ELSEVIER

Available online at www.sciencedirect.com
SCIENCE DIRECT®

Tetrahedron Letters 45 (2004) 359–362

Tetrahedron
Letters

All-Z-hexabenzo[24]annulene with a triangular benzene cluster substructure

Yoshiyuki Kuwatani,* Jun-ichi Igarashi and Masahiko Iyoda*

Department of Chemistry, Graduate School of Science, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

Received 19 September 2003; revised 20 October 2003; accepted 24 October 2003

Abstract—*All-Z*-hexabenzo[24]annulene was synthesized via a poly-*cis*-stilbene intermediate. The single crystal of the annulene has a chiral C_3-symmetry with a central benzene trimer substructure. Although the compound is highly flexible in solution, the C_3-symmetric structure is stabilized by three concurrent CH/π interactions.

Weak intermolecular interactions have been recognized to play an important role in supramolecular chemistry.[1,2] Aromatic interaction is one of these, and this important interaction frequently governs the geometry and stability of supramolecular entities. The interactions between two benzene rings have been thoroughly investigated[3,4] in terms of both the geometry[5] and the stabilizing energy.[6,7] Based on theoretical calculations, the T-shaped interaction can be stabilized with comparable energy to a stacked arrangement.[4] On the other hand, interactions among more than two arene rings are usually difficult to understand because many other factors can affect a practical system. Gas phase studies on benzene aggregates provide interesting information on multiple interactions among some benzene nuclei.[8] Stable benzene trimers with a large binding energy have been observed, and theoretical calculations have predicted a C_3-symmetric cyclic structure.[9] We found a closely similar structure with three benzene nuclei in the title compound, which should have the same CH/π stabilization as the benzene trimer.

We have studied a series of *all-Z*-[*n*]benzo[4*n*]annulenes **1**, which represent a partial structure of cylindrical π-systems **2**.[10] These compounds (**1a**–**c**) have electron rich cavities, which have been utilized for the incorporation of metal cations.[11] Increase of the ring size of **1** makes the structure flexible, so that metal complexes may be formed by induced fit. To investigate the structure and guest-accommodating properties of the larger homologue, **3** has been synthesized. We report here a unique structure of **3** with a triangular benzene trimer substructure both in crystal and solution (Chart 1).

The title compound was synthesized by a similar strategy to that used for the synthesis of **1**, which was based on the intramolecular pinacol coupling of the corresponding linear oligomeric *cis*-stilbene dialdehyde **10**, followed by

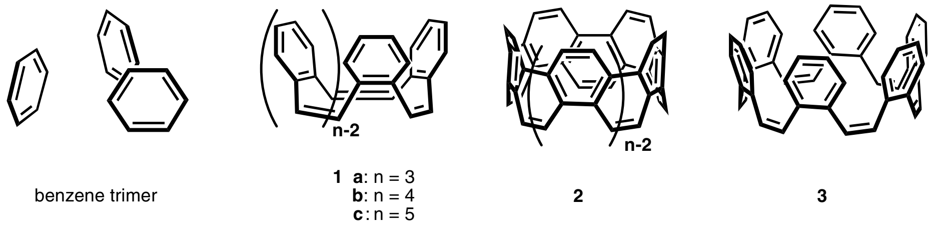
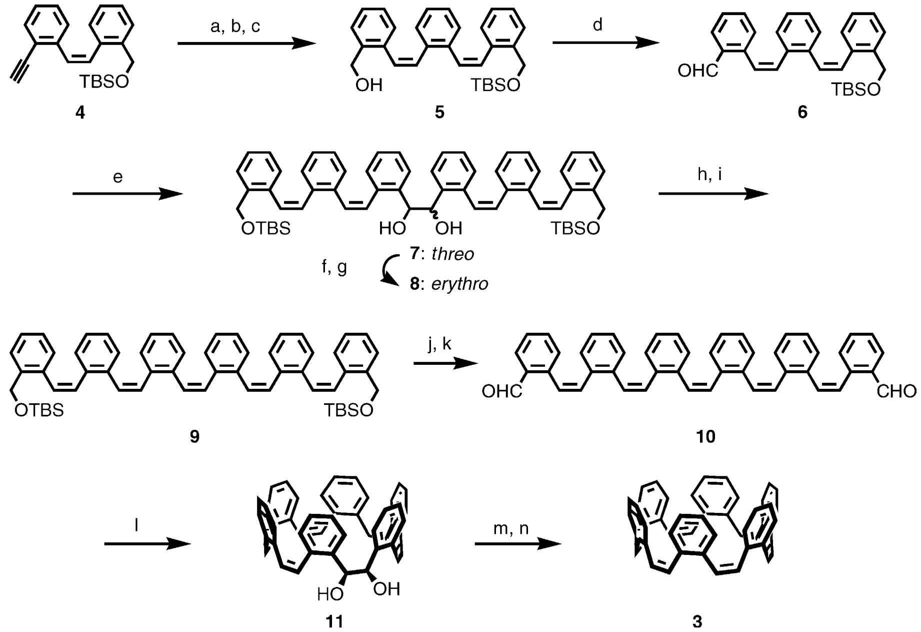


