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Novel Synthesis of Benzalacetone Analogues of Naphth[*a*]azulenes by Intramolecular Tropylium Ion-Mediated Furan Ring-Opening Reaction and X-ray Investigation of a Naphth[1,2-*a*]azulene Derivative

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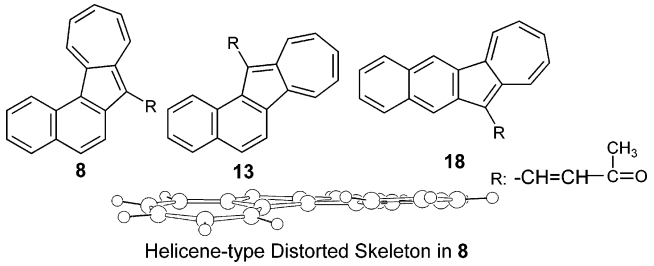
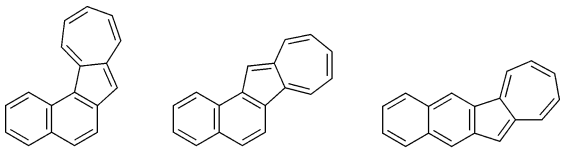


Benzalacetone analogues of naphth[1,2-*a*]azulene (**8**), naphth[2,1-*a*]azulene (**13**), and naphth[2,3-*a*]azulene (**18**) were synthesized from 2-(5-methyl-2-furyl)-1-tropylionaphthalene (**7**), 1-(5-methyl-2-furyl)-2-tropylionaphthalene (**12**), and 2-(5-methy-2-furyl)-3-tropylionaphthalene (**17**), respectively. The synthetic method is based on furan ring-opening reaction by the intramolecular electrophilic attack of a tropylium ion. Single-crystal X-ray work on the naphth[1,2-*a*]azulene derivative (**8**) revealed that its tetracyclic system exhibited deformation from planarity similar to that of benzo[*c*]phenanthrene (tetrahelicene). A centrosymmetric associated dimer structure, just like the molecules of carboxylic acids but via C=O···H−C hydrogen bonds, was found in the crystal. Reduction of bond-length alternation in the seven-membered ring was also found.

Introduction

Naphth[*a*]azulenes, which consist of the naphthalene ring condensed with the 1,2-position of the azulene ring, are molecules of considerable interest from both theoretical and experimental viewpoints. There are three isomeric skeletons of naphth[*a*]azulenes, **1**−**3**.



The molecules having skeletons **2** and **3** have been synthesized by Yasunami et al. through the Takase−Yasunami azulene-synthetic method.[1] To our best knowledge, however, the structure, as well as the synthesis, of compounds with skeleton **1** has not been reported. We recently found a novel, efficient synthetic method for aromatic-fused azulene nuclei having an α,β-unsaturated ketone group from the corresponding aromatic compounds having a 2-furyl group and tropylium ion on their adjacent carbon atoms.[2] This reaction apparently involves an intramolecular electrophilic attack of the tropylium ion on the 2-position of the furan ring, followed by a ring-opening reaction and synchronous aromatization (Scheme 1).

We set out to determine the scope and limitations of the reaction and to prepare novel aromatic-fused azulene

(1) Yasunami, M.; Yang, P. W.; Kondo, Y.; Noro, Y.; Takase, K. *Chem. Lett.* **1980**, 167.

(2) (a)Yamamura, K.; Yamane, T.; Hashimoto, M.; Miyake, H.; Nakatsuji, S. *Tetrahedron Lett*. **1996**, *37*, 4965. (b) Kusuhara, N.; Sugano, Y.; Takagi, H.; Miyake, H.; Yamamura, K. *Chem. Commun.* **1997**, 1951. (c) Sasabe, M.; Houda, Y.; Takagi, H.; Sugane, T.; Bo, X.: Yamamura, K. *J. Chem. Soc., Perkin Trans. 1* **2000**, 3786. (d) Yamamura, K.; Kusuhara, N.; Kondou, A.; Hashimoto, M. *Tetrahedron* **2002**, *58*, 7653. (e) Yamamura, K.; Houda, Y.; Hashimoto, M.; Kimura, T.; Kamezawa, M.; Otani, T. *Org. Biomol. Chem.* **2004**, *2*, 1413.

