacks, however. By using a light-driven molecular motor as a four-state switch, by control of the exact composition of the mixture of isomers and the associated stereo-induction towards the polymer chain upon irradiation becomes a highly complex process. After one rotary cycle of the motor, a mixture of the different isomers is obtained due to the non-perfect PSSs. In the work described in this chapter, therefore first the photochromic unit is re-designed, to allow it to operate as a thermally bi-stable chiroptical molecular switch. The helical polymer can now be switched between a predominant P and M conformation using two different wavelengths of light, in principle over an infinite number of cycles. Serendipitously, it was found that hereby also the stereoinduction to the polymer’s backbone is significantly improved. Moreover, by the hierarchical transmission of chiral information from the molecular level of a chiroptical molecular switch, via the macromolecular level of a helical polymer, to the supramolecular level of a cholesteric liquid crystalline phase, this supramolecular helicity of the LC material can be controlled with the photo-switch (Figure 7.1). Via the photo-induced switching of the preferred helical twist sense of the helical polymer, the magnitude and sign of the supramolecular helical pitch of a lyotropic cholesteric liquid crystalline phase formed by these
helical, rod-like polymers can be fully controlled by irradiation with different wavelengths of light.

**Figure 7.1** Schematic representation of the hierarchical transmission of chiral information from the molecular level of a chiroptical switch molecule, via the macromolecular level of a polyisocyanate, to the supramolecular level of a cholesteric LC phase.

### 7.2 A Benzamide Functionalized Chiroptical Switch

#### 7.2.1 Molecular Design

Unidirectional rotation with the molecular motor system attached at the polymer chain’s terminus in the previously reported poly(\(n\)-hexyl isocyanate) 1-PHIC is achieved in a four step switching cycle by a combination of two photochemically induced *cis-trans* isomerizations, each followed by an essentially irreversible and fast thermal isomerization (Scheme 7.1). At room temperature, these thermal isomerizations take place on the time-scale of minutes (\(t_{1/2} = 3.2 \text{ min}\)). This makes control of the exact composition of the mixture of isomers and the associated chiral induction towards the polymer chain upon irradiation of 1-PHIC a highly complex process.
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Scheme 7.1 Photochemical and thermal isomerizations for previously reported chain-end molecular motor functionalized 1-PHIC.

In order to obtain better control over the stereo-induction towards the helical polymer, the photochromic unit attached at the polymer chain’s terminus first was redesigned into a photochemically bi-stable chiroptical switch with two thermally stable states (3-PHIC in Figure 7.2). By attaching the polymer chain to the upper half of the molecule in 3-PHIC (Figure 7.2a) instead of to the lower-half as was the case in 1-PHIC, a symmetrical fluorenyl-based lower-half is obtained while positioning the polymer well in the fjord region of the switch unit. As the two thermally stable isomers in the rotary cycle (Scheme 7.1), as well as the two unstable isomers, are now degenerate, this effectively reduces the number of possible isomers from four to only two. The molecular motor now operates as a chiroptical switch with two states: (2’S)-(M)-trans-1-PHIC, which after a photochemically induced cis-trans isomerization of the central double bond is converted to (2’S)-(M)-3-PHIC, resulting in an inversion of the intrinsic helical shape of the molecule from P to M (Figure 7.2). In 3-PHIC, one state induces a preferred M helicity, and the other induces a preferred P helicity of the polymer backbone. Moreover, using two different wavelengths of light, the two states of the chiroptical switch are fully photo-addressable.

The thermal helix inversion that follows the photochemical isomerization (step 2 and step 4 in Scheme 7.1), which involves the passage of both the naphthyl moiety and the methyl substituent in the upper half of the molecule past the lower half,
reverts the molecule to the stable isomer with an intrinsic $P$ helical shape. In order to obtain two thermally bi-stable states and create a system that is fully photo-addressable, this thermal helix inversion step needs to be blocked. Therefore, the five-membered ring in the upper-half of the motor molecule connected to the central double bond in $1$-PHIC was changed to a six-membered ring in $3$-PHIC. It was reasoned that in $3$-PHIC, the naphthyl moiety in the upper-half of the molecule is pushed towards the lower-half, hampering the passage of this group along the planar and rigid fluorenyl-based lower-part during the thermal helix inversion step, resulting in a strongly increased energy barrier for this thermal isomerization. The presence of the amide substituent at a position on the naphthalene in the upper-half of the molecule where it points towards the lower-half probably results in an additional raise of this energy barrier. The photochemically induced isomer can however be converted back to the original isomer ($2'S$)-($P$)-$3$-PHIC by irradiation with visible ($\lambda >480$ nm) light, as at these wavelengths only ($2'S$)-($M$)-$3$-PHIC absorbs ($\text{vide infra}$).

![Figure 7.2](image)

**Figure 7.2** a) Benzamide functionalized chiroptical molecular switch $2$, chain-end chiroptical switch functionalized poly($n$-hexyl isocyanate) $3$ and $N$-acylated chiroptical molecular switch $4$ and b) schematic representation of the reversible inversion of the preferred helical twist sense of a polymer backbone by a chiroptical molecular switch present at the terminus. ($2'S$)-($P$)-$3$-PHIC induces a preferred $M$ helical twist of the polymer backbone. UV irradiation ($\lambda = 365$ nm) yields ($2'S$)-($M$)-$3$-PHIC, resulting in an induced preferred $P$ helicity of the polymer chain. Subsequent irradiation with visible light ($\lambda >480$ nm) reverts the system to ($2'S$)-($P$)-$3$-PHIC with a preferred $M$ helicity of the polymer.

As a result of these changes in design, $3$-PHIC can be switched between two states that are fully photo-addressable and thermally stable (Figure 7.2b). ($2'S$)-($P$)-$3$-PHIC is anticipated to induce a preference for one particular helical twist sense of the polymer backbone, as the fluorenyl moiety of the lower half of the molecule

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resides at one specific side of the polymer chain. In (2'S)-(P)-cis-1-PHIC, in which a preferred $M$ helical twist sense of the polymer backbone is induced, the upper half of the motor molecule resides on the same side of the polymer chain as the fluorenyl-based lower-half of the chiroptical switch in (2'S)-(P)-3-PHIC. Therefore, this isomer of the chiroptical switch is also expected to induce a preferred $M$ helical twist sense of the polymer's backbone. In (2'S)-(M)-3-PHIC, the fluorenyl-based lower-half is present at the other side of the polymer chain, which therefore should induce a preferred $P$ helical twist sense of the polymer backbone.

### 7.2.2 Synthesis

The most important step in the synthetic route towards the envisioned chiroptical switch 2, bearing a benzamide functionality to be used as an initiator of the isocyanate polymerization, is the formation of the sterically overcrowded central olefinic bond by coupling the two halves of the molecule using a Staudinger type diazo-thioketone reaction 5 (Scheme 7.2). To avoid problems with the amide functionality arising from the harsh conditions involved with the synthesis of the upper-half thioketone precursor, the benzamide functionality was introduced in the last step of the synthesis via well-precedented palladium-catalyzed amidation conditions developed by Buchwald and coworkers.  

