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Resolution and chiroptical properties of $[3_2](1,4)$barrelenophanedicarbonitrile[†]

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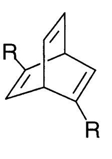
Abstract—(±)-$[3_2]$(1,4)Barrelenophane was completely resolved into its enantiomers by HPLC separation using a chiral stationary phase (Chiralcel OD) with hexane/propan-2-ol (1:9). The specific rotations and circular dichroism spectra of (+)- and (−)-$[3_2]$(1,4)barrelenophanes indicated the enantiomeric relationships. The longest absorption band at 360 nm (ε 541, CH_2Cl_2) is identified mainly as an intramolecular charge transfer band between the benzene ring and the double bond conjugated with cyano groups. The X-ray structure of the (+)-isomer has been determined. © 2001 Published by Elsevier Science Ltd.

1. Introduction

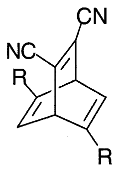
Bicyclo[2.2.2]octa-2,5,7-triene, barrelene **1**, was first synthesized by Zimmerman et al. in 1960 and was named after the barrel-shaped electron cloud of three carbon–carbon double bonds.[1] Barrelene has attracted much attention because of its reactivity, and molecular and electronic structures. Barrelene has D_{3h} symmetry and is non-dissymmetric. Replacement of two hydrogen atoms on sp^2 carbon atoms of **1** makes the molecule dissymmetric as is the case of 2,4- and 2,5-disubstituted derivatives. This was realized by Paquette et al., who reported the synthesis of homochiral 2,5-dideuteriobarrelene **2** {(1*S*)-[2,5-$^2H_2$]bicyclo[2.2.2]octa-2,5,7-triene} and its chiroptical properties.[2] 2,3-Dicyanobarrelene **3** is also non-dissymmetric (C_{2v}),[3] but the 5,7-disubstituted derivative **4** (R = Me) is dissymmetric (C_2). Recently, planar-chiral compounds derived from $[2_2]$(1,4)cyclophane have attracted significant attention as efficient reagents and ligands for asymmetric synthesis and catalysis.[4]

In the previous paper, we reported the synthesis of $[3_2]$barrelenophanedicarbonitrile **5** by the Diels–Alder reaction of $[3_2]$(1,4)cyclophane and dicyanoacetylene, and its photochemical conversion to cyclooctatetraenophane and semibullvalenophane.[5] These cyclophanes were obtained as racemic mixtures, and the optical properties of their enantiomers are of special interest. Herein, we report on the first optically active barrelenophanes (+)- and (−)-**5** with C_2 symmetry.

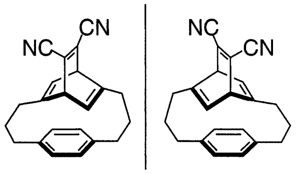
Racemic (±)-**5** was completely resolved into its enantiomers by HPLC separation using a chiral stationary phase {Daicel Chemical Industries, Ltd: Chiralcel OD [cellulose tris(3,5-dimethylphenylcarbamate)]} with hexane/propan-2-ol (10:90). The first-eluted sample is the (+)-barrelenophane **5**, and the second one is the (−)-**5**.



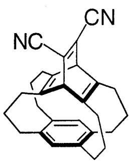
1, R = H
2, R = D



3, R = H
4, R = Me



5



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[†] Multibridged $[3_n]$cyclophanes. Part 15.

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The specific rotation of the former sample is +72 (c = 0.275, $CHCl_3$), whereas that of the latter is −71 (c = 0.188, $CHCl_3$). The circular dichroism (CD) spectra of the resolved enantiomers were measured in order to ensure enantiomeric relationships.