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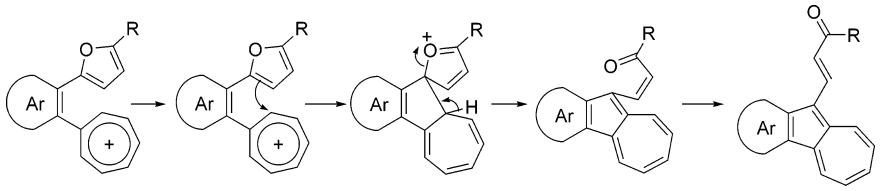
SCHEME 1



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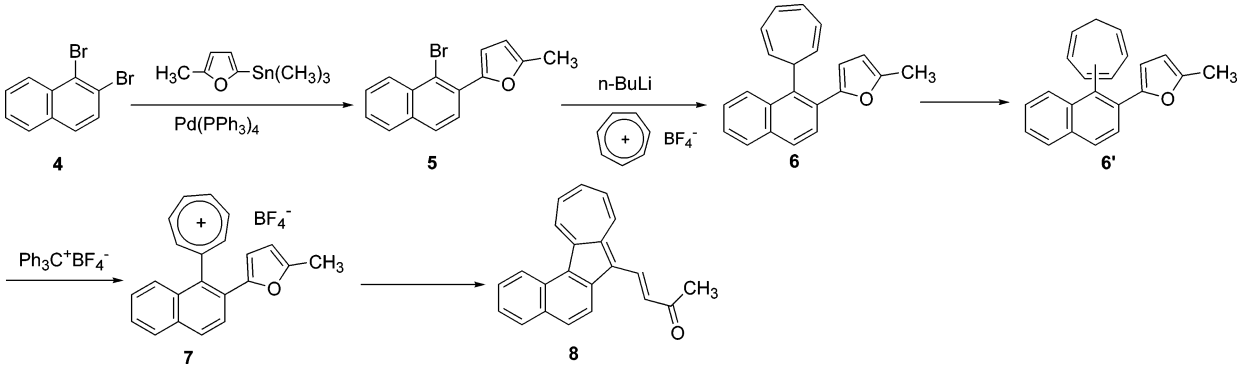

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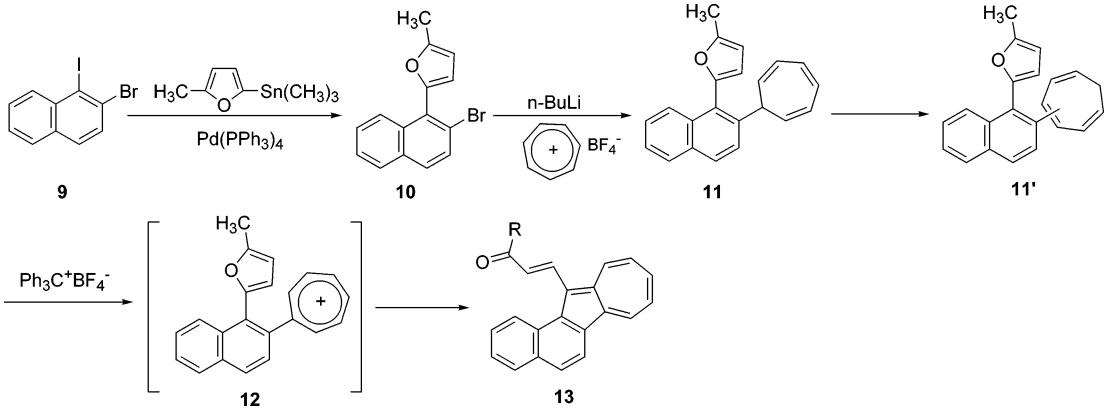


derivatives. Now we report in this paper on the synthesis of three isomers of naphth[*a*]azulenes having a but-2-en-3-one group, which are the analogues of benzalacetone. Furthermore, among these isomers, the naphth-[1,2-*a*]azulene system was predicted from the molecular model to show nonplanarity due to intramolecular steric hindrance. Then, we carried out X-ray work to reveal an unusual structure of the molecule (**8**), and the results are also reported briefly.

