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Enantiopure Anthrylene–Ethynylene Cyclic Tetramer and Racemization via Rotation of Anthracene Unit about Acetylenic Axes[1]

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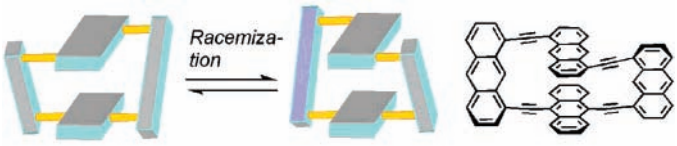
ABSTRACT



Four anthracene and four acetylene units are used to construct a chiral π-conjugate macrocycle, the chirality of which is due to the restricted rotation about acetylenic axes. Enantiomers were readily resolved by chiral HPLC and racemized slowly even at 70 °C.

The rotation about the acetylenic axes plays important roles in the molecular design of arylene−ethynylenes and related compounds that are used to create various types of molecular machines and devices.[2] For example, the rotation of C_{60} or phenylene moieties about the acetylenic axes is the driving force in Tour's nanocars[3] and Garcia-Garibay's gyroscopes.[4] Whereas the rotation of terminal arene units requires very low energy in ordinary diphenylethynes,[5] the basic unit in these molecular machines, the rotational barriers can be enhanced by attaching sterically bulky substituents at both ends. For example, barrier heights were studied by the dynamic NMR technique for diphenylethyne derivatives with four phenyl groups (51 kJ mol^{-1})[6] or four phenylethynyl groups (78 kJ mol^{-1})[7] at all of the ortho positions: the latter is the highest for acyclic diarylethynes.[8] For the cyclic system, a higher barrier was reported by Bedard and Moore for a turnstile-type compound consisting of a spindle moiety and a rigid macrocycle (>86 kJ mol^{-1}), although only the

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lowest limit of the rotational barrier was given.[9] These findings prompted us to prepare conformationally restricted structures with the anthrylene−ethynylene oligomer system, which we have extensively utilized for the creation of new π-conjugated compounds.[10] We designed the cyclic structure of **1**, in which four anthracene groups were connected by acetylene linkers at various positions (Figure 1). Actually,

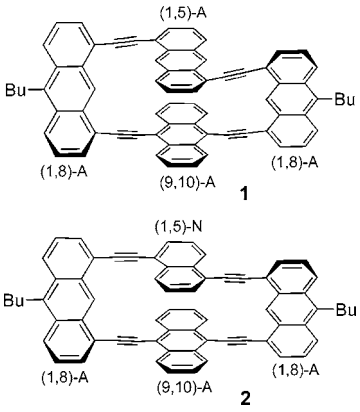
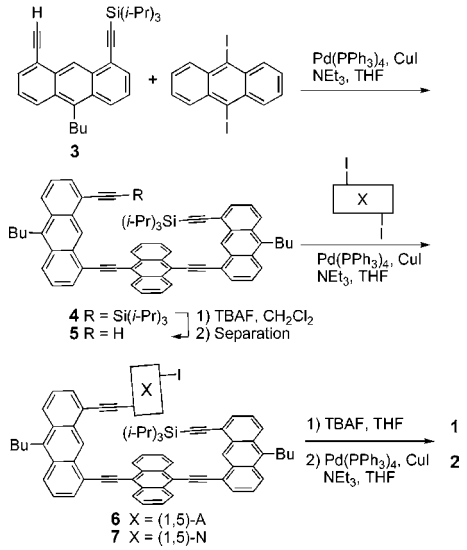


Figure 1. Target macrocyclic compounds with abbreviated designations of arylene moieties: A, anthrylene; N, naphthylene. Numbers in parentheses indicate connection sites.

this structure allowed us to resolve enantiomers at room temperature without racemization via rotation of arylene moieties about the acetylenic axes. We herein report the synthesis, structures, and stereochemical features of the macrocyclic compound as a member of the cyclophyne family.[11]