The CD spectrum of (+)-**5** is a mirror image of that of (−)-**5** as expected (Fig. 1), confirming the enantiomeric nature of the two compounds. Three Cotton effects of (+)-**5** ($\Delta\varepsilon = -5.0$, −4.9, and +2.6) and (−)-**5** ($\Delta\varepsilon = +3.6$, +3.5, and −1.6) at 274, 280, and 354 nm are seen. These enantiomers are the first examples of chiral barrelenophanes. The former two absorptions are assigned to the π–π^* transitions [UV λ_{max} (ε) = 272 (1215), 279 (sh, 1062) nm, CH_2Cl_2], while the Cotton effect with the longest wavelength is identified as the intramolecular charge transfer (CT) band [UV λ_{max} (ε) = 360 (541) nm, CH_2Cl_2].[5a] INDO/S calculations indicate that the CT band corresponds to the transannular π–π^* transition from the benzene ring (HOMO) to the dicyanoethylene moiety (LUMO) as well as the though-space transition from two double bonds of the barrelene framework to the dicyanoethylene moiety (Fig. 2).[6] [3_4]Barrelenophane **6** also shows an intramolecular CT band but at a longer wavelength than that of **5** (408 nm, ε = 347, CH_2Cl_2).[5b] The corresponding CT bands of dicyanobarrelenes **3** and **4** appear at 315 nm (ε = 830) and 339 nm (ε = 450) in CH_3CN,[7] respectively, and these CT bands are attributed to the transition from the two double bonds to the conjugated double bond with two cyano groups. Significant red-shifted CT bands of **5** and [3_4]barrelenophane **6** compared with dicyanobarrelenes **3** and **4** suggest that the CT band is mainly due to the π–π^* transition from the benzene ring to the double bond conjugated with the cyano groups. This type of intramolecular electronic interaction between two chromophores is a characteristic property of [3_n]cyclophanes.[8]

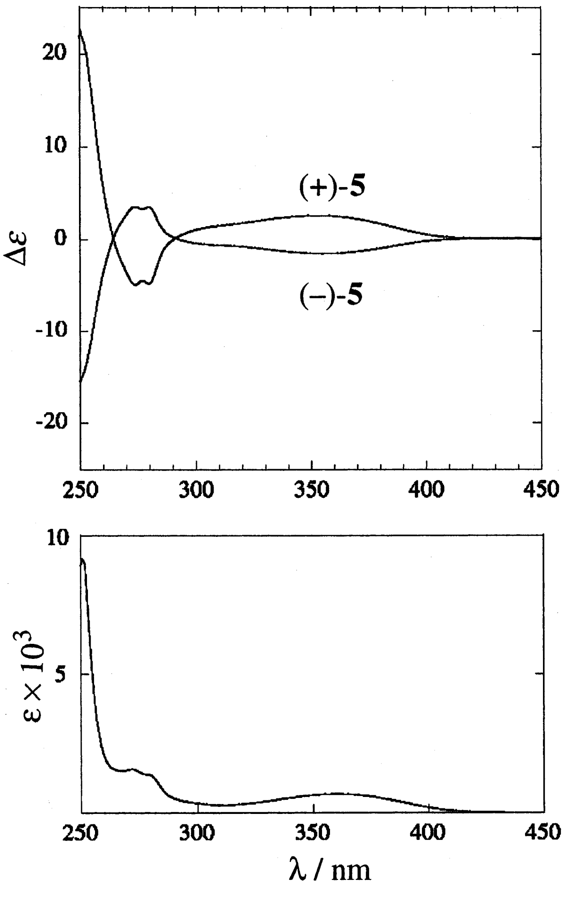

Figure 1. CD and electronic spectra of the barrelenophanes (+)-**5** and (−)-**5** in CH_2Cl_2.

