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Rotational isomerism involving an acetylenic carbon. Part 5: Restricted rotation about acetylenic axis in sterically crowded bis(1-phenyl-9-anthryl)ethynes☆,☆☆

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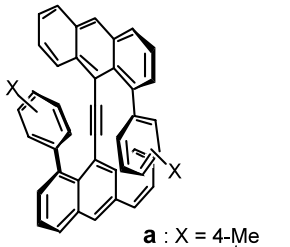
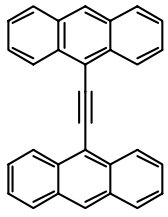
Abstract—The title sterically crowded di-9-anthrylethyne derivative with 3,5-$^{i}Pr_2$-phenyl groups at 1-position showed a barrier to rotation about the acetylenic axis of 18.0 kcal mol^{-1} based on a dynamic NMR study, which is an extremely high value for acyclic diarylethynes. The mechanism of the dynamic stereochemistry and the substituent effect on the rotational barrier are discussed.

An ethynylene unit (–C≡C–) is frequently utilized as a linker of aromatic systems in π-conjugated compounds because of its structural characteristics: it enables conjugation through alkyne p orbitals and linear linkage at a distance of ca. 4.0 Å.[1] In acyclic compounds, diarylethyne subunits usually undergo facile internal rotation about the acetylenic axis because of the negligible interactions between terminal aromatic moieties.[1–4] This conformational mobility about the long axis plays an important role in the dynamics of such functional molecules as a molecular barrow,[5] a gyroscope,[6] and a helix.[7,8] Recently, we reported the syntheses and structures of sterically crowded diphenylethynes bearing phenyl groups at all the *ortho* positions, bis(1,1′;3′,1″-terphenyl-2′-yl)ethynes.[9] Their rotational barriers, however, could not be enhanced sufficiently (ca. 7 kcal mol^{-1}) even though severe steric interactions were expected in a molecular model. By contrast, high rotational barriers were reported for macrobicyclic alkynes (>20.6 kcal mol^{-1})[10] and bis(9-triptycyl)ethynes (max. 18.8 kcal mol^{-1}),[11,12] which have a rigid framework or rigidly bound substituents. We therefore chose 1-substituted 9-anthryl groups as a bulky and rigid rotor for restricted rotation in diarylethyne derivatives. We demonstrate herein the synthesis and dynamic stereochemistry of bis(1-phenyl-9-anthryl)ethynes **1** in which restricted rotation about the acetylenic axis, C(sp^2)–C≡C–C(sp^2), was observed by dynamic NMR spectroscopy for the first time for acyclic diarylethynes.



1

a : X = 4-Me
b : X = 4-^{i}Pr
c : X = 3-^{i}Pr
d : X = 3,5-$^{i}Pr_2$



2

The parent di(9-anthryl)ethyne **2** was prepared by previously reported methods[13] chiefly for structural and spectroscopic studies.[14] However, we applied the Pd-catalyzed coupling reaction to establish another general access to the structure. Compounds **1** were synthesized according to Scheme 1: isopropyl groups in **1b–d** acted as an NMR probe for the dynamic measurement and as sterically demanding substituents. 1-Substituted 9-anthrones **4** were prepared from 1-iodo-9-anthraquinone **3** by the Suzuki coupling and Sn/HCl reduction. Anthrones **4** were converted into 9-TfO-anthracenes **5** (Tf: CF_3SO_2-) by treatment with a base followed by Tf_2O, where the use of LiHMDS and HMPA was essential for improvement of the yield.[15] The Stille coupling[16] of the triflates with bis(tributylstannyl)ethyne afforded the desired alkynes **1** as orange

Keywords: dynamic stereochemistry; sterically crowded alkynes; restricted rotation; dynamic NMR; X-ray analysis.

☆ For Part 4, see Ref. 9.

