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Photoinversion of *Cisoid*/*Transoid* Binaphthyls

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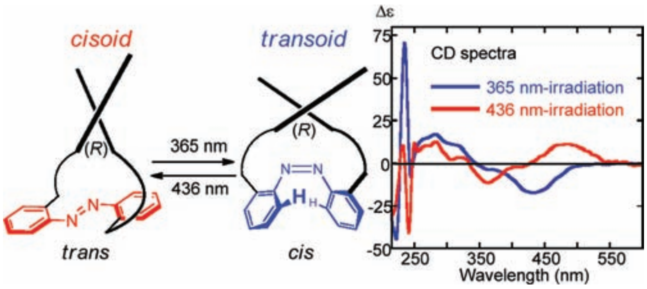
ABSTRACT



Axially chiral binaphthyl-azobenzene cyclic dyads in which the two moieties are connected by two linkers of different lengths were synthesized. In the case of benzylated-binaphthyl analogue 2b, photoirradiation resulted in a dramatic change of the CD spectrum and optical rotation. Experimental and theoretical analyses indicated that the dihedral angle of the two naphthalene rings is strongly coupled to the azobenzene photoisomerization; *cis*-azobenzene induces a *transoid*-binaphthyl structure, while *trans*-azobenzene induces a *cisoid*-binaphthyl structure.

Axially chiral binaphthyls have a wide chiral space around their axes. Hence, they have been extensively used as asymmetric catalysts, for specific molecular recognition, and to induce helical twisting of liquid crystals. In most cases, the dihedral angle between the two naphthalene rings, θ, plays an important direct or indirect role in these functions; moreover, some of the properties of *cisoid*- and *transoid*-binaphthyl (Figure 1b) differ from each other.[1] On the other hand, azobenzenes are widely used in light-driven molecular switches and molecular machines, because they exhibit dramatic structural changes in response to photoirradiation.[2] In general, UV light isomerizes *trans*- to *cis*-azobenzene, whereas visible light or heat isomerizes *cis*- to *trans*-azobenzene. Optically active azobenzene adducts have recently been developed as chiroptical switches.[3−5]

We have previously investigated the helical chirality of *cis*-azobenzenes, the planar chirality of *trans*-azobenzenes, and the switching of chiroptical properties, e.g., optical rotation and circular dichroism (CD), using axially chiral

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binaphthyl-azobenzene cyclic dyads, mainly **1a**, **1c**, **2a**, and **2c** (Figure 1a).[6] Among the chiroptical properties, the CD spectrum is useful to identify the conformation and configuration of all or part of a chiral compound. In the CD spectra of our dyads, the signal in the shorter-wavelength region (around 240 nm) is derived from the ^1B_b transition of the naphthalene rings, which reflects mainly the value of θ (C(9)−C(1)−C(1′)−C(9′), Figure 1b),[7] while the signal in the longer-wavelength region (over 350 nm) reflects the helical chirality of *cis*-azobenzene[6d] and the twisting direction of *trans*- azobenzene.[6e] The CD spectra in the shorter-wavelength region of (*R*)-**1a** and (*R*)-**1c** were very similar (Figure S1) and showed a typical negative split CD, indicating a value of θ of ca. 90°, representing a somewhat *cisoid* conformation. In contrast, the spectral shapes of benzylated (*R*)-**2a** and (*R*)-**2c** were greatly different from each other; that is, the first strong Cotton effects at around 240 nm were negative for (*R*)-**2a** and positive for (*R*)-**2c** (Figure S2). These results indicated that the value of θ of the benzylated analogues depends strongly on the length of the linkers. Based on this finding, we speculated that it might be possible to achieve reversible photoinversion, i.e., *cisoid*/*transoid* transformation, of the benzylated binaphthyl-azobenzene dyads. Compounds in which θ could be controlled by photoirradiation would potentially have wide application.

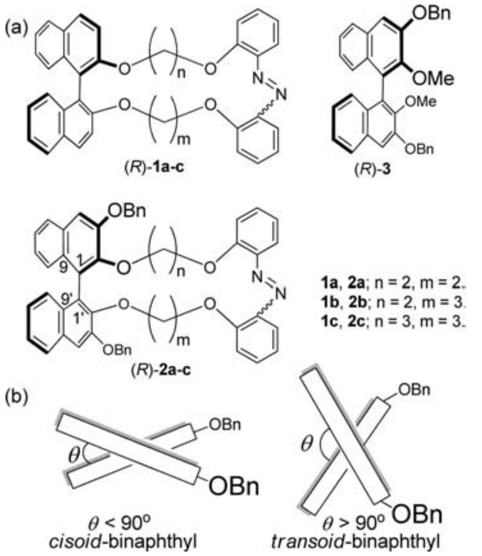

Figure 1. Binaphthyl-azobenzene cyclic dyads (*R*)-**1a**−**c**, (*R*)-**2a**−**c**, and a model binaphthyl (*R*)-**3**. (b) View of the frame format of *cisoid*- and *transoid*-binaphthyls.