![Scheme 7.2 Retrosynthesis for 2.](image)

Synthesis of ketone precursor 13 was feasible in four steps (Scheme 7.3). First, following a procedure described by Diederich and coworkers, 2,7-naphthalenediol 8 was transformed into 7-bromo-naphthalen-2-ol 9 using PPh$_3$-Br$_2$. Subsequently, alkylation using tosylate 10 in refluxing DMF yielded compound 11, which, by oxidation of the terminal primary alcohol, was converted to acid 12. Regioselective ring-closure of the acid was achieved in polyphosphoric acid at elevated temperatures, yielding ketone 13.

After the conversion of ketone 13 to the corresponding thioketone 6 by treatment with Lawesson’s reagent, the diazo-thioketone coupling using diazofluorenone 7 provided episulfide 14 in 33% yield over the two steps (Scheme 7.4). Thioketone 6
proved to be rather unstable and was used directly after a quick purification by flash column chromatography. Desulfurization of 14 by triphenylphosphine yielded alkene 5, which was then used in the palladium-catalyzed amidation reaction\(^6\) to introduce the benzamide functionality. The structure of 2 was confirmed by X-ray analysis (\textit{vide infra}). Enantioresolution of 2 was achieved by CSP-HPLC (Chiralpak OD, \textit{n}-heptane:iso-propanol = 95:5). Assignment of the absolute configuration was done by comparison with the CD spectra of related compounds.\(^8\)

\begin{scheme}
\centering
\includegraphics[width=\textwidth]{scheme3}
\caption{Synthesis of upper half ketone precursor 13.}
\end{scheme}

\begin{scheme}
\centering
\includegraphics[width=\textwidth]{scheme4}
\caption{Synthesis of benzamide-functionalized chiroptical switch 2.}
\end{scheme}
7.2.3 Photochemical Isomerization Studies

The photoisomerizations of 2 (Scheme 7.5) were studied using UV/vis, circular dichroism (CD) and $^1$H NMR spectroscopy. Irradiation of a sample of (2’S)-(P)-2 in Et$_2$O at 20°C ($\lambda = 365$ nm) resulted in the appearance of a distinct absorption band around 450 nm in the UV/vis spectrum (Figure 7.3a) and a change in sign of the CD absorptions (Figure 7.3b), indicative for the helix inversion of the molecule to provide diastereo-isomer (2’S)-(M)-2. Upon irradiation ($\lambda = 365$ nm) of a sample of a racemic mixture of (2’S*)-(P*)-2 in CD$_2$Cl$_2$ for 3 h at 20°C, new signals corresponding to the newly formed isomer (2’S*)-(M*)-2 appeared in the $^1$H NMR spectrum. The signal of the methyl substituent, a doublet at 1.42 ppm for (2’S*)-(P*)-2, shifted downfield to 1.58 ppm for (2’S*)-(M*)-2.

Using HPLC analysis, a ratio of (2’S)-(P)-2 to (2’S)-(M)-2 of 9:91 at the photostationary state (PSS) of this photoequilibrium was determined. Subsequent irradiation of the sample containing the PSS mixture with visible light ($\lambda >480$ nm)
lead to a near complete reversal of the changes in the UV/vis, CD and ¹H NMR spectra, as at these wavelengths the extinction coefficient of (2'S)-(M)-2 is much higher than that of (2'S)-(P)-2 (Figure 7.3a), leading to the efficient conversion back to (2'S)-(P)-2. The experimental PSS ratio of (2'S)-(P)-2 and (2'S)-(M)-2 of this photoequilibrium was 89:11, indicating that efficient and selective switching in two directions is indeed possible with this system.

Figure 7.4 Pluto drawings of a) (2'S*)-(P*)-2 and b) (2'S*)-(M*)-2. One enantiomer shown for both isomers, this structure does not express the absolute stereochemistry of the molecule.

The geometry of both isomers was unequivocally determined by X-ray analysis of the racemates (Figure 7.4). A solution of racemic (2'S*)-(P*)-2 in CH₂Cl₂ was irradiated (λ = 365 nm) for 5 h. Thereafter, via slow evaporation under n-pentane atmosphere, crystals suitable for X-ray analysis were obtained, containing both (2'S*)-(P*)-2 and (2'S*)-(M*)-2. In the (2'S*)-(P*)-2 isomer, the upper heterocyclic ring adopts the twisted boat conformation (Figure 7.4a), which was observed before with structurally analogous chiroptical switches and molecular motors.⁸,⁹ The methyl substituent adopts a pseudo-axial orientation, which allows it to point away from the lower half of the molecule, in the same direction as the naphthyl group does. With the systems previously described,⁸,⁹ the twisted boat conformation of the six-membered ring in the upper-half is inverted in the isomer obtained after the photochemically induced cis-trans isomerization, and with the molecular motors this forces the methyl substituent in a pseudo-equatorial orientation, in close proximity to the lower half of the molecule and residing on the same side of this lower half as the naphthyl moiety. In the case of photochemically generated isomer (2'S*)-(M*)-2 (Figure 7.4b), the twisted boat conformation of this six-membered ring in the upper-half is not inverted with respect to the conformation in (2'S*)-(P*)-2. As a result of this, the methyl substituent retains a pseudo-axial orientation, yet it ends up at the other face of the fluorenyl-based lower-half with respect to the substituted naphthyl moiety, resulting in the twisted structure shown.
In order to observe the reversal of the spectral changes, corresponding to the conversion of (2'S)-(M)-2 to (2'S)-(P)-2 via the thermal helix inversion process, heating to at least 80°C was required. The kinetics and thermodynamic parameters of this thermal helix inversion were determined by monitoring the UV signal at 470 nm over time in the dark at five different temperatures ranging from 80°C to 100°C. Using the various rate constants, the Gibbs energy of activation was calculated using the Eyring equation (see the Eyring plot in Figure 7.5): \[ \Delta^\ddagger G^0 = 112.9 \text{ kJ mol}^{-1}, \Delta^\ddagger H^0 = 112.0 \text{ kJ mol}^{-1}, \Delta^\ddagger S^0 = -3.0 \text{ J mol}^{-1} \text{ K}^{-1} \]. By extrapolation of the kinetic data, a half-life of (2’S)-(M)-2 at 20°C of 459 d was determined \( k = 1.75 \times 10^{-8} \text{ s}^{-1} \), indicating that for the irradiation experiments using the switchable LC film at room temperature \( \textit{vide infra} \) this thermal step is effectively blocked.