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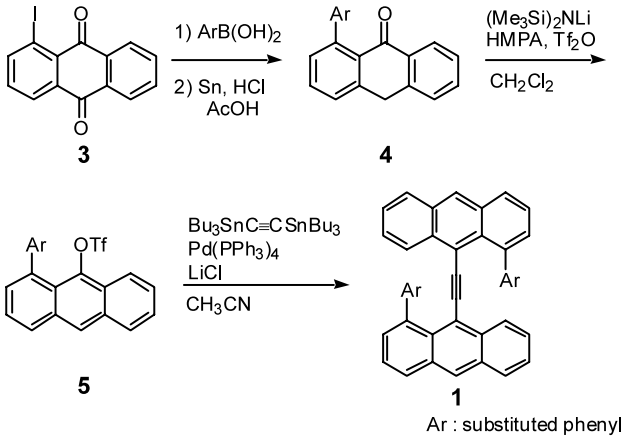
crystals (oil for **1c**) in moderate to good yields.[17] The UV–vis spectra of **1** showed a strong absorption at ca. 270 nm and weak ones at 380–450 nm, the latter bands being slightly blue-shifted compared with those of **2**.[18]

The X-ray structure of **1a** is shown in Figure 1.[19] The acetylenic axis is slightly deformed into a zigzag form with the bond angle at *sp* carbons being 170.5 and 171.5°.[20] Two 9-anthryl groups are staggered from each other about the acetylenic axis by 58.8°, and each 4-methylphenyl group is twisted relative to the attaching anthracene ring by ca. 59° to assume a parallel orientation with respect to the other anthracene ring (interfacial distance: ca. 3.7 Å). This structure reasonably explains the high-field shift of the ^{1}H NMR signals due to the 4-methylphenyl groups caused by the ring current effect: δ 1.12 (s, 6H), 6.29 (d, 4H), and 7.06 (d, 4H). Significant out-of-plane bending deformations were observed at the anthracene carbons at 1- and



Scheme 1. Synthesis of **1**.

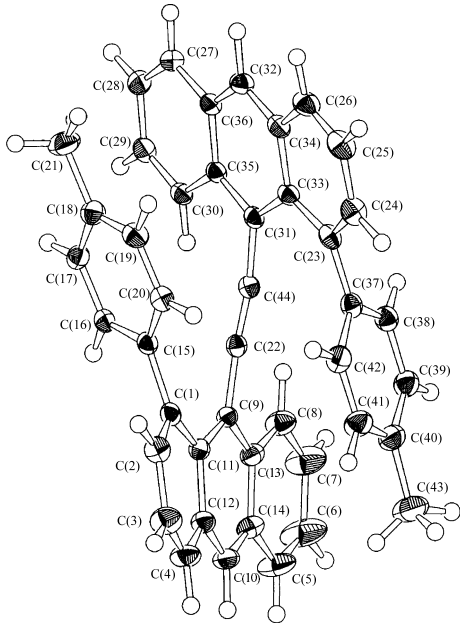


Figure 1. ORTEP drawing of **1a** with thermal ellipsoids at 50% probabilities.