Chart 1.

Keywords: π-Conjugated system; Annulene; CH/π Interaction; Host molecule; X-ray crystal structure.

* Corresponding authors. Tel.: +81-426-77-1111; fax: +81-426-77-2525; e-mail: kuwatani@comp.metro-u.ac.jp; iyoda-masahiko@c.metro-u.ac.jp

0040-4039/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetlet.2003.10.163



Scheme 1. Synthesis of **3**. Reagents and conditions: (a) 2-bromobenzaldehyde, $Pd(PPh_3)_4$, CuI, NEt_3, reflux, 10 min; (b) $NaBH_4$, EtOH; (c) Lindlar's catalyst, H_2, quinoline, benzene; (d) Dess–Martin periodinane, CH_2Cl_2; (e) $VCl_3(thf)_3$, Zn, DMF, CH_2Cl_2; (f) $(COCl)_2$, DMSO, NEt_3, CH_2Cl_2; (g) $NaBH_4$, EtOH, 0 °C; (h) thiophosgene, DMAP, CH_2Cl_2, 0 °C; (i) 1,3-dimethyl-2-phenyl-1,3,2-diazaphospholidine, benzene, reflux; (j) *n*Bu_4NF, THF; (k) Dess–Martin periodinane, CH_2Cl_2; (l) $VCl_3(thf)_3$, Zn, DMF, CH_2Cl_2; (m) thiocarbonyldiimidazole, toluene, reflux; (n) DMPD, benzene, reflux.

the formation of the final *cis*-double bond using reductive dehydroxylation[10] (Scheme 1). The poly-*cis*-stilbene dialdehyde **10** was prepared from **4**. Sonogashira coupling of the alkyne **4** and subsequent reductions afford the alcohol **5**, which was readily oxidized to the corresponding aldehyde **6** (73% from **4**). This aldehyde **6** was dimerized by the low valent vanadium complex generated in situ to afford the *threo*-pinacol **7** (87% with 7% of **8**), which was selectively converted to *erythro*-pinacol **8** by a Swern oxidation and $NaBH_4$ reduction sequence (two steps, **8**: 82% and **7**: 12%). The central double bond was introduced by Corey–Winter reaction of the corresponding thionocarbonate with 1,3-dimethyl-2-phenyl-1,3,2-diazaphospholidine (DMPD) in refluxing benzene to afford **9** (83% from **8**). The oligo-stilbene **9** was converted to the dialdehyde **10** (93% from **9**) by conventional functional group transformations. The cyclization of **10** and the construction of the final double bond completed the synthesis of **3**. Intramolecular cyclization of **10** by the low valent vanadium complex proceeded smoothly to afford the *erythro*-pinacol **11** in 70% yield with the formation of the *threo*-isomer (14%). The predominant formation of *erythro*-pinacol is unusual for this reaction,[12] probably because of the preference for a transition state leading to this isomer. *All*-*Z*-hexabenzo[24]annulene **3** was obtained by the Corey–Winter reaction of the corresponding thionocarbonate derived from **11** using DMPD in refluxing benzene (two steps, 55%).[13]