![Figure 7.5 Eyring plot for the conversion of (2’S)-(M)-2 to (2’S)-(P)-2 via the thermal helix inversion.](image)

### 7.3 A Chain-End Chiroptical Switch Functionalized Polyisocyanate

#### 7.3.1 Polymerization

The polymerization of \( n \)-hexyl isocyanate (HIC) was accomplished via a slightly altered version of the procedure developed by Lee and coworkers. After the addition of NaH to a solution of (2’S)-(P)-2 in THF at room temperature, the mixture was cooled to -90°C and 100 equivalents of the monomer (HIC) were added (Scheme 7.6). After 45 min, acetyl chloride and pyridine were added to end-cap the polymers. Precipitation of the polymer from MeOH afforded the polymer in 71% yield. Analysis by GPC, \(^1\text{H} \) NMR and UV/vis spectroscopy (via the same methods as were described in detail in Chapter 6) showed an average degree of polymerization of 200 (Mw = 32650). Acetylation of (2’S)-(P)-2 afforded switch
molecule (\(2'S\)-(P)-4) (Scheme 7.6), which was used as a CD reference compound: the CD spectra of the different isomers of 4 allowed to discriminate between the CD absorptions of the helical polymer and that of the chiroptical switch molecule connected to it.

![Scheme 7.6 Anionic polymerization of \(n\)-hexyl isocyanate using the sodium salt of benzamide-functionalized chiroptical switch 2 as the initiator (top), and acetylation of the amide yielding chiroptical switch 4 (bottom).](image)

7.3.2 CD Analysis Photoswitching of Polymer in Solution

The photoisomerizations of 3-PHIC were followed by CD spectroscopy, using the CD spectra of the different isomers of 4 to distinguish between the CD contributions of the helical polymer and those of the chiroptical molecular switch connected to it (Figure 7.6). The CD spectra of the polymer and the acetylated switch completely overlap between 300 and 500 nm. In this wavelength region, polyisocyanate does not absorb and the CD signals of the polymer-switch hybrid originate solely from the attached switch molecule. Between 210 and 280 nm a strong deviation of the CD curve of 3-PHIC from the CD curve of acetylated switch 4 was observed (Figure 7.6a), and subtraction of the CD spectrum of (\(2'S\)-(P)-4) from the CD spectrum of (\(2'S\)-(P)-3-PHIC) yielded a CD difference spectrum typical of PHIC with an excess of the M (left-handed) helical sense of the backbone (solid line in Figure 7.6d). Interestingly, a threefold increase in intensity of the molar ellipticity (Figure 7.6d), compared to that obtained with the previously described system 1 (see Figures 9d and 10d in Chapter 6), was found.
Figure 7.6 CD spectra (Et$_2$O, 20°C) of a) (2'S)-(P)-3-PHIC (38.3 mg/L) (solid) and (2'S)-(P)-4 (3.2 µM) (dashed), b) the PSS mixture with (2'S)-(P)-3-PHIC and (2'S)-(M)-3-PHIC (solid) and the PSS mixture with (2'S)-(P)-4 and (2'S)-(M)-4 (dashed) after UV irradiation (λ = 365 nm), c) the PSS mixture of (2'S)-(M)-3-PHIC and (2'S)-(P)-3-PHIC (solid) and the PSS mixture of (2'S)-(M)-4 and (2'S)-(M)-4 (dashed) after irradiation with visible light (λ >480 nm) and d) molar ellipticity of the polymer backbone (CD difference spectra polymer 3 – acetylated switch 4) for the stable (2'S)-(P) isomer of the chiroptical switch (solid), after UV irradiation (λ = 365 nm) (dotted) and after irradiation with visible light (λ >480 nm) (dashed).
Apparently, the chiral induction from the chiroptical switch to the polymer chain is significantly increased in 3-PHIC compared to 1, which is attributed to a more pronounced influence of the molecular helix structure of the switching unit at this new position of attachment (in the fjord region) to the photochromic molecule. We reason that this effect is also caused by the fact that the 5-membered ring in the upper-half of the motor molecule connected to the central double bond in 1 has expanded to a 6-membered ring in 3 by introduction of the oxygen atom. Together with the naphthyl moiety in the upper-half, the polymer chain is thereby "pushed" closer to the fluorenyl-based lower-half of the molecule, leading to the enhanced chiral induction.

Upon irradiation of a sample of (2'S)-(3-PHIC in Et2O at 20°C with UV light (\(\lambda = 365\) nm), providing (2'S)-(M)-3-PHIC, the prominent absorption maxima around 220 nm and 260 nm inverted (Figure 7.6b). Irradiation of a sample of (2'S)-(P)-4 under the same conditions resulted in an inversion of the CD absorptions in accordance with the inversion of the intrinsic chirality of the molecule to provide (2'S)-(M)-4. Most obvious is the inversion of the CD difference spectrum (solid vs dotted line in Figure 7.6d), indicating that the polymer backbone has switched from a predominant M to P helical sense.

Subsequent irradiation of the sample containing (2'S)-(M)-3-PHIC with visible light (\(\lambda > 480\) nm), providing (2'S)-(P)-3-PHIC, resulted again in an inversion of the prominent CD signals of the polymer (Figure 7.6c). Irradiation under the same conditions of a sample containing (2'S)-(M)-4 resulted also in an inversion of the CD absorptions, again in accordance with the inversion of the intrinsic helicity of the acetylated switch to provide (2'S)-(P)-4. The inverted CD signals of the polymer, again clearest observed from the CD difference spectrum (dashed line in Figure 7.6d), indicate that the polymer backbone has switched back to a preferred M helical sense. The CD spectrum does not return completely to the spectrum obtained before the irradiation experiments, as a PSS mixture still containing a small amount of (2'S)-(M)-3-PHIC is obtained.

7.4 Switching of Supramolecular Helicity in a Polymeric Cholesteric LC

7.4.1 Optical Microscopy Analysis Photoswitching Polymer in the LC Phase
The effect of the photo-induced inversion of the predominant helicity of the polymer, on a lyotropic cholesteric liquid crystalline phase generated by these polymers, was subsequently investigated. It is known that polyisocyanates, when mixed in sufficiently high concentrations in certain solvents, orient themselves to
form a LC phase.\textsuperscript{11} Also, a nematic-to-cholesteric phase transition of such polyisocyanate-based LCs, upon the addition of certain chiral dopant molecules, has been demonstrated.\textsuperscript{12} Therefore, first (2'S)-(P)-2 was added as a chiral dopant to an LC of unfunctionalized PHIC (formed by initiation of the polymerization with benzanilide, see ref. 10) in toluene, and it was found that this did not induce a transition of the LC phase from nematic to cholesteric. Apparently, the intermolecular interactions of the switch with the polymers alone are not sufficient to induce a nematic-to-cholesteric phase-transition of the LC.