Results and Discussion

Synthesis of 4-(10-Naphth[1,2-a]azulenyl)-3-buten-2-one (8). The synthetic sequence leading to **8** from 1,2-dibromonaphthalene (**4**)[3] is depicted in Scheme 2. The palladium(0)-catalyzed Stille coupling reaction of 1,2-dibromonaphthalene (**4**) with 2-methyl-5-trimethylstannylfuran[2c] gave 1-bromo-2-(5-methyl-2-furyl)naphthalene (**5**) in 48% yield.[4] Compound **5** was treated with *n*-butyllithium in THF at −78 °C, followed by addition of powdered tropylium tetrafluoroborate to give 1-cycloheptatrienyl-2-(5-methyl-2-furyl)naphthalene (**6**) in 62% yield. To decrease the steric hindrance at the subsequent hydride-abstraction process, **6** was thermally isomerized by sigmatropic rearrangement to **6′**. The isomeric mixture **6′** was treated with triphenylmethyl tetrafluoroborate at ambient temperature for 5 min, followed by addition of ether, to afford 2-(5-methyl-2-furyl)-1-tropylionaphthalene (**7**) as a dark-colored precipitate. The spectra of **7** were not measured because **7** was fairly unstable. Refluxing the acetonitrile solution of **7** for 2 h gave the desired 4-(10-naphth[1,2-*a*]azulenyl)-3-buten-2-one (**8**), but the yield was only 26%. The use of 2,6-di-*tert*-butyl-4-methylpyridine as an acid scavenger[5] brought about marked increase in the yield (73%). Employing methoxymethylsilane[5] as an acid scavenger also brought about an increase in the yield (48%).

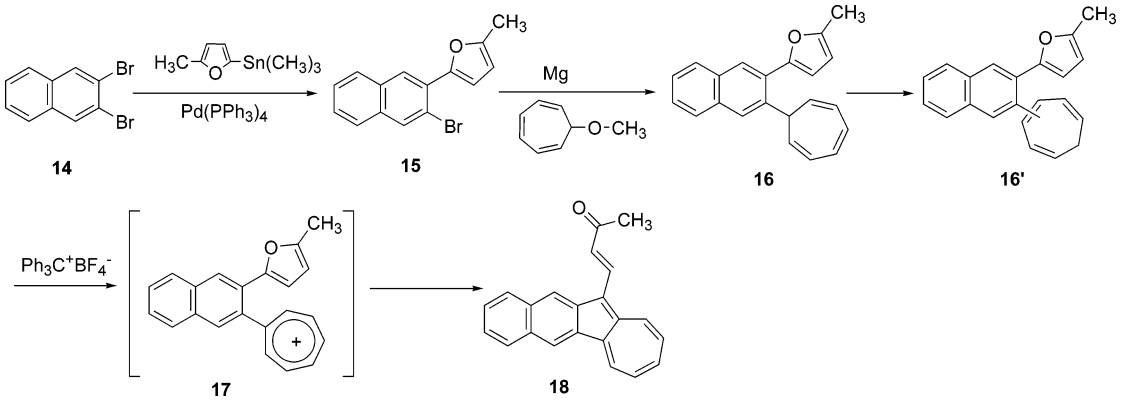
Synthesis of 4-(12-Naphth[2,1-a]azulenyl)-3-buten-2-one (13). Similarly, 4-(12-naphth[2,1-*a*]azulenyl)-3-buten-2-one (**13**) could be obtained as shown in Scheme 3. As the starting material for the synthesis of **13**,

(3) Miller, J. J.; Meek, J. S.; Strickler, S. J. *J. Am. Chem. Soc*. **1977**, *99*, 8175.

(4) The formation of 2-bromo-1-(5-methylfuryl)naphthalene was not detected.

(5) Becker, D. A.; Danheiser, R. L. *J. Am. Chem. Soc.* **1989**, *111*, 389.

SCHEME 4



2-bromo-1-iodonaphthalene (**9**)[6] was used instead of 1,2-dibromonaphthalene, because as mentioned above the Stille coupling reaction of 1,2-dibromonaphthalene with 2-methyl-5-trimethylstannylfuran exclusively gave 1-bromo-2-(5-methyl-2-furyl)naphthalene (**5**).

In contrast to the situation with 1,2-dibromonaphthalene, the Stille coupling reaction of 2-bromo-1-iodonaphthalene (**9**) with 2-methyl-5-trimethylstannylfuran proceeded on the 1-position of the naphthalene ring to give 2-bromo-1-(5-methyl-2-furyl)naphthalene (**10**) predominantly. Compound **10** was treated with *n*-butyllithium, followed by addition of tropylium tetrafluoroborate to give 2-cycloheptatrienyl-1-(5-methyl-2-furyl)naphthalene (**11**). The sigmatropic 1,5-shift of **11** gave **11′** quantitatively. When **11′** was treated with an equimolar amount of triphenylmethyl tetrafluoroborate in acetonitrile for 5 min at 0 °C, followed by addition of dry ether, a cationic dark-colored precipitate was obtained. The acetonitrile solution of this dark-colored precipitate changed rapidly into a mixture including the desired 4-(12-naphth[2,1-*a*]-azulenyl)-3-buten-2-one (**13**). Consequently, conversion of **11′** to **13** was achieved without isolation of the tropylium ion derivative (**12**) at room temperature. Without any acid scavengers, the yield of **13** was only 20%. When 2,6-di-*tert*-butyl-4-methylpyridine or dimethoxymethylsilane was used as the acid scavengers, the yield of **13** reached 54% or 49%,[7] respectively.