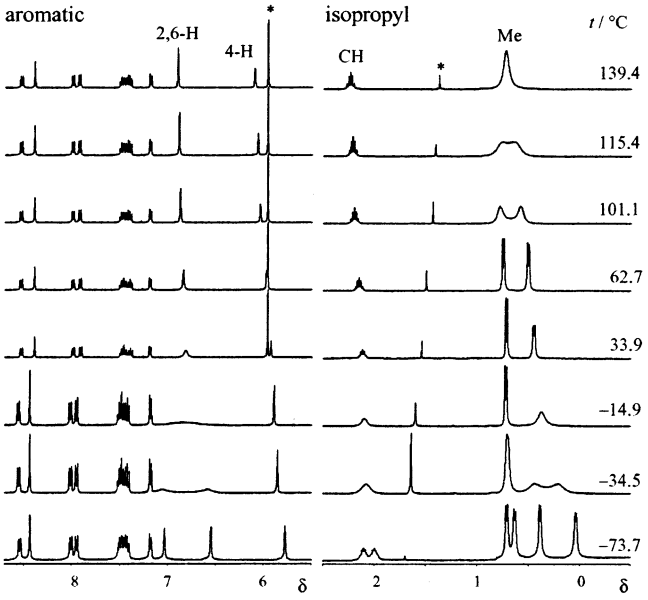
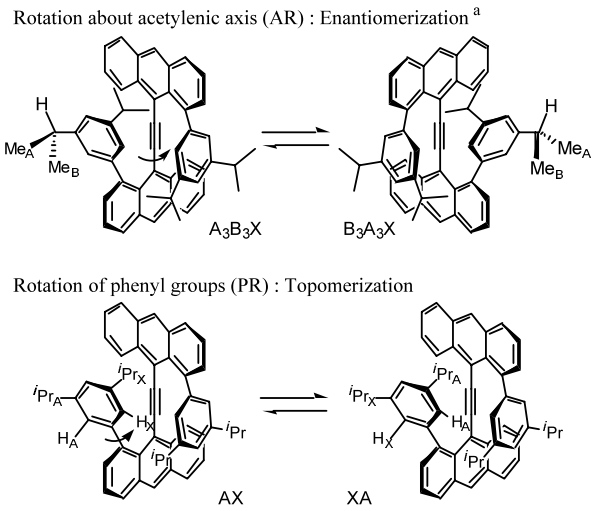


Figure 2. VT ^{1}H NMR spectra of **1d** in CD_2Cl_2 (<33.9°C) or $C_2D_2Cl_4$ (>62.7°C). *Signals due to solvents or H_2O.

9-positions to avoid steric hindrance between the *peri* substituents.

Variable temperature (VT) ^{1}H NMR measurements revealed lineshape changes in some proton signals of **1a**–**d**. The observed spectra of **1d** are shown in Figure 2 as a typical case. The signals due to the isopropyl-Me groups showed dramatic changes over a wide temperature range involving two steps: from four d (doublet coupled with a methine proton) to two d (−74→63°C) and then to one d (63→139°C), where each change was accompanied by broadening and coalescence. In the former temperature range, signals assigned to 2,6-H in the phenyl groups and the methine protons also showed lineshape changes, whereas the other aromatic signals remained unchanged throughout the measurements.

The above observations can be rationally explained by two independent dynamic processes: the rotation about the acetylenic axis (AR) and the rotation of phenyl groups with respect to the anthracene ring (PR) (Scheme 2). The AR leads to enantiomerization of two staggered conformations with a stereogenic axis, namely, site exchange of two diastereotopic Me groups in each ^{i}Pr group. On the other hand, the PR leads to topomerization that involves site exchange of two ^{i}Pr groups (or 2,6-H) in each Ph group. The two processes are almost frozen on the NMR time scale at −70°C to give a total of four d signals for the Me protons. At ca. 60°C, the facile PR averages the signals due to ^{i}Pr groups, and the AR is still sufficiently slow to keep the two Me signals of each ^{i}Pr group nonequivalent. The AR process is facilitated at higher temperatures and the signals are converged into one d. Total lineshape analysis of those signals allowed us to obtain the kinetic parameters of the two processes independently.[21] The analyses were similarly carried out for the other compounds (Table 1).



Scheme 2. Two independent dynamic processes observed in **1d**. [a]Actually, this AR process is coupled with the facile PR, which renders four ^{i}Pr groups magnetically equivalent.

The barrier to the AR process of **1d** (18.0 kcal mol^{-1}) is significantly high, and to the best of our knowledge, this is the first example of acyclic diarylethynes that show restricted rotation about the C(sp^2)–C≡C–C(sp^2) acetylenic axis on the NMR time scale.[22] Such a high barrier is attributed to the destabilization of the transition state of the AR process in the rigid system, where the 1-phenyl groups must pass over the anthracene groups. The substituent effect on the AR barrier follows the order **1d**≈**1c**>**1b**, suggesting that the presence of one ^{i}Pr group at the *meta* position is effective for the further enhancement.