First, we attempted to predict θ of (*R*)-**2a** and (*R*)-**2c** by calculation. Inoue et al. reported calculations on the relationship between the θ, energy difference, and CD spectra of 2,2′-dimethoxy-1,1′-binaphthyl.[8] With reference to their work, we examined the relationship between the CD spectra and θ of model binaphthyl (*R*)-**3** by calculation at the DFT-D-B97D/TZVP level[9] (Figure S5).[10] The predicted CD spectra suggested that the binaphthyl skeleton of (*R*)-**2a** favors the *cisoid* form, while that of (*R*)-**2c** favors the *transoid* form, whether the azobenzene structure is in *cis*- or *trans*-form. Therefore, we considered that (*R*)-**2b**, in which the two moieties are connected by two linkers of different lengths, might exhibit novel behavior; i.e., it might be possible to achieve *cisoid*/*transoid* binaphthyl conversion by means of photoirradiation.

Figure 2a shows the optimized structures of the *cis* and *trans* forms of (*R*)-**2b**. Dihedral angles θ of the optimized structures were 110° for (*R*)-*cis*-**2b** and 81° for (*R*)-*trans*-**2b**. However, it should be noted that the permissible conformations of each compound may include these optimized conformations but do not seem to be limited to them, because of metastable states due to molecular flexibility. Therefore, the relationship between energy difference and θ was analyzed (Figure 2b). Energy minima of both (*R*)-*cis*- and (*R*)-*trans*-**2b** appeared to be localized to a

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(8) Nishizaka, M.; Mori, T.; Inoue, Y. *J. Phys. Chem. Lett.* **2010**, *1*, 1809. They pointed out that the DFT calculations with common density functionals (e.g. B3LYP, PBE0) were not suitable for this type of calculation, but the DFT-D-B97D or RI-CC2 level should be used.

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small region, i.e., the *transoid*-binaphthyl region for (*R*)-*cis*-**2b**, and the *cisoid*-binaphthyl region for (*R*)-*trans*-**2b**. Essentially, the binaphthyl skeleton, (*R*)-**3**, was more stable in the *transoid* than the *cisoid* form, and the plot pattern was in agreement with that of (*R*)-*cis*-**2b** (Figure S6). Based on the calculated energies, it appeared that photoinversion of *cisoid*/*transoid* binaphthyls with $\Delta\theta$ of ca. 30° might be feasible using (*R*)-**2b**. To test this idea, we synthesized and analyzed (*R*)-**2b**.

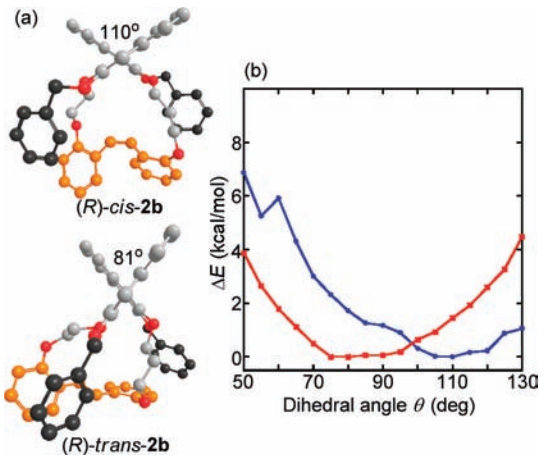
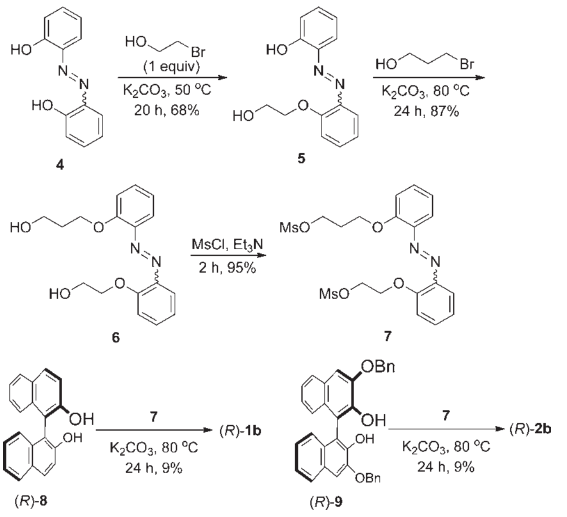


Figure 2. (a) Optimized structures of (*R*)-*cis*-**2b** and (*R*)-*trans*-**2b** at the DFT-D-B97D/TZVP level. Azobenzene moieties are shown in orange, and benzyl groups in black. Hydrogen atoms are not shown. (b) Relationship between energy difference and binaphthyl dihedral angle of (*R*)-*cis*-**2b** (blue line) and (*R*)-*trans*-**2b** (red line) at the DFT-D-B97D/TZVP level.