We synthesized compound **1** having four anthracene moieties and its mononaphthalene analogue **2** according to the reactions in Scheme 1. Butyl groups at (1,8)-A units (see Figure 1 for abbreviations) practically improve the solubility, and the incorporation of the (1,5)-arylene moiety is important not only to restrict the cranking motion by the nonlinear connection but also to reserve an NMR probe for the observation of conformational changes. Trimer **4** was prepared by the coupling of **3**[10b] with 9,10-diiodoanthracene.[12] Then, one of the silyl groups in **4** was removed with TBAF. The terminal alkyne moiety in **5** was coupled with 1,5-diiodoanthracene[13] to give tetrameric precursor **6**. Desilylation and subsequent Sonogashira coupling afforded desired macrocyclic compound **1** in 30% yield after chromatographic purification in addition to a mixture of sparingly soluble higher oligomers. Naphthylene compound **2** was similarly synthesized with 1,5-diiodonaphthalene[14] in 25% yield in the macrocyclization step. Both compounds were obtained as orange crystals and reasonably characterized by spectroscopic methods (see the Supporting Information).

Scheme 1. Synthesis of Compounds **1** and **2**



The X-ray structure of **1** is shown in Figure 2.[15] The structure is approximately C_2 symmetric, as expected from

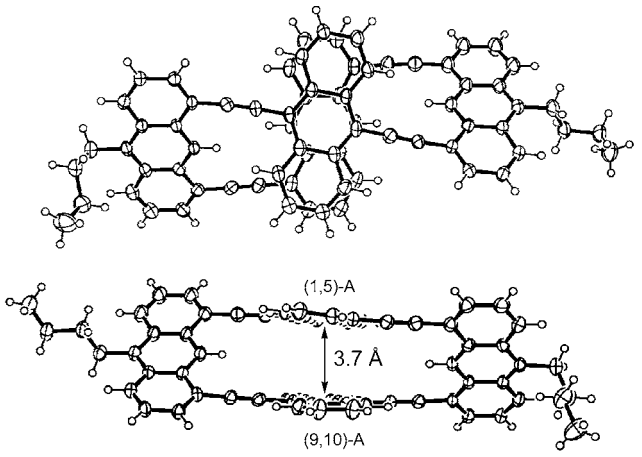


Figure 2. Two views of the X-ray structure of **1**. Solvent molecules are omitted for clarity.

the molecular model. There is no significant bending deformation at alkynic carbons (bond angles 174.8−178.8°). The dihedral angles between (1,8)-A and (9,10)-A and those between (1,8)-A and (1,5)-A are all ca. 40°, creating a relatively flat box structure. The two anthracenes, (9,10)-A and (1,5)-A, are nearly parallel and almost completely overlapped with each other with the interlayer distance of 3.7 Å. This distance is slightly large for significant intraannular $\pi-\pi$ interactions between aromatic moieties (cf. vdW radius of C(sp^2) 1.7 Å). Although we were unsuccessful with the X-ray analysis of **2**, the molecule is expected to take a C_2-symmetric structure with a parallel oriented pair of (9,10)-A and (1,5)-N.[16]

In the UV−vis spectra, compound **1** showed a broad absorption band centered at 453 nm with a shoulder extending to 530 nm (Figure 3). The corresponding absorp-

