ELUCIDATING THE BACKBONE CONFORMATION OF PHOTOSWITCHABLE FOLDAMERS USING VCD

The backbone conformation of amphiphilic oligo(azobenzene) foldamers is investigated using vibrational circular dichroism (VCD) spectroscopy on a mode involving the stretching of the N=N bonds in the backbone. From denaturation experiments, we find that the VCD response in the helical conformation arises mainly from through-space interaction between the N=N-stretch transition-dipole moments, so that the coupled-oscillator model can be used to predict the VCD spectrum associated with a particular conformation. Using this approach, we elucidate the origin of the VCD signals in the folded conformation, and can assign the observed partial loss of VCD signal upon photo-induced unfolding to specific conformational changes. Our results show that the N=N-stretch VCD response provides an excellent probe of the helical conformation of the N=N bonds in this type of switchable molecular systems.

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The content of this chapter has been published in:
4.1 INTRODUCTION

Molecular systems with the ability of undergoing conformational changes triggered by light have inspired the design of light-activated molecular machinery. [41, 42, 43, 44, 45, 46] An interesting class of such artificial molecular architectures are photoswitchable amphiphilic oligo(azobenzene) foldamers, which can be manipulated to undergo a helix-coil conformational transition upon photoisomerization around the N=N bonds, with extraordinary folding-unfolding efficiencies.[42, 47, 48, 49] The backbone of these foldamers consists of azobenzene monomeric units, which can be assembled to obtain molecular systems of various lengths (Fig. 13). The photo-induced trans-to-cis isomerization triggers a conformational change in the backbone of the $X_n$ azo helix (where $X$ denotes the number of phenylene units, and $n$ indicates the number of azobenzene moieties), causing it to unfold.[47, 48, 49] Refolding to the helical conformation can be achieved by irradiation with visible light or alternatively by thermal relaxation.[47, 48, 49]

![Figure 13: Side view along the y axis (left) and top view along the z axis (right) of the backbone structure of an $X_n$ azobenzene foldamer in its folded conformation. In this case, $X = 14$ and $n = 7$. The structure is optimized with the MM2[50] force field.](image)

As yet, the folding and unfolding of synthetic foldamers is generally investigated using electronic circular dichroism (CD).[51] which
provides a rather indirect probe of the helical backbone conformation. Here, we investigate the conformation and photo-induced conformational changes in azo-foldamers using vibrational circular dichroism (VCD) spectroscopy\(^{[52, 15]}\) on a vibrational mode involving the N=N-stretch and in-plane vibrations of the aromatic rings of the azobenzene units in the foldamer backbone. In the last decade VCD has emerged as a powerful structure-resolving tool to study chiral molecules. In most cases, the interpretation of VCD spectra relies on complementary density-functional theory (DFT) calculations, and combined with such calculations VCD provides detailed information on the configuration and conformation of chiral molecules in the condensed phase.\(^{[53, 40, 54, 55, 56, 57, 58, 59, 60, 61]}\) In particular, studies that combine VCD spectroscopy and \textit{ab initio} calculations show convincing results regarding the preferred secondary structures of foldamers.\(^{[62, 63, 64]}\) As an alternative to spectral interpretation using DFT calculations, the simpler, semiquan-
titative coupled-oscillator method, in which the molecular vibrations are treated as localized, interacting transition dipoles, is attractive because of its transparency and computational ease.\(^{[26, 27, 28, 29]}\) in particular for larger systems such as foldamers. Since we find that the N=N-stretch VCD signal of azo-foldamers arises predominantly from through-space interaction between the N=N-stretch transition-dipole moments, we can use this coupled-oscillator approach to interpret the observed foldamer VCD spectra. We find that the N=N groups give rise to unique VCD signatures, which not only provide direct access to the twist sense of the helical structure, but also contain more structural information than the conventional (electronic) CD spectrum.

4.2 MATERIALS AND METHODS

The synthesis and purification of the foldamers have been reported elsewhere.\(^{[47]}\) Fourier-transform infrared (FTIR) and VCD spectra were obtained with a Bruker Vertex 70 spectrometer in combination with a PMA 50 module for polarization modulation measurements. Samples of the 147 foldamer were prepared in CD\(_3\)CN and CD\(_2\)Cl\(_2\) and kept
in sealed infrared cells with CaF$_2$ windows. Photo-switching of the 147 foldamer was performed using a 450W Xe lamp (Müller Elektronik) and a notch filter with T=12% at $\lambda=358$ nm (FWHM=45 nm). The cartesian coordinates of the nitrogen atoms in the backbone of the 147 foldamer were retrieved from an optimized structure obtained using the MM2[50] force field (Fig. 13).