Dyads (*R*)-**2b** and (*R*)-**1b**, a reference compound, were synthesized as shown in Scheme 1. Compound **5** was prepared in moderate yield by the coupling of 2,2′-dihydroxyazobenzene (**4**) and 1 equiv of 2-bromo-1-ethanol. Subsequently, compound **6** was obtained from **5** and 3-bromo-1-propanol. Usual dimesylation of **6** gave **7** in high yield. (*R*)-**1b** was prepared by tandem etherification of (*R*)-BINOL (**8**) and dimesylate **7**. (*R*)-**2b** was synthesized similarly, using benzylated binol (*R*)-**9**.[11] As is typical, *trans*→*cis* isomerization was efficiently induced by irradiation at 365 nm, whereas *cis*→*trans* isomerization was induced by irradiation at 436 nm. The isomerization ratio of the *cis*-form in $CDCl_3$ after irradiation at 365 nm was 0.88, and that of the *trans*-form after irradiation at 436 nm was 0.82 for (*R*)-**2b**.

Scheme 1. Synthesis of Binaphthyl-azobenzene Cyclic Dyads (*R*)-**1b** and (*R*)-**2b**



Absorption spectra of (*R*)-**2b** after photoirradiation are shown in Figure 3b. The spectra at shorter wavelength are similar for the two isomers. But, there was an enormous change in the absorption in the longer wavelength region over 350 nm, which is due to the azobenzene moiety, since the absorption wavelength of the binaphthyl skeleton is under 340 nm.[6,7] Absorption at about 350 nm is derived from the allowed π–π* transition of the *trans*-azobenzene and is useful as an indicator of isomerization. Meanwhile, there are major and global differences in CD spectra between the isomers (Figure 3a). The longer wavelength region (over 350 nm) reflects the twisting of azobenzene.[6d,e,12] Theoretical analysis indicated that (*R*)-*cis*-(*P*)-**2b** and (*R*)-*trans*-(p*S*)-**2b** were favored over other configurations.[13] Next, at shorter wavelengths, the CD spectra were drastically altered upon photoirradiation ($\Delta\varepsilon = +70$ at 235 nm after 365 nm irradiation; $\Delta\varepsilon = -41$ at 242 nm after 436 nm irradiation). These changes suggested that θ was altered as a result of the photoirradiation. To eliminate the influence of azobenzene, the CD spectra of the binaphthyl moiety (i.e., (*R*)-**3**) extracted from each optimized (*R*)-**2b** were calculated (Figure 4). These theoretical CD spectra were in good agreement with the experimental spectra and strongly supported the occurrence of *cisoid*-*transoid* photoinversion of (*R*)-**2b** as shown in Figure 2.[14] Compounds showing such a major photoinduced CD change have potential for the development of characteristic optical switches.[15] In contrast, the absorption and CD spectra of (*R*)-**1b** showed similar changes to those of (*R*)-**1a** and (*R*)-**1c** (Figure S3).

Regarding the conformation of our dyads, especially (*R*)-*trans*-**2b**, we suggest that the two different short linkers result in differential interaction between the benzyl groups and the azobenzene moiety, and suppress the twisting motion of the binaphthyl structure. This is supported by the splitting patterns and the chemical shifts of the benzyl

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[13] See Figures S10 and S11 in the Supporting Information. The results of calculation at the B97D and B3LYP levels were essentially the same. In all calculations on (*R*)-**2b** in the manuscript, these configurations were employed.

[14] The calculated CD of optimized (*R*)-**3** did not completely correspond to that of (*R*)-**3** extracted from (*R*)-**2b** because of the differences in the position of benzyl groups, linkers, and the molecular symmetry.

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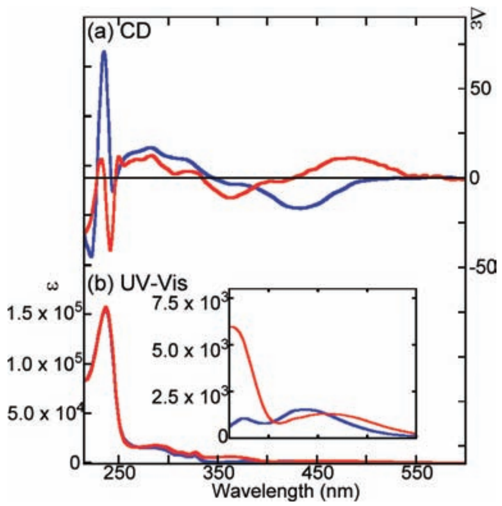

Figure 3. (a) CD spectra of (*R*)-**2b**; (b) absorption spectra of (*R*)-**2b** after irradiation at 365 nm (blue, rich in *cis*-form) and after irradiation at 436 nm (red, rich in *trans*-form). The inset shows an expanded version of part of the spectra. Conditions: 1,4-dioxane 1.0 × 10^{-5} M, 20 °C, light path length = 10 mm, irradiation at 10 mW/cm^2 for 100 s.