It is notable that the two dynamic processes are independently observed in **1d**, the difference in energy reaching 6 kcal mol^{-1} at 273 K ($\Delta G^{\neq}_{AR}>\Delta G^{\neq}_{PR}$); namely, the tumbling of 1-phenyl groups over the *peri* group takes place ca. 7×10^4 times faster than the AR.[23] In contrast to **1d** as well as **1c**, the kinetic data obtained from the two probes are not so different for **1b**. We consider that the site exchange between the 3- and 5-Hs in the phenyl group in **1b** and perhaps in **1a** is partially or completely accompanied by the AR process ($\Delta G^{\neq}_{AR}\approx\Delta G^{\neq}_{PR}$) because the AR also gives rise to the site exchange required by the PR.[24] Further study is necessary to clarify the kinetic relationship between the two dynamic processes.

In conclusion, the rotation about the acetylenic axis can be sufficiently restricted on the NMR time scale at room temperature by using the rigid system of bis(1-phenyl-9-anthryl)ethyne. A marked preference of this structure over the bis(9-triptycyl)ethyne system is the synthetic accessibility from the corresponding anthrone. By introducing appropriate substituents on the anthracene rings, it may be possible to isolate a novel type of chiral aromatic compound with a long stereogenic axis.

Acknowledgements

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Table 1. Kinetic data of the dynamic processes in **1** as determined by the dynamic NMR method

	Probe[a]	$\Delta H^{\neq}$ (kcal mol^{-1})	$\Delta S^{\neq}$ (cal mol^{-1} K^{-1})	$\Delta G^{\neq}_{273}$ (kcal mol^{-1})
1a[b]	3,5-H (PR)	7.1±0.2	−16.3±0.8	11.5
1b	3,5-H (PR)	8.9±0.1	−6.0±0.6	10.5
	^{i}Pr (AR)	6.5±0.1	−17.6±0.8	11.3
1c[c]	2,6-H (PR)			ca. 11.0
	^{i}Pr (AR)			ca. 17.5
1d	2,6-H (PR)	9.0±0.2	−10.6±0.9	11.9
	^{i}Pr (AR)	15.4±0.2	−9.7±0.5	18.0

[a] 3,5-H or 2,6-H: phenyl proton signals at the indicated positions. ^{i}Pr: isopropyl-methyl signals. PR and AR: see text.
[b] This compound lacks a probe for the AR.
[c] Because the signals are very complicated due to the presence of diastereomeric conformers, only estimated free energies of activation are given.