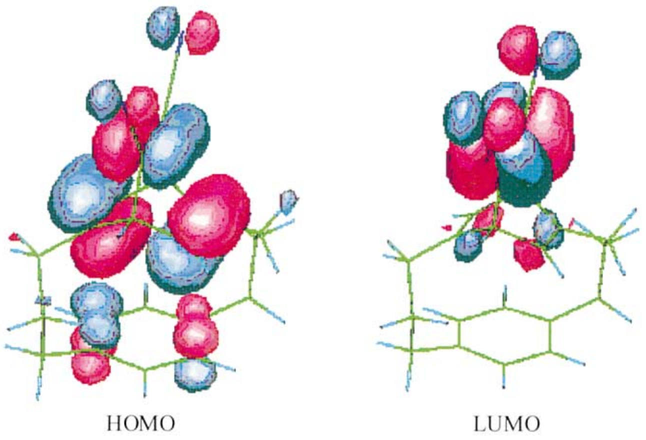

Figure 2. INDO/S calculated molecular orbitals of [3_2]barrelenophanes **5**.

The X-ray structure of (+)-barrelenophane **5** is shown in Fig. 3. The (+)-**5** is present as a chiral space group $P1$. The distances and angles are similar to those of racemic barrelenophane **5**.[5a] Four molecules of **5** have almost the same structures, but one carbon bridge chain of the molecule **D** is disordered. The populations of these carbons C83, C84, and C85 are 45:55. The bridgehead carbons of the barrelene moiety are normal sp^3 hybridized, and two cyano groups are located in the same plane. The absolute structure of (+)-**5** cannot be determined at this stage.

In conclusion, the resolution of racemic barrelenophane **5** was achieved by HPLC using a chiral stationary column, the specific rotations of the enantiomers were determined in $CHCl_3$ solution and their CD spectra showed an antipodal relationship. The CT band of **5** is ascribed to a π–π^* transition from the benzene ring to the dicyanoethylene framework. X-ray structural analysis of (+)-barrelenophane **5** revealed the molecular geometry of the barrelene moiety.

2. Experimental

Barrelenophane **5** was prepared according to literature procedures.[5a] Resolution of (±)-barrelenophane **5**: (±)-**5** was achieved by high performance liquid chromatography using a Chiralcel OD column (4.6×250 mm) of Daicel Chemical Industries, Ltd. eluting with 2-propanol/hexane = 9:1 and 1 mL/min flow speed. The fractions were detected by UV (λ = 254 nm). About 5 mg of (±)-**5** was dissolved in ca. 10 mL of propan-2-ol. Each time 0.1 mL of the sample solution was injected