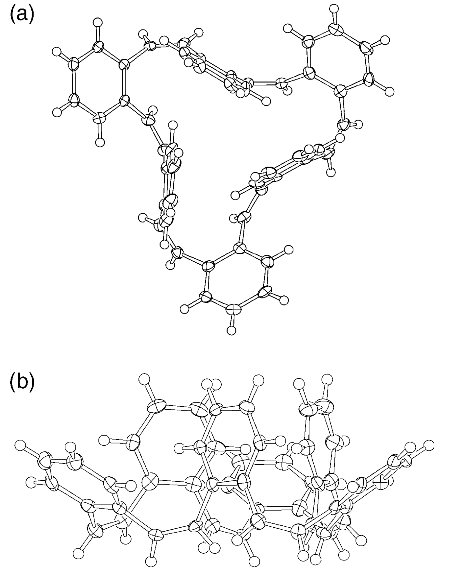


Figure 1. ORTEP drawing of **3**: (a) top view and (b) side view.

The product **3** is a stable crystalline compound. The single crystal X-ray diffraction of **3** was measured by using a hexagonal column crystal obtained from CH_2Cl_2–hexane.[14] As shown in Figure 1, the molecular structure of **3** was found to be a C_3-conformation in which three benzene rings were projected outward and the others were assembled inside, with dihedral angles ca. 60° to each other. This structure is analogous to 'flattened cone' conformation in C_3-symmetric calix[6]arene derivatives,[15] but has a more compressed structure. The intramolecular assembly of the inner benzene rings is attributed to the three concurrent CH/π interactions among these benzene rings. The averaged distance between the hydrogen atom and the center of the arene nuclei is only 2.65 Å (the corresponding C···Ar distance is 3.44 Å) and the averaged centroid–centroid distance of these arene rings is 4.70 Å.