Subsequently, a 30 wt\% solution of (2'S)-(P)-3-PHIC in toluene was placed between two flat KBr plates in a liquid IR cell, in which the layer thickness of 200 \( \mu m \) was controlled using a Teflon spacer. The LC was allowed to organize and orient for a period of 16 h, after which it was analyzed using an optical microscope equipped with crossed polarizers.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.7}
\caption{Optical micrographs of a thin film (thickness: 200 \( \mu m \)) of (2'S)-(P)-3-PHIC in toluene (30 wt\%) a) before irradiation \( (p = 6.0 \mu m) \), b) after 15 min \( (p = 6.2 \mu m) \), c) 45 min, d) 90 min and e) 150 min of UV irradiation \( (\lambda = 365 \text{ nm}) \), after which a PSS mixture is obtained that consists of a large excess of (2'S)-(M)-3-PHIC over (2'S)-(P)-3-PHIC, and f) after leaving the irradiated sample in the dark overnight \( (p = 4.5 \mu m) \) (inset shows an enlarged section under 5x higher magnification). Scalebar, 50 \( \mu m \). The arrows indicate the directions of the crossed polarizers.}
\end{figure}

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Initially, a polygonal fingerprint texture was observed (Figure 7.7a), which is typical for a cholesteric LC phase with an alignment of the cholesteric helix axis parallel to the surface. The periodicity of the polygonal texture corresponds to a half pitch length, which was used to determine a pitch length of 6.0 \( \mu m \). The sample was then followed in time at a fixed location throughout the irradiation experiments. UV irradiation (\( \lambda = 365 \) nm) leads to the conversion of \( (2'S)-(P)-3\)-PHIC, a polymer with a preferred M helical twist sense, to \( (2'S)-(M)-3\)-PHIC with preferred P helicity. This resulted in a clear increase of the distance between the lines of the polygonal texture, indicating an elongation of the cholesteric helical pitch of the LC. Initially, only a slight increase in the line-distance in the fingerprint texture was observed, as after 15 min of irradiation a pitch length of 6.2 \( \mu m \) was determined (Figure 7.7b). After 45 min, the distance between the lines had increased much further, and the lines slowly started to fade out until almost no fingerprint texture was observed anymore (Figure 7.7c). At this point the pitch has elongated to such an extent that the cholesteric lines are no longer detectable by eye. Upon further UV irradiation the fingerprint texture redeveloped, indicating a shortening of the pitch length. Interestingly, during this process, initially circular patterns were observed (Figure 7.7d, after 90 min of UV irradiation). These circular patterns have been reported in literature and were assigned to defects in cholesteric LCs. During continual irradiation, the circular patterns slowly merged (Figure 7.7e), generating more homogeneous areas of the polygonal fingerprint texture. The UV irradiation was stopped after 150 min, as no changes in the polygonal fingerprint texture seemed to occur anymore. However, a fully homogeneous fingerprint texture, similar to that observed before the irradiation experiment, was observed after the sample had been left in the dark overnight (Figure 7.7f). At this point a pitch length of 4.5 \( \mu m \) was determined, which is shorter than the pitch of 6.0 \( \mu m \) observed before the irradiation experiment (Figure 7.7f vs Figure 7.7a).

Subsequent irradiation of the sample with visible light (\( \lambda >480 \) nm), leading to the conversion of \( (2'S)-(M)-3\)-PHIC, a polymer with a preferred P helical twist sense, to \( (2'S)-(P)-3\)-PHIC with preferred M helicity, resulted again in an increase in the distance between the lines in the polygonal texture, indicating an increase in the cholesteric pitch length. For this irradiation experiment, the light-source of the microscope (put on maximum intensity) was a used after it had been equipped with a 480 nm cut-off filter. Owing to the lower intensity of this light source used for the visible light irradiation compared to that used with the UV irradiation, longer irradiation times were needed to generate the same changes of the LC phase in this experiment. After 5 h of irradiation, an increase to 7.8 \( \mu m \) was determined (Figure 7.8a). Continuing irradiation of the phase led to a further elongation of the pitch (13 \( \mu m \) after 6 h, see Figure 7.8b), and eventually a disappearance of the cholesteric lines (Figure 7.8c). The fingerprint texture reappeared upon further
visible light irradiation, and the distance between the lines slowly decreased with time, indicating a shortening of the pitch length from approximately 22 μm after 8 h (Figure 7.8d) to 9.0 μm after 9 h (Figure 7.8e). After 24 h of visible light irradiation, the fingerprint texture of the LC phase ceased to change, at which point a pitch length of 3.7 μm was reached (Figure 7.8f), again remarkably shorter than the 6.0 μm pitch observed before the irradiation experiments. The irradiation cycles of the liquid crystalline system and the concomitant changes in the LC phase are reversible and can be repeated several times.

Figure 7.8 Optical micrographs of a thin film (thickness: 200 μm) of the PSS mixture obtained upon UV irradiation that consists of a large excess of (2'-S)-(M)-3-PHIC over (2'-S)-(P)-3-PHIC in toluene (30 wt%), after a) 5 h (p = 7.8 μm), b) 6 h (p = 13 μm), c) 7 h, d) 8 h (p = 22 μm), e) 10 h (p = 9.0 μm) and f) 24 h of irradiation with visible light (λ >480 nm), after which a PSS mixture is obtained that consists of a large excess of (2'-S)-(P)-3-PHIC over (2'-S)-(M)-3-PHIC (p = 3.7 μm) (inset shows a selection under 5x higher magnification). Scalebar, 50 μm. The arrows indicate the directions of the crossed polarizers.

7.4.2 A Polymeric LC with a Light-Controlled Cholesteric Pitch Length
Initially the sample contains solely (2'S)-(P)-3-PHIC, a polymer with a preferred M helical twist sense, leading to an M helical cholesteric LC phase with a tight pitch (Figure 7.7a and Figure 7.9a). Upon UV irradiation (λ = 365 nm), (2'S)-(P)-3-PHIC
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is converted to \((2'S)-(M)-3\)-PHIC with a preferred \(P\) helical twist sense, which induces a cholesteric LC phase with the opposite helicity \((P)\). This results in the observed elongation of the cholesteric pitch length upon UV irradiation (Figure 7.7b and Figure 7.9b).

![Diagram showing the conversion of cholesteric and nematic phases through UV and visible light irradiation](diagram.png)

**Figure 7.9** Schematic representation of the full photocontrol of the magnitude and sign of the supramolecular helical pitch of a cholesteric LC phase generated by a polyisocyanate with a single chiroptical molecular switch covalently linked to the polymer’s terminus. a) Initially, \((2'S)-(P)-3\)-PHIC adopts a \(M\) helical cholesteric LC phase with a tight pitch. b) UV irradiation \((\lambda = 365\) nm) converts the switchable polymer to \((2'S)-(M)-3\)-PHIC, leading to an elongation of the cholesteric pitch of the LC. c) Equal amounts of \((2'S)-(P)-3\)-PHIC and \((2'S)-(M)-3\)-PHIC are present in the mixture, resulting in an infinite pitch of the cholesteric LC, which appears as an optically nematic phase. d) After prolonged UV irradiation, \((2'S)-(M)-3\)-PHIC is present in excess, resulting in the LC matrix returning to cholesteric with inverted helicity \((P)\). e) A PSS is reached, predominantly consisting of \((2'S)-(M)-3\)-PHIC, resulting in a \(P\) helical cholesteric LC phase with a tight pitch. Irradiation with visible light \((\lambda > 480\) nm) leads to a reversal of the process \((e \rightarrow a)\).
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At a certain point, equal amounts of $M$ and $P$ helical polymer are present in the LC film, effectively cancelling each other's helical induction towards the cholesteric LC. This results in a near-infinite pitch length, leading to a sample that appears to be nematic, explaining the observed disappearance of the cholesteric lines (Figure 7.7c and Figure 7.9c). Further irradiation leads to an excess $(Z'S)-(M)$-3-PHIC over $(Z'S)-(P)$-3-PHIC, resulting in a shortening of the pitch length of the now $P$ helical cholesteric phase, which is observed as the reappearance of the fingerprint texture (Figure 7.7d-e and Figure 7.9d). Continuous UV irradiation gradually increases the $(Z'S)-(M)$-3-PHIC to $(Z'S)-(P)$-3-PHIC ratio, explaining the observed shortening of the periodicity of the cholesteric corrugation, until the PSS is reached (Figure 7.7f and Figure 7.9e). Subsequent irradiation with visible light ($\lambda > 480$ nm) leads to the conversion of $(Z'S)-(M)$-3-PHIC back to $(Z'S)-(P)$-3-PHIC. This results in the reversal of the changes of the cholesteric LC phase, leading to a repetition of the observations that were described before (Figure 7.8 and Figure 7.9e→a).