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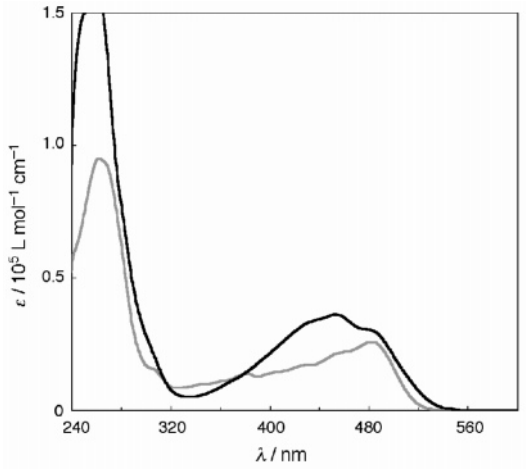
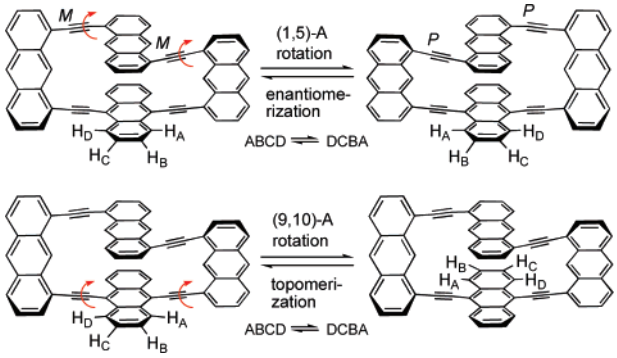


Figure 3. UV−vis spectra of **1** (black) and **2** (gray) in $CHCl_3$.

tion for **2** was observed in the same region but with weak intensity. Emission bands were observed at 547 nm (Φ_f 0.21) and 525 nm (Φ_f 0.35) for **1** and **2**, respectively. These electronic spectra gave no direct evidence of transannular interactions between the aromatic moieties, CT-type absorption, or excimer-type emission, being consistent with the molecular structures discussed above.

The NMR signal pattern of **1** was consistent with the C_2-symmetric structure, where the protons in (9,10)-A were observed as an ABCD system rather than an AA′BB′ system at room temperature and even at +140 °C (Scheme 2). This

Scheme 2. Rotation of (1,5)-A and (9,10)-A Moieties and Site Exchange of Protons in (9,10)-A in **1** (Butyl Groups Are Omitted for Simplicity)



means that the dynamic processes averaging H_A and H_D (or H_B and H_C) are frozen on the NMR time scale even at high temperature: the barrier should be higher than 92 kJ mol^{-1}. These exchanges are caused either by the rotation of (1,5)-A about the acetylene linkers by 180° (enantiomerization) or by that of (9,10)-A (topomerization).

We successfully resolved the enantiomers of **1** by chiral HPLC with a Daicel CHIRALPAK IA column. Two peaks were separated surprising well for hydrocarbon samples, and their retention times were 27.2 and 52.4 min (α 2.96) under the conditions (see Supporting Information). The specific rotations of the easily and less easily eluted isomers were $[\alpha]^{22}_D$ +800 and −830, respectively. The CD spectra of (+)- and (−)-isomers are mirror images of each other, and the (+)-isomer showed a strong peak at 272 nm ($\Delta\epsilon$ +228) and weak troughs at 249 and 418 nm (Figure 4). Racemization

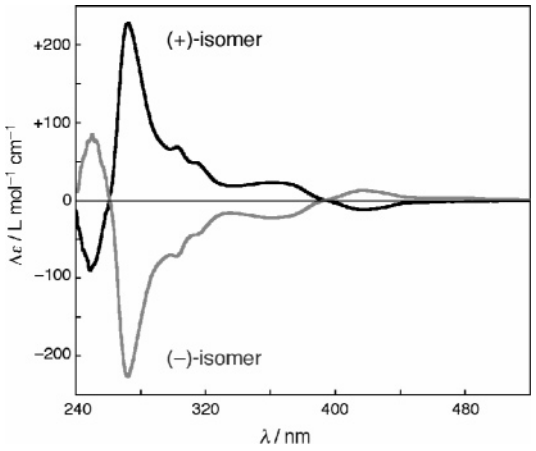


Figure 4. CD spectra of enantiomers of **1** in $CHCl_3$.