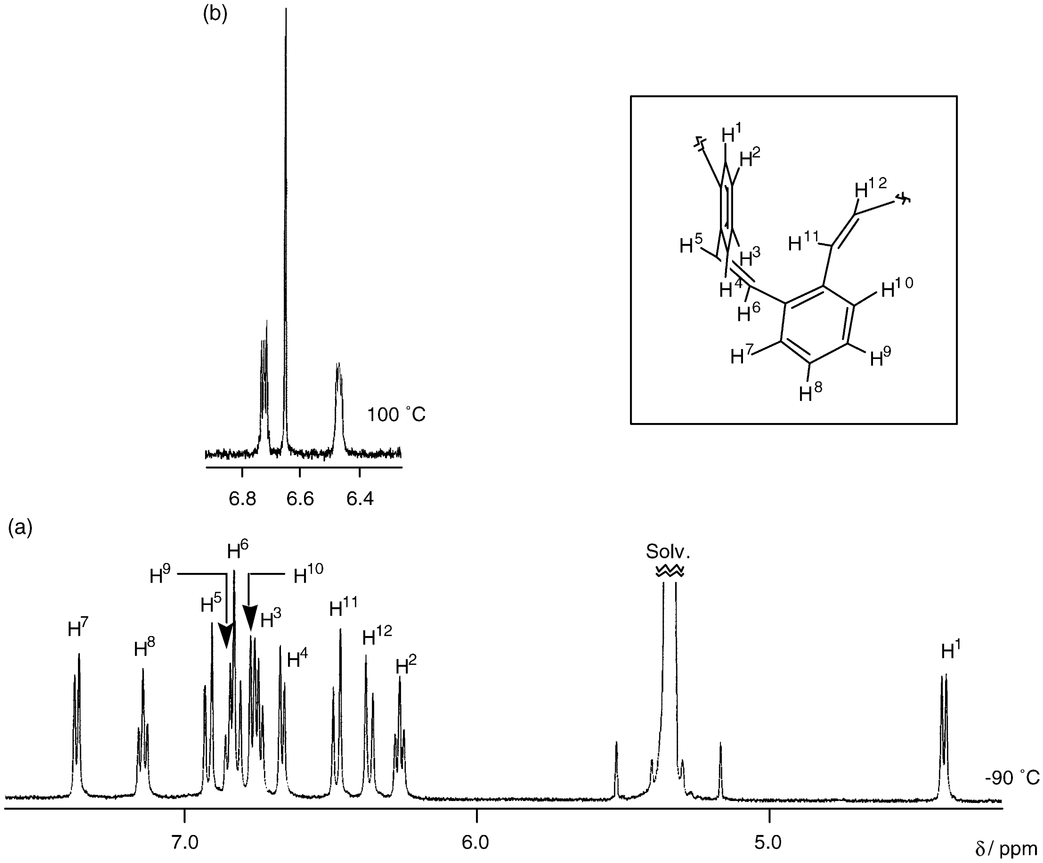


Figure 2. ^{1}H NMR spectra of **3**: (a) Spectrum at −90 °C in CD_2Cl_2 with the signal assignment. The numbering scheme was shown above. (b) Spectrum at 100 °C in $(CDCl_2)_2$.

The molecular structure of **3** in solution was also studied by temperature dependent ^{1}H NMR spectra. The spectrum at ambient temperature showed broad aromatic signals centered at δ 6.75 and 6.44 and an olefinic singlet at δ 6.66 in 1,1,2,2-tetrachloroethane-d_2. The aromatic signals changed to sharp AA′BB′ multiplets at δ 6.72 and 6.47 when the temperature was elevated, as shown in Figure 2b. This type of spectral change is ascribed to the slow conformational change of the molecule. The spectrum in CD_2Cl_2 at room temperature showed the same signals as that in $(CDCl_2)_2$ and broadened when the temperature was lowered. Sharp separated signals appeared below −70 °C, as shown in Figure 2a. All signals were assigned by the experimentally observed coupling connectivity and by comparison with the theoretically calculated shift values.[16] The spectrum at −90 °C is composed of signals from two types of symmetrical disubstituted benzene rings and two sets of *cis*-double bonds, and shows good accordance with the C_3-symmetric structure observed in the crystal. The characteristic signal here is observed at a chemical shift of δ 4.4, which is assigned to the *o*-aryl proton (H^1) shielded by a neighboring arene ring. Such a large higher-field shift suggests considerable proximity of the proton to the neighboring arene π-cloud, as is found in the crystal structure. The distance between the proton (H^1) and the arene ring can be estimated as 2.50–2.70 Å based on the chemical shift,[18] which is consistent with the X-ray analysis.

The optimized molecular structure by B3LYP/6-31G* level calculation is also represented by the folded C_3-conformation with close contact between three benzene rings with slightly longer distances (Ar–Ar: 5.13 Å; H–Ar: 3.01 Å). The expansion in the structure obtained by the DFT calculation is probably due to underestimation of the interaction energy between arene rings. Interestingly, the arrangement of the inside three benzene rings in **3** is essentially identical to the arrangement of the benzene trimer. The structure of **3** obtained from crystallographic analysis, and the structure of the benzene trimer optimized by MP2/6-31G* level MO calculation, are shown in Figure 3. Both structures have a C_3-symmetric arrangement and the structural parameters between two benzene rings in **3** are very close to those of the trimer. The Ar–Ar, C–Ar, and H–Ar distances in the trimer are 4.70, 3.40, and 2.47 Å, respectively. The binding energy of the benzene trimer has been reported to be 6.2 kcal/mol, as determined by a gas phase experiment.[8] This large binding energy could be attributable to the three concurrent cyclic CH/π interactions. The structural similarity suggests that the same magnitude of attractive interaction takes place in the C_3-conformation of **3**.