### 7.5 Discussion and Conclusions

The thermal reorganization observed for the UV irradiated sample after it had been stored in the dark overnight (Figure 7.7e vs Figure 7.7f) implies that the reorganization of the LC is slow compared to the photoisomerization of the chiroptical switch-polymer hybrid. A similar slow reorganization after photoisomerization, over the course of hours, has been reported in the literature in the case of a polymeric LC based on a polymer with chiral photo-switchable groups introduced in the side-chains.16 As the photoisomerization upon visible light irradiation takes place on a much longer time-scale compared to the UV irradiation experiment, caused by the fact that a light source of much lower intensity was used, this thermal reorganization process was not observed after terminating the visible light irradiation. Apparently, in this case the photoisomerization and the thermal reorganization of the LC phase take place on the same time-scale.

A puzzling observation is the fact that the pitch length of the cholesteric phase at both PSSs (4.5 $\mu$m at PSS$_{365}$, Figure 7.7f, and 3.7 $\mu$m at PSS$_{480}$, Figure 7.8f) are substantially shorter than the pitch length of the non-irradiated sample (6.0 $\mu$m, Figure 7.7a). A slight reduction of the pitch has also been observed after irradiation of an azobenzene functionalized helical polymer, and was attributed to solvent evaporation due to heating of the sample under the UV lamp, leading to a change in concentration.3b Upon increasing the concentration of $(Z'R)-(P)$-3-PHIC in the lyotropic LC phase from 30 wt% to 40 wt%, indeed a decrease in pitch length from 6.0 $\mu$m to 2.9 $\mu$m was observed. To verify if this could provide an explanation for the observed effect, a sample of $(Z'R)-(P)$-3-PHIC in toluene was submitted to a
number of irradiation cycles, in which first 1 h of UV irradiation (\(\lambda = 365\) nm) was applied, resulting in an increase in pitch length of the LC sample to almost nematic, after which it was irradiated for 20 h with visible light (\(\lambda >480\) nm) (Figure 7.10).

![Figure 7.10](image)

**Figure 7.10** Optical micrograph of a thin film (thickness: 200 \(\mu\)m) of a) \((2'S)-(P)-3\)-PHIC in toluene (~30 wt\%, \(p = 6.9\) \(\mu\)m), b) after a first cycle of 1 h of UV (\(\lambda = 365\) nm) and 20 h of visible light (\(\lambda >480\) nm) irradiation (\(p = 4.4\) \(\mu\)m), c) after a second (\(p = 4.1\) \(\mu\)m), d) a third (\(p = 4.0\) \(\mu\)m) and e) a fourth irradiation cycle (\(p = 4.2\) \(\mu\)m). Scalebar, 50 \(\mu\)m. The arrows indicate the directions of the crossed polarizers. Insets show enlarged sections under 5x higher magnification.

The initial pitch length of the sample, before irradiation was applied, was 6.9 \(\mu\)m (Figure 7.10a). This pitch is somewhat longer than the 6.0 \(\mu\)m observed with the previous sample before irradiation, which is assumed to be caused by a slightly lower concentration of this particular sample. After the first irradiation cycle, the pitch had decreased to a value of 4.4 \(\mu\)m (Figure 7.10b), a similar decrease in pitch length over one switch cycle as observed before (6.0 \(\mu\)m to 3.7 \(\mu\)m). Three subsequent switch cycles however did not result in a further decrease in pitch length: similar pitch values, varying between 4.0 \(\mu\)m and 4.4 \(\mu\)m, were obtained (Figure 7.10c-e). It is therefore highly unlikely that the observed decrease in pitch length after irradiation is caused by solvent evaporation due to heating of the
sample under the irradiation conditions applied, as a gradual further decrease in pitch length over subsequent irradiation cycles would be expected. We propose that the observed tightening of the pitch is actually the result of the photo-induced switching of the polymer’s helicity causing an overall improvement in the packing of the polymers in the helical organization of the LC phase.

In this chapter, it has been shown that the preferred helical twist sense of a polyisocyanate can be controlled by a single photochemically bi-stable chiroptical molecular switch, of which the two thermally stable states are fully addressable with light, which is covalently attached to the polymer’s terminus. The hierarchical transmission of chiral information from the molecular level of the chiroptical switch, via the macromolecular level of the helical polymer to the supramolecular level of a cholesteric liquid crystalline phase formed by these helically switchable polymers, allows for the full control of the magnitude and sign of the supramolecular helical pitch of this LC phase using two different wavelengths of light.

7.6 Acknowledgement
The optical microscopy study on the effects of photoswitching of the polymers in a cholesteric LC film was performed in collaboration with Maathild G. M. Jongejan, who is gratefully acknowledged for her contributions.

7.7 Experimental Section
General remarks
For general remarks, see Section 2.6 and 6.5. UV and visible light irradiation experiments on spectroscopic samples, and UV irradiation experiments on LC samples, were performed with a Spectroline ENB-280C/FE UV lamp at 365 nm and a 200 W Oriel Xe-lamp adapted with a 480 nm cut-off filter.