Synthesis of 4-(11-Naphth[2,3-a]azulenyl)-3-buten-2-one (18). Another isomer, 4-(11-naphth[2,3-*a*]azulenyl)-3-buten-2-one (**18**), could be obtained in a similar manner (Scheme 4). Because the tropylium ion derivative **17** was very unstable and its acetonitrile solution changed rapidly into a complex mixture, the conversion of **16** to the desired azulene derivative **18** was achieved without isolation of **17** using 2,6-di-*tert*-butyl-4-methylpyridine as the acid scavenger at room temperature. However, the yield of **18** from **16** was very low (13%). Although the reason for the low yield is not clear at present, a likely explanation is that in naphthalene the C(2)−C(3) bond is fairly longer than the C(1)−C(2) bond.

The structures of the naphthalene-fused azulene derivatives **8**, **13**, and **18** were established by their ^{1}H NMR and ^{13}C NMR spectra, as well as elemental analyses. The coupling constants between the olefinic protons on **8** (15.9 Hz), **13** (15.8 Hz), and **18** (15.8 Hz) show that the naphth[*a*]azulene ring and the carbonyl group are *trans* to each other. Moreover, the structure of **8** was unequivocally established by X-ray crystallographic analysis. If the above-mentioned reaction mechanism for the formation of these naphth[*a*]azulene derivatives is correct, the naphth[*a*]azulene ring and the carbonyl group are *cis* to each other. The reason for the formation of *trans*-isomers is not yet clear, but the following consideration may be permitted. Since the carbon−carbon double bond in these naphth[*a*]azulene derivatives has a certain single bond character due to the contribution of the dipolar resonance structure **8b** (vide infra) including a stable tropylium ion moiety, the initially formed *cis*-isomer changes into the more stable *trans*-isomer by the acid generated in the course of the reaction and/or by the posttreatment for the purification of the products.

Single-Crystal X-ray Analysis of 8. Molecular Structure of 8. The X-ray structures (top and side views) of **8** are shown in Figure 1 together with the atom-numbering scheme. In this figure, one can see the significant nonplanarity of the molecule. The angle between the mean planes of the terminal six-membered and the seven-membered rings (**A** and **D**, respectively) amounts to 11.0(2)°, and those between the mean planes of the neighboring ring systems are 2.6−8.4° (Table 1). The deviation from planarity observed for the tetracyclic system of **8** is analogous to that reported for benzo[*c*]-phenanthrene (tetrahelicene), which is the smallest nonplanar helicene.[8] The degree of the deviation of **8** is, however, less than that of the latter molecule, because the presence of the five-membered ring in **8** is effective in reducing the intramolecular overcrowding between H7 and H11 (see Figure 1).

Crystal Structure of 8. One of the molecular aggregation motifs in the crystal of **8** is the dimer structure, just like the molecules of carboxylic acid, via C−H···O=C hydrogen bonds (Figure 1). For the pair of molecules shown in Figure 1, the C(13)···O(1′) and H(13)···O(1′) distances (3.411(4) and 2.47(3) Å, respec-

(6) Bromo-1-iodonaphthalene (**9**) was synthesized from 2-bromo-1-naphthylamine according to the usual manner. 2-Bomo-1-naphthylamine was prepared from 1-tetralone in 31% yield according to the literature for the synthesis of 2-bromo-6,7-dimethoxy-1-naphthylamine: Geen, G. R.; Mann, I. S.; Mullane, M. V. *Tetrahedron* **1998**, *54*, 9875. **9**: yellow oil; ^{1}H NMR (250 MHz, $CDCl_3$) δ 7.51−7.56(m, 2H), 7.66−7.70(m, 2H), 7.76(d, 1H, J = 8.4 Hz), 8.23(d, 1H, J = 8.8 Hz). Anal. Calcd for $C_{10}H_6BrI$: C, 36.07; H, 1.82. Found: C, 36.33, H, 1.64.

(7) The yields of **13** are based on **11**.