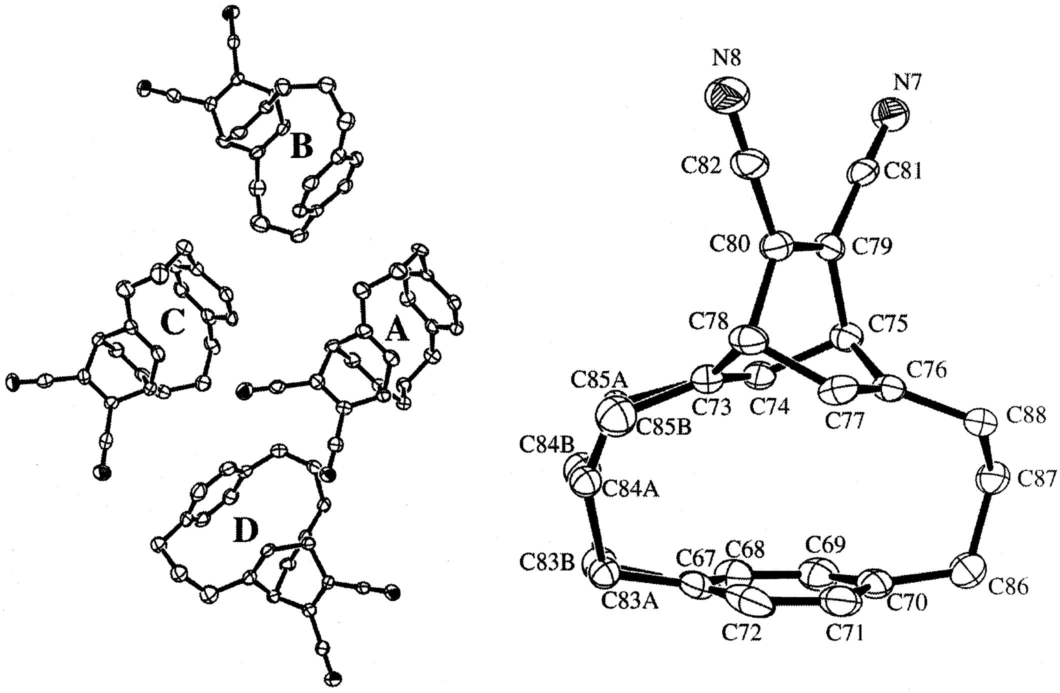

Figure 3. Crystal packing diagram of (+)-**5** (left) and ORTEP drawing of molecule **D** (right) at 50% probability. All hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (°): C73–C74 1.313(7), C74–C75 1.533(6), C75–C79 1.536(6), C79–C80 1.350(6), C79–C81 1.432(6), C81–N7 1.145(6), C73–C74–C75 115.7(4), C74–C75–C76 106.2(4), C74–C75–C79 105.0(3).

and separated. After repetition of the separation, all fractions containing pure enantiomers were combined to give (+)-**5** (4.4 mg, retention time 8.5 min) and (−)-**5** (3.9 mg, retention time 10.8 min). The optical rotations of (+)- and (−)-**5** were measured in $CHCl_3$ $\{[\alpha]_D^{23}=+72$ ($c=0.275$), $[\alpha]_D^{24}=-71$ ($c=0.188$)$\}$ by a Jasco P-1020 digital polarimeter. The enantiomeric purity was determined by HPLC with Chiralcel OD after recrystallization from CH_3CN: (+)-**5** 100% e.e.; (−)-**5** 100% e.e. Circular dichroism (CD) spectra were recorded on a Jasco J-720W spectropolarimeter. UV–vis spectra were recorded on a Hitachi U-3500 spectrophotometer.

Pale yellow crystals (+)-**5** suitable for X-ray crystallography were grown by slow evaporation of the solvent from a CH_3CN solution. X-ray crystal data for **5**: Rigaku R-AXIS-RAPID diffractometer, Mo Kα ($\lambda=$ 71069 Å), crystal dimensions 0.20×0.10×0.05 mm (yellow prism), $a=14.7035(7)$, $b=14.8250(7)$, $c=7.8818(4)$ Å, $\alpha=97.6770(10)°$, $\beta=91.6050(10)°$, $\gamma=96.449(2)°$, triclinic, space group $P1$ (no. 1), $T=93(2)$ K, $Z=4$, $V=1690.28(14)$ Å^3, $\mu_{Mo}=0.072$ mm^{-1}, $F(000)=664$, anode power 40 kV×32 mA, $\rho_{calc}=1.228$ g cm^{-3}, $2\theta_{max}=55.0°$; 7524 reflections were observed, number of parameters 863. The structure was solved by direct methods using SYSTEM90[9] and refined by full least-squares on F^2 using SHELXL-97.20.[10] The positions of all hydrogen atoms were calculated geometrically and refined by the riding model. The disordered part was refined isotropically. Goodness-of-fit on $F^2=0.967$, final R indices [$I>2.00\sigma(I)$]: $R_1=0.0549$, $wR_2=0.1040$. Largest difference peak and hole = 0.302 and −0.233 e Å^{-3}. The absolute structure cannot be determined reliably [Flock's χ-parameter −10(3)]. All computations were performed using the teXsan package.[11] Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-153556 **5**. Copies of the data can be obtained free of charge on application to the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: int. code+44-1223/336-033; e-mail: deposit@ccdc.cam.ac.uk].

Acknowledgements

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