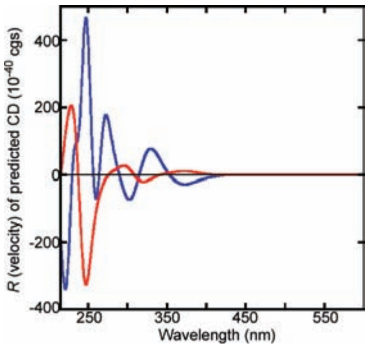

Figure 4. Calculated CD spectra of (*R*)-**3** extracted from optimized (*R*)-*cis*-**2b** (blue line) and from (*R*)-*trans*-**2b** (red line) at the DFT-D-B97D/TZVP level. Gaussian bands with a half-bandwidth of 2500 cm^{-1}.

protons of (*R*)-**2b** in the ^{1}H NMR spectra (Figure 5). The benzyl proton signals of (*R*)-*cis*-**2b** appeared as two singlets, one of which overlapped with a signal of (*R*)-*trans*-**2b**.[16] But, in (*R*)-*trans*-**2b**, one of the benzyl proton signals appeared as a singlet, while the other appeared as an AB quartet with a Δν of 0.18 ppm (53 Hz). The singlet peak may be that of the free rotatable benzyl group, which is located further from azobenzene, while the other benzyl group, which may interact with azobenzene owing to the shorter linker, shows the AB quartet. These signals indicated that benzyl substituents have an important influence on the overall conformation of dyads of this type. We were unable to detect NOEs between the benzyl groups, linkers, and azobenzene. (*R*)-**2b** should also be available as an optical rotation switch, as well as a CD switch. The value of optical rotation, $[\alpha]_D$ ($CHCl_3$, *c* 0.10, 20 °C), after irradiation of (*R*)-**2b** at 365 nm was −246°, whereas it was +710° after irradiation at 436 nm; i.e., there was a large, reversible change, with sign inversion. These changes derive from the anomalous dispersion of helical *cis*-azobenzene and twisted *trans*-azobenzene.[6d,e] The half-life of the *cis*-form of (*R*)-**2b** is over 300 h at 298 K.

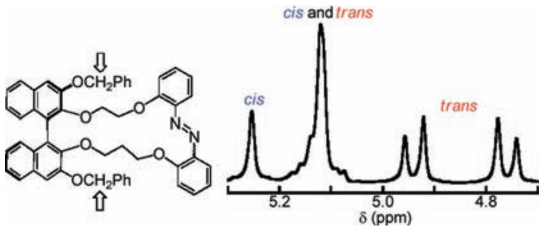

Figure 5. ^{1}H NMR spectra of benzyl protons of (*R*)-**2b** ([*cis*]/[*trans*] = 1:2.4, $CDCl_3$, 1 × 10^{-3} M, 295 K, 300 MHz).

In summary, axially chiral binaphthyl-azobenzene cyclic dyads connected by two different short linkers were synthesized. The azobenzene moieties were photoisomerized easily and efficiently. In the benzyl-substituted derivative (*R*)-**2b**, the *cis*-azobenzene structure induced the *transoid*-binaphthyl structure, and the *trans*-azobenzene structure induced the *cisoid*-binaphthyl structure. These structural changes were induced by photoirradiation at distinct wavelengths and were accompanied by changes of the CD spectrum and $[\alpha]_D$, including sign inversion. These results are relevant to the development of photocontrolled organocatalysts,[17] chiral dopants for liquid crystals, chiroptical switches, and other intelligent chiral materials.

Acknowledgment. We are grateful to members of the molecular characterization team at RIKEN for the spectral measurements. The calculations were performed by using the RIKEN Integrated Cluster of Clusters (RICC).

Supporting Information Available. Synthesis, spectra, computational details, and thermodynamic parameters of novel compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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[16] It is also possible that the overlapped peaks of (*R*)-*cis*- and (*R*)-*trans*-**2b** are AB quartets with small Δν.

[17] Wang, J.; Feringa, B. L. *Science* **2011**, *331*, 1429. (b) Berryman, O. B.; Sather, A. C.; Lledó, A.; Rebek, J., Jr. *Angew. Chem., Int. Ed.* **2011**, *50*, 9400.