The annulene **3** forms a silver complex on treatment with $AgClO_4$ in CD_2Cl_2 or $CDCl_3$. The ^{1}H NMR spectra of $3{\cdot}AgClO_4$ showed lower field shifts for the aromatic and olefinic protons, reflecting the formation

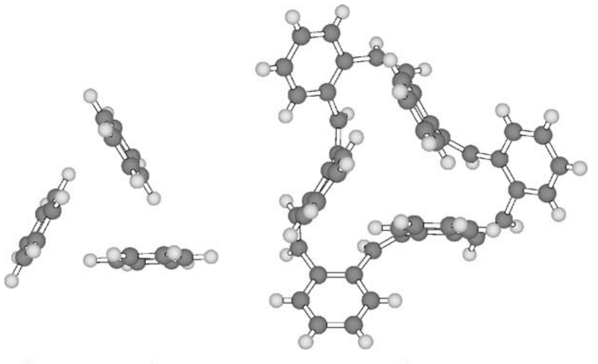


Figure 3. Relative geometry of three benzene rings in the benzene trimer optimized by MP2/6-31G* level MO calculation and the molecular structure of **3** obtained by the X-ray crystallographic analysis.

of the aromatic and olefinic complexes in equilibrium. Since **3** possesses no inner cavity to incorporate a silver cation, the complexation of **3** with $AgClO_4$ may take place outside the annulene ring or inside by induced-fit. Further studies on the properties of **3** as a cylindrical π-system are now being carried out.

Acknowledgements

This work has been supported in part by CREST of Japan Science and Technology Corporation (JST) and a Grant-in-Aid for Scientific and Research no. 14540501 from the Ministry of Education, Science, Sports and Culture.