of enantiopure **1** proceeded slowly at high temperature, and its barrier was determined by classical kinetics with chiral HPLC to be $\Delta G^{\ddagger}_{343}$ 114 kJ mol^{-1} in octane at 70 °C. Because the enantiomerization takes place only by the rotation of (1,5)-A as illustrated in Scheme 2, this barrier is necessarily equal to the rotational barrier. These enantiomers are novel because their chirality is solely due to the restricted rotation of the arylene moiety about the acetylenic axes in the ring structure. To the best of our knowledge, this rotational barrier is the highest for cyclic diarylethyne systems of which barriers were experimentally established.[17]

Similar experiments were carried out with (1,5)-N derivative **2**. Proton signals due to (9,10)-A were observed as an

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(15) Crystal data for **1**: orange crystals, formula $C_{72}H_{48}\cdot{}^1/_2(C_6H_{14})$, M = 956.24; monoclinic, space group $P\bar{1}$ (No. 2), a = 13.5511(19) Å, b = 14.798(2) Å, c = 14.896(3) Å, α = 106.893(6)°, β = 108.340(7)°, γ = 101.250(5)°, V = 2574.5(7) Å^3, Z = 2, μ(Mo Kα) = 0.39 cm^{-1}, T = 93 K, F(000) = 544, 11754 unique reflections, R1 = 0.084, Rw = 0.244 (all data). CCDC 669771 contains supplementary crystallographic data for this paper. These data can be obtained online free of charge (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: (+44) 1223-336-033; or deposit@ccdc.cam.ac.uk).

(16) We calculated the structures of **1** and **2** without butyl groups at the B3LYP/6-31G level. In the optimized structures, the interlayer distances between (9,10)-A and (1,5)-arylene are 4.4 and 4.9 Å for the model compounds of **1** and **2**, respectively: the former is clearly larger than the experimental value. This trend, namely, the underestimation of attractive $\pi-\pi$ interactions, is common to similar oligomers at this calculation level.

AA′BB′ system even at −90 °C in CD_2Cl_2. Therefore, the rotation of either or both (1,5)-N and (9,10)-A takes place rapidly on the NMR time scale in **2**: the barrier is expected to be <40 kJ mol^{-1}. We failed to resolve its enantiomers of **2** by chiral HPLC. These kinetic data show that length of the crank moiety, (1,5)-arylene, considerably influences the rotational barriers. In the transition state, one flanking side of the crank moiety should roll into the macrocyclic ring. Therefore, the transition state of **1** is much more destablized by the steric repulsion between the arene moieties as well as the deformation of the actylenic linkers than that of **2**.

These molecules are considered to be chiral with respect to a plane defined by the (1,5)-arylene moiety. We can designate the enantiomers of **1** in Scheme 2 as (*M*,*M*)- and (*P*,*P*)-forms according to the helical arrangement of anthracene moieties along the two acetylene linkers connecting (1,5)-A and (1,8)-A.[18] Further studies are expected to clarify the absolute stereochemistry.

In summary, we constructed a chiral macrocyclic structure with four anthracenes and four acetylenes units. Racemization via rotation of the (1,5)-A moiety within the macrocyclic framework is sufficiently slow to enable separation of the enantiomers of **1** at room temperature. This compound shows versatility of the molecular design based on two kinds of simple building units and reveals a new aspect of isolable enantiomers in conformational studies of rotation about acetylenic axes.

Acknowledgment. This work was partly supported by a Grant-in-Aid for Scientific Research on Priority Areas "Advanced Molecular Transformations of Carbon Resources" (No. 19020069) from MEXT (the Ministry of Education, Culture, Sports, Science and Technology, Japan) and by "High-Tech Research Center" Project for Private Universities: matching fund subsidy from MEXT. We thank Prof. J. Otera of Okayama University of Science for useful discussions. The X-ray analysis was carried out with a diffractometer installed at the Institute for Materials Chemistry and Engineering, Kyushu University.

Supporting Information Available: Experimental procedures, compound characterization data, ^{1}H NMR, ^{13}C NMR, fluorescence spectra, HPLC chart, and X-ray data of **1** (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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