4.3 MODE ASSIGNMENT

The folded conformation of a 147 azo-foldamer is structurally organized as follows: an alternating sequence of seven azobenzene units is connected through ethynylene bridges. The side chains consist of oligo(ethylene glycol) moieties, which are attached to the main chain azobenzene phenyl rings and thus provide the necessary solvophobic driving force for folding in a polar medium.[47] In addition, the presence of the side-chains causes a symmetry breaking around the N=N bond. This lower symmetry as compared to non-substituted azobenzene gives rise to infrared activity of the vibrational mode involving mainly the stretching of the N=N bond. For simplicity, we will from now on refer to this mode (which also involves the phenyl ring vibration) as the N=N-stretch mode. The infrared activity of the N=N-stretching mode in such non-symmetrically substituted trans-azobenzene systems has been convincingly demonstrated for a series of compounds in a recent combined experimental and theoretical study. [65] We confirmed our assignment of the IR band at $\approx 1450$ cm$^{-1}$ to this mode by quantum-chemical calculations on an isolated substituted azobenzene unit (Fig. 14). The geometry optimization and calculation of harmonic vibrational frequencies were performed at the DFT/BLYP/6-31G(d) level of theory for a simplified model of the system, where we substitute the oligo(ethylene glycol) branches by ethyl-ester groups. Fig. 14 displays the calculated displacement vectors and direction of the transition-dipole moment for the N=N-stretching mode. We find the transition dipole to be approximately collinear ($\approx 15^\circ$) with the N=N bond.
Initially we investigate to what extent the observed VCD signal arises from through-space interactions between the N=N-stretch transition-dipole moments. Previous studies with electronic CD have shown that the helical content of 147 in CD$_3$CN solution progressively vanishes upon addition of CDCl$_3$ to the solution due to the reduction of the solvophobic effect. We therefore measured the IR and VCD spectra of a $10^{-4}$ M solution of 147 in CD$_3$CN and CD$_2$Cl$_2$ (Fig. 15; CD$_2$Cl$_2$ rather than CDCl$_3$ was used as a solvent because of strong infrared absorption of CDCl$_3$ in the N=N-stretch region). We find no N=N-stretch VCD signal arising from the denatured, optically-inactive conformation of the foldamer in apolar media. This proves that the VCD signals observed for the folded conformation (black solid line in Fig. 15) arise mainly from the helical arrangement and through-space coupling of the N=N-stretch vibrational chromophores.

4.4.1 Coupled-oscillator model for the N=N-stretch modes

To calculate the vibrational frequencies and the vibrational circular dichroism of a helical azo-foldamer containing n N=N groups using
Figure 15: Infrared absorption (upper panel) and VCD (lower panel) spectra of the 147 azo-foldamer in the folded (CD3CN, solid black lines) and unfolded conformation (CD2Cl2, dashed red lines).

In the coupled-oscillator model, we use the formalism derived by Diem et al.[30] Due to the interaction between the N=N-stretch modes, the N=N-stretch normal modes will be delocalized over the helix, i.e., they will involve the vibrational motion of more than one chromophore. These delocalized normal modes are the eigenstates of the excitonic Hamiltonian

$$H = \begin{bmatrix}
\nu_0 & J_{12} & J_{13} & \cdots & J_{1n} \\
J_{21} & \nu_0 & J_{23} & \cdots & J_{2n} \\
J_{31} & J_{32} & \nu_0 & \cdots & J_{3n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
J_{n1} & J_{n2} & J_{n3} & \cdots & \nu_0
\end{bmatrix}$$

(51)

where $\nu_0$ is the frequency of an unperturbed N=N-stretch mode, $J_{ij}$ the coupling between N=N-stretch modes $i$ and $j$. The Hamiltonian $H$ is a symmetric (Hermitian and real) matrix so that $J_{ij} = J_{ji}$. The interaction between the N=N groups is described by transition-dipole coupling:

$$J_{ij} = \frac{1}{4\pi\epsilon_0} \left[ \frac{\langle \mu_i \cdot \mu_j \rangle}{|r_{ij}|^5} - \frac{3(\langle \mu_i \cdot r_{ij} \rangle)(\langle \mu_j \cdot r_{ij} \rangle)}{|r_{ij}|^5} \right],$$

(52)
where \( \vec{r}_{ij} \) is the distance vector between dipoles \( \vec{\mu}_i \) and \( \vec{\mu}_j \) (Fig. 16). Note that the meta-linkages between the individual azobenzene repeated units prevent any through-bond coupling due to cross-conjugation.