References and Notes

1. Lehn, J. M. *Supramolecular Chemistry*; VCH: Weinheim, 1990.
2. Philp, D.; Stoddart, J. F. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1154–1196.
3. Hunter, C. A.; Lawson, K. R.; Perkins, J.; Urch, C. J. *J. Chem. Soc., Perkin Trans. 2* **2001**, 651–669.
4. Theoretical calculations for benzene dimers: (a) Tsuzuki, S.; Honda, K.; Uchimaru, T.; Mikami, M.; Tanabe, K. *J. Am. Chem. Soc.* **2002**, *124*, 104–112; (b) Jaffe, R. L.; Smith, G. D. *J. Chem. Phys.* **1996**, *105*, 2780–2788.
5. (a) Takahashi, H.; Tsuboyama, S.; Umezawa, Y.; Honda, K.; Nishio, M. *Tetrahedron* **2000**, *56*, 6185–6191; (b) Nishio, M.; Umezawa, Y.; Hirota, M.; Takeuchi, Y. *Tetrahedron* **1995**, *51*, 8665–8701.
6. (a) Carver, F. J.; Hunter, C. A.; Jones, P. S.; Livingstone, D. J.; McCabe, J. F.; Seward, E. M.; Tiger, P.; Spey, S. E. *Chem. Eur. J.* **2001**, *7*, 4854–4862; (b) Adams, H.; Carver, F. J.; Hunter, C. A.; Morales, J. C.; Seward, E. M. *Ang. Chem., Int. Ed. Engl.* **1996**, *35*, 1542–1544.
7. (a) Kim, E.; Paliwal, S.; Wilcox, C. S. *J. Am. Chem. Soc.* **1998**, *120*, 11192–11193; (b) Paliwal, S.; Geib, S.; Wilcox, C. S. *J. Am. Chem. Soc.* **1994**, *116*, 4497–4498.
8. Krause, H.; Ernstberger, B.; Neusser, H. J. *Chem. Phys. Lett.* **1991**, *184*, 411–417.
9. (a) Gonzalez, C.; Lim, E. C. *J. Phys. Chem. A* **2001**, *105*, 1904–1908; (b) Engkvist, O.; Hobza, P.; Selzle, H. L.; Schlag, E. W. *J. Chem. Phys.* **1999**, *110*, 5758–5762.
10. (a) Kuwatani, Y.; Yoshida, T.; Kusaka, A.; Oda, M.; Hara, K.; Yoshida, M.; Matsuyama, H.; Iyoda, M. *Tetrahedron* **2001**, *57*, 3567–3576; (b) Kuwatani, Y.; Yoshida, T.; Kusaka, A.; Iyoda, M. *Tetrahedron Lett.* **2000**, *41*, 359–363.
11. (a) Kuwatani, Y.; Yoshida, T.; Hara, K.; Yoshida, M.; Matsuyama, H.; Iyoda, M. *Org. Lett.* **2000**, *2*, 4017–4020; (b) Yoshida, T.; Kuwatani, Y.; Hara, K.; Yoshida, M.; Matsuyama, H.; Iyoda, M.; Nagase, S. *Tetrahedron Lett.* **2001**, *42*, 53–56.
12. In the case of strained-ring formation, a few examples of *erythro*-selective pinacol coupling by the vanadium complex have been reported: (a) Raw, A. S.; Pedersen, S. F. *J. Org. Chem.* **1991**, *56*, 830–833; (b) Iyoda, M.; Fuchigami, K.; Kusaka, A.; Yoshida, T.; Yoshida, M.; Matsuyama, H.; Kuwatani, Y. *Chem. Lett.* **2000**, 860–861; (c) Iyoda, M.; Horino, T.; Takahashi, F.; Hasegawa, M.; Yoshida, M.; Kuwatani, Y. *Tetrahedron Lett.* **2001**, *42*, 6883–6886.
13. Spectroscopic data for **3**: mp ca. 340 °C (decomp.); EI-MS (m/z) 612 (M^+); ^1H NMR (500 MHz, $CDCl_3$, 60 °C) δ 6.75–6.72 (12H, m), 6.67 (12H, s), 6.46 (12H, br m); ^{13}C NMR (125 MHz, $CDCl_3$, 60 °C) δ 136.7, 130.7, 129.9, 126.1; IR (KBr) 3057, 3007, 2957, 2361, 2341, 1466, 1154, 773 cm^{-1}; UV (cyclohexane) λ_{max} ($\log \varepsilon$) 285 (4.71) nm; Anal. Calcd C, 94.08; H, 5.92. Found C, 93.68; H, 6.05.
14. Crystal data for **3**: $C_{48}H_{36}$, $M_w = 612.81$, $T = -150\,°C$, orthorhombic, space group $Pna2_1$ (#33), $a = 22.621(4)$, $b = 13.043(5)$, $c = 11.422(3)\,Å$, $V = 3370(1)\,Å^3$, $Z = 4$, $D_c = 1.208\,g/cm^3$, $R = 0.110$, $R_w = 0.183$, GOF = 1.73 for 2497 reflections with $I > 1.0\ \sigma(I)$. Crystallographic data (excluding structure factors) for the structures in this paper, have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 219642. 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).
15. (a) Otsuka, H.; Suzuki, Y.; Ikeda, A.; Araki, K.; Shinkai, S. *Tetrahedron* **1998**, *54*, 423–446; (b) Rondelez, Y.; Rager, M.-N.; Duprat, A.; Reinaud, O. *J. Am. Chem. Soc.* **2002**, *124*, 1334–1340.
16. ^1H NMR chemical shifts of **3** were calculated by GIAO/HF/6-31G*//B3LYP/6-31G*. All calculations were performed on the Gaussian 98 program.[17]
17. Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Rega, N.; Salvador, P.; Dannenberg, J. J.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Baboul, A. G.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Andres, J. L.; Gonzalez, C.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian98*; Gaussian: Pittsburgh, PA, 1998.
18. Klod, S.; Kleinpeter, E. *J. Chem. Soc., Perkin Trans. 2* **2001**, 1893–1898.