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15. Triflates **5** are useful precursors and a source of substituted 9-anthryl groups for various coupling reactions. Akiba et al. reported the synthesis of 9-TfO-1,8-dimethoxyanthracene from the corresponding 9-hydroxyanthracene under the condition of NaH+Tf_2O/THF; however, this protocol gave a poor result for ordinary 9-anthrones. See, Akiba, K.-y.; Yamashita, M.; Yamamoto, Y.; Nagase, S. *J. Am. Chem. Soc.* **1999**, *121*, 10644–10645. A typical procedure of synthesis of **5**: To a solution of 2.70 g (9.50 mmol) of **4a** in 120 ml of dry CH_2Cl_2 were added 3.0 ml of HMPA and 15 ml of a solution of LiHMDS in THF (1.0 mol l^{-1}) at −78°C under an Ar atmosphere. The solution was stirred for 2 h below −70°C, to which 1.62 ml (9.60 mmol) of Tf_2O was added slowly. The reaction mixture was stirred for 12 h at the temperature, warmed up to room temperature, and then quenched with water. The organic materials were extracted with CH_2Cl_2. The organic layer was dried over $MgSO_4$, and evaporated. The crude product was purified by chromatography on silica gel with hexane–CH_2Cl_2 (1:1) eluent to give 2.95 g (74%) of **5a** as pale yellow solid. Mp 125.5–127.5°C (dec); Found FAB: M^+ 416.0673, calcd for $C_{22}H_{15}O_3F_3S$: M 416.0694; ^1H NMR ($CDCl_3$): δ 2.46 (s, 3H), 7.28 (d, $J=7.8$ Hz, 2H), 7.39 (brs, 2H), 7.49–7.62 (m, 4H), 7.99 (d, $J=8.3$ Hz, 1H), 8.05 (d, $J=8.1$ Hz, 1H), 8.19 (d, $J=8.6$ Hz, 1H), 8.55 (s, 1H).
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17. Compounds **1a**–**d** were satisfactorily identified by ^1H, ^{13}C NMR and mass spectroscopies as well as microanalysis. A typical procedure of synthesis of **1**: To 5 ml of degassed CH_3CN were added 37.8 mg (0.90 mmol) of LiCl, 83.3 mg (0.20 mmol) of **5a**, 11.6 mg (0.010 mmol) of $Pd(PPh_3)_4$, and 79 μl (0.15 mmol) of bis(tributylstannyl)ethyne. The whole was refluxed for 15 h under Ar atmosphere. After cooling, the reaction mixture was quenched with water, and extracted with ether. The separated organic solution was washed with aqueous NaCl, dried over $MgSO_4$, and evaporated. The crude product was purified by chromatography on silica gel to give 54 mg (96%) of **1a** as orange crystal. Mp 246.0–246.5°C. Found: C, 94.16%; H, 5.33%, calcd for $C_{44}H_{30}$: C, 94.59%; H, 5.41%. ^1H NMR (CD_2Cl_2): δ 1.12 (s, 6H), 6.29 (d, $J=7.6$ Hz, 4H), 7.06 (d, $J=7.6$ Hz, 4H), 7.22 (dd, $J=1.3$, 6.7 Hz, 2H), 7.43–7.55 (m, 6H), 8.01–8.04 (m, 4H), 8.38 (dd, $J=1.2$, 8.7 Hz, 2H), 8.44 (s, 2H).
18. A weak emission (λ_{em} 500 nm) was observed in the fluorescence spectra of **1**, its intensity being much lower than that of the reference compound **2**.
19. Crystallographic data for **1a**: $C_{44}H_{30}$, FW 558.72, monoclinic, C_2/c, $a=26.905(1)$, $b=14.784(2)$, $c=15.660(2)$ Å, $\beta=108.610(6)°$, $V=5903.4(10)$ Å^3, $Z=8$, $D_{calcd}=1.257$ g cm^{-3}, $R=0.070$, $R_w=0.111$. Crystallographic data (excluding structure factors) for the structure, have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 213941. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (Fax: +44(0)-1223-336033 or e-mail: deposit@ccdc.cam.ac.uk).
20. The ^{13}C NMR signal due to *sp* carbons was observed at ca. δ 104 for **1** (cf. δ 97.4 for **2**). This deshielding is partly attributed to the bending deformation.
21. Total lineshape analysis was performed using the DNMR3K program, which is a modified version of the DNMR3 program. (a) Binsch, G. *Top. Stereochem.* **1968**, *3*, 97–192; (b) Kleier, D.; Binsch, G. QCPE #165, Indiana University, Bloomington, IN, USA.
22. As for acyclic dialkylethynes, the highest barrier was recorded by (1,4-dimethyl-9-triptycyl)(1-mesityl-9-triptycyl)ethyne at 18.8 kcal mol^{-1}. See Ref. 11c.
23. One example of a similar dynamic behavior is the diastereomerization of 1,8-bis(3-substituted phenyl)-naphthalenes via the rotation of phenyl groups (barrier: 15–16 kcal mol^{-1}). House, H. O.; Campbell, W. J.; Gall, M. *J. Org. Chem.* **1970**, *35*, 1815–1819.
24. Strictly, this point should be discussed on the basis of the correlated rotation. At present, the extent of correlation is unclear from available data.