Figure 16: Schematic representation of a \( X_n \) foldamer backbone with three monomeric N=N units. Each transition dipole is considered to be collinear with the respective N=N bond.

The dipole-dipole interaction lifts the degeneracy of the N=N-stretching frequencies, and gives rise to as many delocalized normal modes as there are interacting N=N oscillators. The vibrational frequencies of these delocalized normal modes (excitons) are the eigenvalues of the excitonic Hamiltonian matrix \( H \). The dipole (D) and rotational (R) strengths for the kth exciton are given by[30]

\[
D_k = \sum_{i=1}^{N} \sum_{j=1}^{N} b_{ik} b_{jk} (\vec{\mu}_i \cdot \vec{\mu}_j) 
\]

and

\[
R_k = -\left( \pi \nu_0 / c \right) \sum_{i=1}^{N} \sum_{j=1}^{N} b_{ik} b_{jk} (\vec{r}_{ij} \cdot \vec{\mu}_i \times \vec{\mu}_j),
\]
where \( c \) is the velocity of light in vacuum, and the \( b_{ij} \) are the components of the eigenvectors of the Hamiltonian. The infrared absorption and vibrational circular dichroism spectra are calculated using Eqs. 53 and 54, respectively, and convoluted with a Lorentzian band profile of 4 \( \text{cm}^{-1} \) FWHM.

### 4.4.2 147 azo-foldamer

In Fig. 17a and 17b (solid lines) we show experimental FTIR and VCD spectra of the 147 azo-foldamer, respectively, in the N=N-stretch spectral region. Using the experimental infrared absorption spectrum (Fig. 17a, solid line), we determine the magnitude of \( \tilde{\mu} \) from the integrated absorption coefficient \( A = \int \epsilon(\nu)\,d\nu \). This value is used to calculate the coupling terms in Eq. 52 and construct the Hamiltonian with solely \( \nu_0 \) as a free parameter. Fig. 17c and 17d show simulated infrared absorption and VCD spectra (with \(|\tilde{\mu}| = 0.12 \text{ Debye}\)), respectively, for the N=N-stretch modes calculated using the coupled-oscillator formalism described above. The experimental VCD pattern, which exhibits a characteristic bisignate signal (positive couplet), is nicely reproduced in the simulated spectrum. The three most IR-intense calculated eigenmodes have vibrational frequencies 1452, 1451 and 1450 \( \text{cm}^{-1} \). The remaining four predicted eigenmodes have extremely weak intensities (less than 5% of the total intensity) and therefore are neglected in the following analysis.

Fig. 18 displays the three most intense normal modes as color coding on schematic representations of the 147 backbone structure. The color code is used to illustrate the relative amplitudes (eigenvector coefficients \( b_{ij} \)) of the N=N oscillators in the eigenmodes that constitute the VCD spectrum (Fig. 17d). Eigenmode I (Fig. 18–I), which gives rise to the negative VCD peak (\( \approx 1452 \text{ cm}^{-1} \)) has its origin in a strong coupling (with negative amplitudes) of the three vertically aligned N=N units (terminal and central unit), while the interior units are not strongly involved. On the other hand, eigenmode II (Fig. 18–II), which gives rise to the positive VCD peak (\( \approx 1448 \text{ cm}^{-1} \)), originates from strong coupling (with positive amplitudes) of the terminal and central N=N unit (as opposite to eigen-
Figure 17: Observed (a,b) and calculated (c,d) infrared absorption and VCD spectra of the $\text{N=N-stretching mode}$ for the $\text{147 azo-foldamer}$ in its folded conformation (E form, red curves). Infrared absorption and VCD spectra for the $\text{147 azo-foldamer}$ upon photo-excitation are depicted in dashed-lines (Z form, black curves). Observed (b) and calculated (d) VCD spectra of a native $\text{105 azo-foldamer}$ (dashed blue curves).