Preparation and study of the liquid crystalline phase
The LC samples were prepared by mixing 15 mg (2'S)-(P)-3-PHIC and 35 mg freshly distilled toluene. The LC films with a controlled 200 μm thickness were prepared by placing a drop of this sample between two KBr plates of a liquid IR cell (demountable liquid IR cell as sold by Sigma-Aldrich number Z12003-1KT), controlling the distance between the KBr plates using a teflon spacer. The optical micrographs of the LC phases were recorded using an Olympus BX 60 microscope, equipped with crossed polarizers and a Sony 3CCD DXC 950P digital camera, attached to a PC running Matrox Inspector 8.0 imaging software.
X-ray crystallographic data of N-(1-(9H-fluoren-9-ylidene)-2-methyl-2,3-dihydro-
1H-benzo[f]chromen-9-yl)benzamide (2)

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7-Bromonaphthalen-2-ol (9)

A procedure slightly modified from the one described in ref. 7 was followed. To a vigorously stirred mixture of triphenylphosphine (31.5 g, 120 mmol) in MeCN (50 mL), Br\(_2\) (19 g, 6.2 mL, 120 mmol) was added dropwise at 0°C. The reaction mixture was allowed to reach room temperature and 2,7-dihydroxynaphthalene 8 (16 g, 100 mmol) was added in one portion. The mixture was heated to 70°C for 30 min, after which the solvent was removed by rotary evaporation. The flask was equipped with a gas trap and the black residue was heated to 250°C for 45 min. After cooling to room temperature, the mixture was dissolved in 200 mL CH\(_2\)Cl\(_2\) and filtered over a plug of silica. The pure product was obtained after column chromatography (SiO\(_2\), \(n\)-pentane:CH\(_2\)Cl\(_2\) = 1:1, \(R_t\) = 0.22, to pure CH\(_2\)Cl\(_2\)) as a beige powder (18.6 g, 83.4 mmol, 84%). mp 127-129°C; \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 5.15 (b, 1H), 7.01 (d, \(J = 2.6\) Hz, 1H), 7.08 (dd, \(J = 8.8, 2.6\) Hz, 1H), 7.37 (dd, \(J = 8.8, 1.8\) Hz, 1H), 7.59 (d, \(J = 8.4\) Hz, 1H), 7.68 (d, \(J = 8.8\) Hz, 1H), 7.79 (d, \(J = 2.2\) Hz, 1H); \(^13\)C NMR (100 MHz, CDCl\(_3\)) \(\delta\) 108.7 (d), 118.1 (d), 120.8 (s), 127.0 (d), 127.3 (s), 128.3 (d), 129.4 (d), 129.9 (d), 135.7 (s), 154.0 (s); m/z (EI\(^+\), %) = 224, 222 (M\(^+\), 100), 115 (38); HRMS (EI\(^+\)): calcld for C\(_{10}\)H\(_{7}\)BrO: 221.9680, found 221.9676; Anal. calcld for C\(_{10}\)H\(_{7}\)BrO: C, 53.84; H, 3.16, found: C, 53.85; H, 3.12.
3-Hydroxy-2-methylpropyl-4-methylbenzenesulfonate (10)

To a solution of 2-methyl-1,3-propanediol (9.0 g, 8.9 mL, 0.10 mmol) in CHCl₃ (100 mL), pyridine (15.8 g, 16.0 mL, 200 mmol) and p-toluenesulfonyl chloride (21 g, 0.11 mol) were added at 0°C. The stirred solution was allowed to reach room temperature overnight. After addition of water (200 mL), the mixture was extracted with ethyl acetate (3 x 200 mL). The organic extracts were washed with aqueous solutions of HCl (2M, 100 mL), saturated NaHCO₃ (100 mL), brine and dried (Na₂SO₄). Evaporation of the solvent yielded a slightly yellow oil. The pure product was obtained after column chromatography (SiO₂, gradient n-pentane:EtOAc = 2:1, Rf = 0.17, to pure EtOAc), yielding a colorless oil (7.42 g, 31 mmol, 31%). ¹H NMR (400 MHz, CDCl₃) δ 0.86 (d, J = 7.0 Hz, 3H), 1.95 (m, 1H), 2.39 (s, 3H), 2.68 (b, 1H), 3.43-3.53 (m, 2H), 3.96 (d, J = 5.8 Hz, 2H), 7.30 (d, J = 8.4 Hz, 2H), 7.73 (d, J = 6.6 Hz, 2H); ¹³C NMR (100 MHz, CDCl₃) δ 13.0 (q), 21.5 (q), 35.4 (d), 65.7 (t), 70.8 (t), 105.8 (d), 119.2 (d), 120.5 (d), 126.9 (d), 128.6 (d), 132.7 (s), 135.7 (s), 157.5 (s); m/z (EI⁺, %) = 262 (M+NH₄⁺, 100), 108 (2.6).

3-(7-Bromonaphthalen-2-yloxy)-2-methylpropan-1-ol (11)

To a stirred solution of 9 (12.7 g, 57.2 mmol) in DMF (500 mL), Cs₂CO₃ (37 g, 114 mmol) and 10 (18 g, 74 mmol) were added, and the mixture was refluxed for 48 h. After cooling to room temperature, the mixture was diluted in ethyl acetate and washed with an aqueous solutions of HCl (10%, 3 x 200 mL), saturated NaHCO₃ (200 mL), brine and dried (Na₂SO₄). After removal of the solvent under reduced pressure, the pure product was obtained after column chromatography (SiO₂, n-pentane:Et₂O = 2:1, Rf = 0.54) as a white solid (12.4 g, 42 mmol, 74%), mp 77-79°C; ¹H NMR (400 MHz, CDCl₃) δ 1.06 (d, J = 7.0 Hz, 3H), 2.10-2.26 (m, 2H), 3.71 (d, J = 6.9 Hz, 2H), 4.00 (d, J = 6.2 Hz, 2H), 6.99 (d, J = 2.6 Hz, 1H), 7.10 (dd, J = 8.8, 2.6 Hz, 1H), 7.36 (dd, J = 8.4, 1.8 Hz, 1H), 7.57 (d, J = 8.8 Hz, 1H), 7.65 (d, J = 8.8 Hz, 1H), 7.82 (d, J = 2.2 Hz, 1H); ¹³C NMR (100 MHz, CDCl₃) δ 13.6 (q), 35.6 (d), 65.7 (t), 70.8 (t), 105.8 (d), 119.2 (d), 120.5 (d), 126.9 (d), 127.3 (s), 128.6 (d), 129.2 (d), 129.3 (d), 135.7 (s), 157.5 (s); m/z (EI⁺, %) = 294, 296 (M⁺, 30), 222, 224 (100); HRMS (EI⁺): calcd for C₁₄H₁₃BrO₂: 294.0255, found 294.0243; Anal. calcd for C₁₄H₁₃BrO₂: C, 56.97; H, 5.12; found: C, 57.15; H, 5.06.
Light-Controlled Supramolecular Helicity of a Polymeric Liquid Crystalline Phase

3-(7-Bromonaphthalen-2-yloxy)-2-methylpropanoic acid (12)