(8) Lakshman, M. K.; Kole, P. L.; Chaturvedi, S.; Saugier, J. H.; Yeh, H. J. C.; Glusker, J. P.; Carrell, H. L.; Katz, A. K.; Afshar, C. E.; Dashwood, W.-M.; Kenniston, G.; Baird, W. M. *J. Am. Chem. Soc*. **2000**, *122*, 12629.

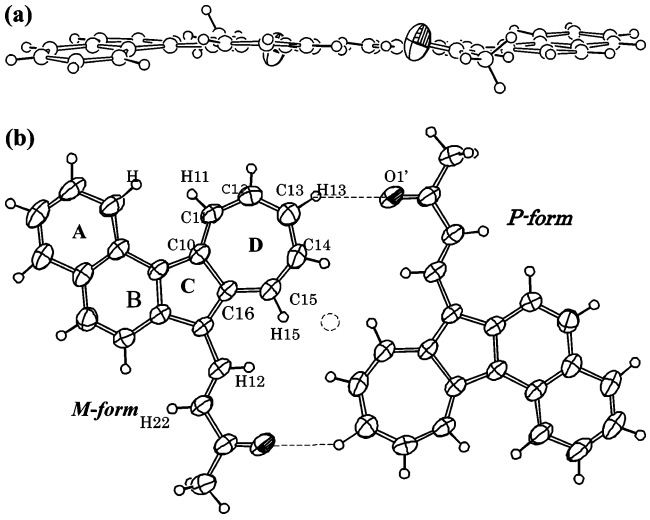


FIGURE 1. Structure of the molecule **8** and its dimer: (a) side view; (b) top view. A part of the numbering of the atoms is shown in (**b**). A, B, C, and D indicate the six-, six-, five-, and seven-membered rings, respectively. Broken lines and a circle in (b) indicate C−H···O hydrogen bonds and the center of symmetry, respectively.

TABLE 1. Angles between Mean Planes[a] (planes 1 and 2) of Ring Systems of 8

plane 1	plane 2	angle (deg)
A	B	4.6(2)
B	C	4.5(2)
C	D	2.6(2)
A	D	11.0(2)
naphthalene	azulene	8.4(1)

[a] For definition of the plane, see Figure 1.

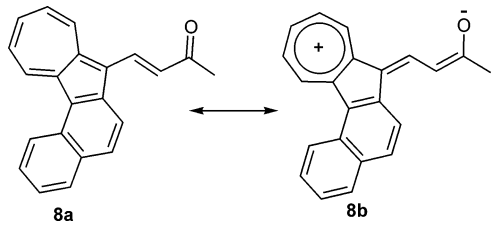


FIGURE 2. Resonance structure of **8**.

tively) satisfy the criteria reported for the general C−H···O hydrogen bond. This C−H···O=C hydrogen bond would be responsible for the stabilization of the *s-cis* form of the α,β-unsaturated carbonyl group found for **8**.

In compound **8**, contribution of the dipole resonance structure (**8b**) is thought to be fairly large because one of the resonance structures includes the stable tropylium ion moiety (Figure 2).

This dipole resonance structure contributes to increase in both the acidity of the hydrogen atoms on the seven-membered ring and the electron density of the carbonyl oxygen atom. This situation is favorable for the formation of the C−H···O=C hydrogen bonds. Analogous dimer structures have been found for the thiophene-fused and benzene-fused azulenes with the enone group, 4-(4-azuleno[1,2-*b*]thienyl)but-3-en-2-one[9] and 1,1,1-triphenyl-4-(10-benz[*a*]azulenyl)-but-3-en-2-one,[10] respectively.

It is known that aromatic annelation on the five-membered ring of the azulenes results in bond-length alternation in the seven-membered ring. The C(10)−C(11), C(11)−C(12), C(12)−C(13), C(13)−C(14), C(14)−C(15), and C(15)−C(16) bond lengths in **8** are 1.354(4), 1.388(5), 1.374(5), 1.385(5), 1.359(5), and 1.403(5) Å, respectively. The maximum difference between the longest and the shortest C−C bond lengths in the seven-membered ring of **8** is 0.049 Å, smaller than the corresponding ones for azuleno[1,2-*b*]thiophene (0.23 Å),[11] 9-phenylazulene (0.099 Å),[12] and 1,1,1-triphenyl-4-(10-benz[*a*]azulenyl)-2-butanone (0.098 Å).[13] Thus, the bond length alternation within the seven-membered ring of **8** is not prominent. This fact is understandable by the dipole resonance structure including the tropylium ion moiety.