mode I) in addition to a strong coupling (with negative amplitudes) between the remaining interior N=N groups. Finally, eigenmode III arises from strong contributions with opposite signs from the interior N=N units (the N=N units involved are depicted with the same color code in Fig. 18), while both terminal and central units have negligible contributions (Fig. 18–III). It is thus clear that the most intense VCD peaks arise from normal modes involving triply stacked terminal N=N groups. This is confirmed by measurement on a $\text{105 foldamer}$ which lacks such triple-stacked arrangement. The VCD spectrum of a native-helical $\text{105}$
Figure 18: Schematic representation of the relative amplitudes (eigenvector coefficients $b_{ij}$) of the N=N oscillators in the eigenmodes I–($1452$ cm$^{-1}$), II–($1451$ cm$^{-1}$) and III–($1450$ cm$^{-1}$) respectively.

foldamer is shown in Fig. 17b (dashed blue curve). The lack of signal intensity is consistent with a helical conformation lacking triple-stacked N=N units when compared with that of the 147 foldamer (with 7 N=N
units). Moreover, in Fig. 17d (dashed blue curve) we show the simulated VCD spectrum of a 10₅ foldamer obtained with $|\vec{\mu}| = 0.12$ Debye as an input parameter in the model. The signal magnitudes are extremely weak compared with those of the 14₇ foldamer, which confirms our conclusion that the VCD arises mainly from the triple-stacked N=N bonds.

Clearly, the coupled-oscillator formalism applied to the backbone N=N units successfully describes the observed features in the VCD spectrum of the 14₇ azo-foldamer. The good agreement of simulated and observed spectral features confirms the conclusions from the previously reported ECD spectra regarding the native-folded conformation of the azo-foldamer backbone.[47, 48, 49] The nice agreement between the observed and the modeled VCD spectra furthermore nicely corroborates the right-handed helix twist sense (P-helicity), which was previously assigned based on the shape of the exciton couplet.[66, 67]

4.4.3 Photo-induced 14₇ unfolding

To determine the effect of azobenzene E→Z photoisomerization on the VCD response we irradiated a 10⁻⁴ M solution of 14₇ in CD₃CN at $\lambda = 358$ nm using a 500W Xe lamp equipped with a notch filter for a period of 24 h to assure reaching the photostationary state (PSS). Upon irradiation, the 14₇ azo-foldamer undergoes a helix-coil transition, leading to a PSS in which a fraction of the N=N units is in the Z-configuration, leading to partial denaturation of the folded helical state. Previous studies have shown that in the PSS approximately 40% of the N=N units that are in the Z-form belong to the termini.[47] The IR and VCD spectra in the PSS are shown in Fig. 17a and 17b (dashed lines). While the IR spectrum shows only a slight red-shift, the VCD couplet is reduced in intensity by approximately 50%. This decrease in signal magnitude corroborates the previous conclusions based on electronic circular dichroism experiments, [47] where the decrease in signal intensity was assigned to the loss of excess helicity of the azo-foldamer. The observed decrease in intensity of the VCD bisignate signal (Fig. 17b) is consistent with the predicted role of eigenmodes I, II as local probes for the coupling of
the N=N termini and core units, which is partially disrupted upon photoisomerization. Moreover, the partial denaturation of the foldamer, i.e., the reorientation of the termini and subsequent loss of helical content, effectively leads to the formation of a 10₅-type foldamer, in which the backbone is still a helical structure, but now with less transoid backbone N=N units. This observation is in agreement with the unfolding mechanism proposed in which unfolding occurs predominantly starting from the termini of the foldamer.[47]

4.5 CONCLUSION

Our results demonstrate that VCD can be used to probe conformational changes during the folding and unfolding of azobenzene foldamers. The fact that the measurements can be interpreted using a simple coupled-oscillator approach ensures a straightforward relation between observed VCD spectra and the foldamer conformation. Much more detailed information can be obtained from VCD measurements on foldamers in which specific N=N bonds have been isotope-labeled. These labeled N=N bonds will have a different local-mode stretching frequency, and will be spectrally isolated from the other N=N bonds. They can therefore be described by a smaller (ideally 2 × 2, if two N=N bonds are labeled) Hamiltonian. Such experiments should make it possible to probe conformational changes at specific sites in the foldamer backbone, and the interpretation should be just as straightforward as for the unlabeled foldamers studied here.