To a stirred solution of 11 (8.9 g, 30 mmol) in acetone (250 mL), KMnO₄ was added (24 g, 0.15 mol), after which stirring was continued overnight. An aqueous saturated solution of NaHSO₃ was added to destroy the excess of KMnO₄, the aqueous mixture was acidified by addition of aqueous HCl (10%), and extracted with CH₂Cl₂ (3 x 200 mL). The organic extracts were washed with brine, dried (Na₂SO₄) and the solvent was removed under reduced pressure. The pure product was obtained after column chromatography (SiO₂, EtOAc, Rf = 0.66) as a white solid (5.6 g, 18 mmol, 60%). mp 156-159°C; ¹H NMR (400 MHz, DMSO-d₆) δ 1.22 (d, J = 7.0 Hz, 3H), 2.90 (m, 1H), 4.12 (dd, J = 9.4, 5.4 Hz, 1H), 4.22 (dd, J = 8.2, 7.0 Hz, 1H), 7.10 (m, 1H), 7.38 (s, 1H), 7.45 (d, J = 8.4, 1H), 7.84 (d, J = 8.2, 1H), 8.07 (s, 1H); ¹³C NMR (100 MHz, DMSO-d₆) δ 13.8 (q), 38.9 (d), 69.5 (t), 106.2 (d), 119.1 (d), 119.8 (s), 125.3 (d), 127.5 (s), 128.4 (d), 129.4 (d), 135.6 (s), 157.1 (s), 175.1 (s); m/z (EI+, %) = 308, 310 (M⁺, 48), 222, 224 (100); HRMS (EI⁺): calcd for C₁₄H₁₃BrO₃: 308.0048, found 308.0063; Anal. calcd for C₁₄H₁₃BrO₃:


9-Bromo-2-methyl-2,3-dihydro-1H-benzo[f]chromen-1-one (13)

To mechanically stirred polyphosphoric acid (100 mL) at 70°C, 12 (4.0 g, 13 mmol) was added. The temperature was raised to 110°C and the mixture was vigorously stirred for 3 h. After cooling to 70°C, the reaction mixture was cautiously poured on ice (250 g) and the resulting aqueous solution was stirred at room temperature overnight. The aqueous mixture was extracted with ethyl acetate (4 x 150 mL), the organic extracts were washed with brine and dried (Na₂SO₄) and the solvent was removed under reduced pressure, yielding a brown oil. Further purification could be performed by column chromatography (SiO₂, n-pentane:EtOAc = 4:1, Rf = 0.8), providing a light-brown solid (2.3 g, 8.0 mmol, 62%). mp 87-89°C; ¹H NMR (400 MHz, CDCl₃) δ 1.21 (d, J = 7.0 Hz, 3H), 2.87 (m, 1H), 4.19 (dd, J = 9.2, 8.8 Hz, 1H), 4.54 (dd, J = 11.3, 5.1 Hz, 1H), 7.01 (d, J = 9.1 Hz, 1H), 7.42 (d, J = 8.4 Hz, 1H), 7.49 (d, J = 8.4 Hz, 1H), 7.75 (d, J = 8.8 Hz, 1H), 9.64 (s, 1H); ¹³C NMR (50 MHz, CDCl₃) δ
(Dispiro[9-bromo-2-methyl-2,3-dihydro-1H-naphto[2,1-b]pyran-1,2'-thirane-3',9''-(9''H)-fluorene] (14))

A solution of 13 (500 mg, 1.70 mmol) and P2S5 (1.2 g, 5.2 mmol) in benzene (20 mL) was refluxed for 1 h. After cooling to room temperature, the mixture was directly pulled over a plug of silica, eluted with n-pentane:CH2Cl2 = 1:1, to quickly purify the rather unstable thioketone 6. The first deep-green colored fraction (thioketone 6) was collected and directly added to a solution of diazofluorenone 7 (660 mg, 3.4 mmol) in toluene (75 mL). The solution was refluxed overnight, and after cooling to room temperature the solvent was removed under reduced pressure. The pure product was obtained after column chromatography (SiO2, pentane:CH2Cl2 = 8:1, Rf = 0.3) as a yellow solid (270 mg, 0.57 mmol, 33%). mp 177-179°C; 1H NMR (400 MHz, CDCl3) δ 1.18 (d, J = 6.6 Hz, 3H), 3.13 (m, 1H), 3.61-3.67 (m, 2H), 6.13 (d, J = 7.7 Hz, 1H), 6.54 (t, J = 8.1 Hz, 1H), 6.77 (d, J = 8.8 Hz, 1H), 7.08 (t, J = 8.1 Hz, 1H), 7.32 (t, J = 8.3 Hz, 1H), 7.44 (t, J = 8.2 Hz, 1H), 7.50-7.66 (m, 5H), 7.76 (d, J = 7.3 Hz, 1H), 9.48 (s, 1H); 13C NMR (100 MHz, CDCl3) δ 19.1 (q), 39.6 (d), 53.4 (s), 56.3 (s), 72.4 (t), 116.4 (s), 118.7 (d), 119.4 (d), 120.5 (d), 120.8 (s), 123.5 (d), 124.2 (d), 124.8 (d), 126.0 (d), 126.4 (d), 126.6 (d), 127.6 (d), 127.7 (s), 128.4 (d), 129.5 (d), 130.4 (d), 135.5 (s), 140.0 (s), 141.9 (s), 142.8 (s), 142.9 (s), 155.9 (s); m/z (EI+, %) = 470, 472 (M+, 45), 438, 440 (100); HRMS (EI+): calcd for C27H19BrO3: 470.0340, found 470.0358.
9-Bromo-1-(9H-fluoren-9-ylidene)-2-methyl-2,3-dihydro-1H-benzo[f]chromene (5)

A solution of episulfide 10 (0.30 mg, 0.64 mmol) and triphenylphosphine (0.83 g, 3.2 mmol) in toluene (20 mL) was heated at reflux overnight. After removal of the solvent under reduced pressure the alkene was purified by column chromatography (SiO₂, n-pentane:CH₂Cl₂ = 8:1, Rf = 0.41), yielding a yellow solid (0.25 g, 0.57 mmol, 89%). mp 176-177°C; ¹H NMR (400 MHz, CDCl₃) δ 1.41 (d, J = 7.0 Hz, 3H), 4.20 (m, 1H), 4.37-4.44 (m, 2H), 6.47 (d, J = 8.1 Hz, 1H), 6.74 (t, J = 7.7 Hz, 1H), 7.12-7.18 (m, 2H), 7.32-7.41 (m, 3H), 7.62 (d, J = 8.8 Hz, 1H), 7.68 (d, J = 7.3 Hz, 1H), 7.76 (d, J = 8.8 Hz, 1H), 7.81 (d, J = 7.0 Hz, 1H), 7.92-7.94 (m, 2H); 13C NMR (100 MHz, CDCl₃) δ 15.8 (q), 32.8 (d), 72.5 (t), 113.1 (s), 118.6 (d), 119.1 (d), 120.0 (d), 121.9 (s), 124.5 (d), 125.0 (d), 126.6 (d), 126.8 (d), 127.3 (d), 127.4 (d), 127.5 (s), 127.6 (d), 129.8 (d), 131.5 (d), 133.0 (s), 133.1 (s), 136.9 (s), 137.4 (s), 138.3 (s), 139.7 (s), 140.8 (s), 154.2 (s); m/z (EI⁺, %) = 438, 440 (M⁺, 100), 423, 425 (14); HRMS (EI⁺): calcd for C₂₇H₁₉BrO: 438.0619, found 438.0639; Anal. calcd for C₂₇H₁₉BrO: C, 73.81; H, 4.36, found: C, 73.55; H, 4.28.