The nonplanarity of the molecular skeleton mentioned above indicates that the molecule of **8** is chiral, although the present crystal was racemic as demonstrated by the presence of the centrosymmetric dimer (see Figure 1).

Conclusions

We have developed a facile, efficient synthetic method to provide three isomers of 4-naphth[*a*]azulenylbut-3-en-2-one, which are difficult to synthesize by other methods. Single-crystal X-ray work on the naphth[1,2-*a*]azulene derivative revealed that its tetracyclic system exhibited deformation from planarity. A centrosymmetric associated dimer structure via C=O···H−C hydrogen bonds was found in the crystal.

Experimental Section

Preparation of 8. A solution of triphenylmethyl tetrafluoroborate (1.10 mmol) in dry dichloromethane (3 mL) was added to a solution of the isomeric mixture of 2-cycloheptatrienyl-3-(5-methyl-2-furyl)naphthalene (**6′**) (1.10 mmol), which was prepared from 2,3-dibromonaphthalene according to the previously reported method,[2e] in dry dichloromethane (2 mL) at ambient temperature and was stirred for 5 min. After addition of 100 mL of dry ether, the resulting precipitate was collected and washed with dry ether to yield 2-(5-methyl-2-furyl)-3-tropylionaphthalene tetrafluoroborate as a dark-colored precipitate. A solution of the precipitate **7** and 2,6-di-*tert*-butyl-4-methylpyridine (8.80 mmol) in 50 mL of acetonitrile was refluxed for 20 h, and the solvent was evaporated in vacuo. The residue was purified by column chromatography over silica gel (Wako-gel C200) and recrystallized from toluene. Yield: 73%. Dark-green prisms, mp 110−111 °C. Anal. Calcd for $C_{22}H_{16}O$: C, 89.16; H, 5.44. Found: C, 89.28, H, 5.33.

Preparation of 13. A solution of triphenylmethyl tetrafluoroborate (0.58 mmol) in dry acetonitrile (1 mL) was added to a solution of the isomeric mixture of 2-cycloheptatrienyl-1-(5-methyl-2-furyl)naphthalene (**11′**) (0.58 mmol), which was prepared from 2-bromo-1-iodonaphthalene according to the previously reported method,[2e] in dry acetonitrile (2 mL) at 0

(9) Yamamura, K.; Kusuhara, N.; Houda, Y.; Sasabe, M.; Takagi, H.; Hashimoto, M. *Tetrahedron Lett*. **1999**, *40*, 6609.
(10) Yamamura, K.; Kitagawa, Y.; Hashimoto, M. *Anal. Sci.* **2002**, *18*, 373.
(11) Kashino, M.; Haisa, M.; Fujimori, K.; Yamane, K. *Acta Crystallogr., Sect. B* **1982**, *38*, 2729.
(12) Buhl, M.; Kozminski, W.; Linden, A.; Nanz, D.; Sperandio, D.; Hansen, H.-J. *Helv. Chim. Acta* **1996**, *79*, 837.
(13) Yamamura, K.; Kitagawa, Y.; Hashimoto, M. *Anal. Sci*. **2002**, *18*, 499.

°C. The mixture was stirred for 5 min, and then 2,5-di-*tert*-butyl-4-methylpyridine (4.61 mmol) and acetonitrile (45 mL) were added. The mixture was stirred at ambient temperature. The solvent was evaporated in vacuo. The product was purified by column chromatography (Wako-gel C200) and recrystallized from toluene. Yield: 54%. Dark-green prisms, mp 141−142 °C. Anal. Calcd for $C_{22}H_{16}O$: C, 89.16; H, 5.44. Found: C, 88.96, H, 5.37.

Preparation of 18. Compound **18** was prepared from the isomeric mixture of 2-cycloheptatrienyl-3-(5-methyl-2-furyl)-naphthalene (**16′**) as described above. Yield: 13%. Brown powder, mp 155−156 °C. Anal. Calcd for $C_{22}H_{16}O$: C, 89.16; H, 5.44. Found: C, 89.30, H, 5.31.

Supporting Information Available: General experimental; synthetic procedures for **5**, **6**, **6′**,**7**, **10**, **11**, **11′**, **15**, **16** and **16′**; spectral data of **8**, **13**, and **18**; crystallographic data of **8** in CIF format; ^{1}H NMR spectra of **5**, **6**, **10**, **11**, **15**, and **16**; ^{13}C NMR spectra of **8**, **13**, and **18**. This material is available free of charge via the Internet at http://pubs.acs.org.

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