N-(1-(9H-fluoren-9-ylidene)-2-methyl-2,3-dihydro-1H-benzo[f]chromen-9-yl)benzamide (2)

Following the procedure of Buchwald and coworkers,⁶ a mixture of 5 (0.14 mg, 0.32 mmol), benzamide (96 mg, 0.80 mmol), 4,5-bis(diphenylphosphino)-9,9-dimethyl-xanthene (45 mg, 77 µmol), Pd₂(dba)₃ (24 mg, 26 µmol) and Cs₂CO₃ (209 mg, 0.64 mmol) was stirred in 1,4-dioxane (2 mL) at 100°C overnight. After the mixture was cooled to room temperature, it was diluted in CH₂Cl₂ (20 mL) and filtered over a plug of silica. After removal of all volatiles under reduced pressure, the product was further purified by column chromatography (SiO₂, n-pentane:EtOAc = 4:1, Rf =
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0.5), yielding a yellow solid (150 mg, 0.31 mmol, 98%), mp 180-182°C; $^1$H NMR (400 MHz, CDCl₃) $\delta$ 1.38 (d, $J = 7.3$ Hz, 3H), 4.19 (m, 1H), 4.35-4.43 (m, 2H), 6.56 (d, $J = 8.1$ Hz, 1H), 6.75 (t, $J = 8.1$ Hz, 1H), 7.06 (d, $J = 8.8$ Hz, 1H), 7.13 (t, $J = 7.5$ Hz, 1H), 7.27-7.41 (m, 5H), 7.45 (s, 1H), 7.58-7.64 (m, 4H), 7.73-7.82 (m, 3H), 7.89 (d, $J = 8.8$ Hz, 1H), 8.20 (d, $J = 8.8$ Hz, 1H); $^{13}$C NMR (100 MHz, CDCl₃) $\delta$ 15.9 (q), 33.1 (d), 72.3 (t), 113.1 (s), 113.8 (d), 117.3 (d), 118.0 (d), 119.0 (d), 119.9 (d), 124.5 (d), 125.1 (d), 126.4 (s), 126.7 (d), 126.9 (d), 127.1 (2xd), 127.2 (d), 127.3 (d), 128.3 (2xd), 129.5 (d), 131.5 (d), 131.7 (d), 132.3 (s), 132.5 (s), 134.8 (s), 137.6 (s), 137.8 (s), 138.1 (s), 138.4 (s), 139.4 (s), 140.7 (s), 154.1 (s), 165.8 (s); m/z (EI+, %) = 479 (M⁺, 100), 374 (10); HRMS (EI+): calcd for C₃₄H₂₅NO₂: 479.1885, found 479.1908. Separation of the enantiomers was achieved by CSP-HPLC (Chiralpak OD, n-heptane:2-propanol = 95:5, flow rate = 1.0 mL/min, retention times: 35.8 min for (2'S)-(P)-2 and 40.6 min for (2'R)-(M)-2.

(2'S)-(P)-3-PHIC

Following a modified version of the procedure of Lee and coworkers, NaH (1 mg, 50% in oil, 21 $\mu$mol) was washed with pentane in a Schlenck tube under N₂, after which (2'S)-(P)-2 (9 mg, 19 $\mu$mol) dissolved in THF (5 mL) was added. After stirring at room temperature for 10 min, the mixture was cooled to -90°C, and n-hexyl isocyanate (0.56 $\mu$L, 0.48 g, 3.8 mmol) was added, upon which the mixture slowly turned more viscous. After 45 min, acetyl chloride (18 $\mu$L, 20 mg, 0.25 mmol) and pyridine (20 $\mu$L, 20 mg, 0.25 mmol) were added to the mixture, which was then allowed to warm to room temperature. The mixture was then poured in MeOH (100 mL) and the precipitated poly(n-hexyl isocyanate) was filtered off, washed three times with MeOH and dried in vacuo, which yielded a yellow solid (340 mg, 71%). $^1$H NMR (400 MHz, CD₂Cl₂) $\delta$ 0.85 (b, 3H), 1.30 (b, 6H), 1.60 (b, 2H), 3.70 (b, 2H), 6.50-8.00 (low intensity signals: aromatic protons). $^{13}$C NMR (100 MHz, CDCl₃) $\delta$: 14.0 (q), 22.6 (t), 26.2 (t), 28.4 (t), 31.5 (t), 48.5 (t), 156.8 (s). GPC: Mn = 25850, Mw = 32650, D = 1.26.
(S)-N-(1-(9H-fluoren-9-ylidene)-2-methyl-2,3-dihydro-1H-benzo[f]chromen-9-yl)-N-acetylbenzamide, (2'S)-(P)-4

Sodium bis(trimethylsilyl)amide (50 µL of a 1.0 M solution in THF, 50 µmol,) was added to a solution of (2'S)-(P)-2 (10 mg, 21 µmol) in THF (4 mL), stirred at -78°C. After 5 min acetyl chloride (1.6 µL, 1.7 mg, 22 µmol) was added to the mixture, which was stirred another 5 min and allowed to warm to room temperature. The solution was quenched with a saturated aqueous NaHCO₃-solution (50 mL), which was then extracted with ether (3 × 75 mL). The organic phase was washed with brine, dried (Na₂SO₄) and the solvent was removed under reduced pressure. The pure product was obtained after preparative TLC (SiO₂, n-pentane:EtOAc = 8:1, Rf = 0.25), providing a yellow solid (5.3 mg, 11 µmol, 52%). mp 193-195°C; ¹H NMR (400 MHz, CD₂Cl₂) δ 1.39 (d, J = 7.0 Hz, 3H), 1.62 (s, 3H), 4.18 (m, 1H), 4.40-4.46 (m, 2H), 6.51 (d, J = 8.8 Hz, 1H), 6.64 (t, J = 7.5 Hz, 1H), 7.09-7.15 (m, 2H), 7.20-7.25 (m, 3H), 7.33-7.41 (m, 5H), 7.63-7.67 (m, 2H), 7.82 (d, J = 6.8 Hz, 1H), 7.85-7.89 (m, 2H), 7.94 (d, J = 7.3 Hz, 1H). ¹³C NMR (100 MHz, CD₂Cl₂) δ 15.7 (q), 24.6 (q), 33.3 (d), 73.0 (t), 114.4 (s), 119.6 (d), 119.7 (d), 120.3 (d), 124.3 (d), 124.9 (d), 125.1 (d), 125.3 (d), 127.0 (d), 127.4 (d), 127.8 (d), 127.9 (d), 128.5 (2xd), 128.8 (2xd), 129.0 (s), 130.3 (d), 131.9 (d), 132.1 (d), 132.9 (s), 133.1 (s), 135.7 (s), 137.9 (2xs), 138.5 (s), 138.6 (s) , 140.2 (s), 140.8 (s), 154.7 (s), 173.0 (s), 173.4 (s). m/z (EI⁺, %) = 521 (M⁺, 100), 416 (15). HRMS (EI⁺): calcd for C₃₆H₂₇NO₃: 521.1991, found 521.1992.

7.8 References

Chapter 7


13 The pitch lengths presented are an average of three measurements per optical micrograph. The average deviation is always within 5%.

