ORGANIC LETTERS

2004
Vol. 6, No. 2
229−232

Hydrogen Bond-Induced Rigid Oligoanthranilamide Ribbons That Are Planar and Straight

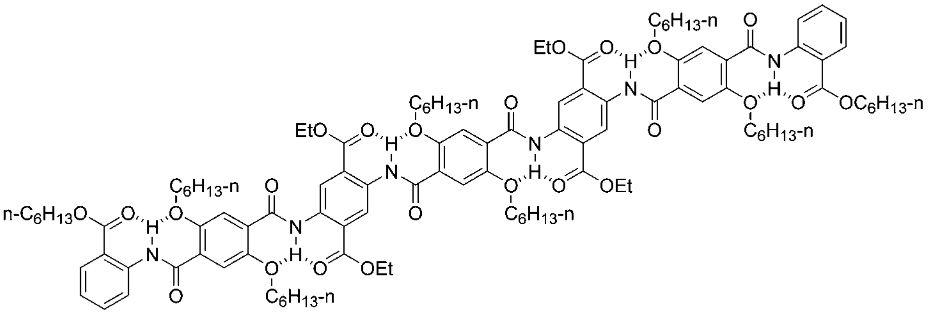
Zong-Quan Wu, Xi-Kui Jiang, Shi-Zheng Zhu, and Zhan-Ting Li*

Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences,
354 Fenglin Lu, Shanghai 200032, China

ztli@mail.sioc.ac.cn

Received October 28, 2003

ABSTRACT



A new series of oligoanthranilamides has been synthesized starting from suitably modified *p*-phenylenediamine and *p*-phthalic acid derivatives. Due to strong intramolecular three-center hydrogen bonds, the new oligomers self-assemble into highly stable straight and planar molecular ribbons, which have been characterized by X-ray crystallography and ^{1}H NMR, IR, and UV–vis spectroscopy.

Linear planar oligo-aromatic molecules with controllable length not only bear great promise as materials for electronic devices[1] but also are important building blocks for assembling discrete supramolecular systems.[2] A large number of conjugated arylene, arylene ethynylene, and vinylene oligomers with extended skeletons have been prepared. Nevertheless, the coplanarity of most of these covalently bonded systems has not been really achieved since the relative rotation of their adjacent subunits cannot be efficiently prevented.[3] Following the increasing use of noncovalent interactions in constructing various non-natural folding systems,[4,5] we had recently initiated a new project for developing new noncovalent approaches to construct rigid and planar molecular ribbons, which could be further functionalized and used as new generation of molecular scaffolds for further supramolecular assembly or recognition chemistry. In this paper, we describe a new series of oligoanthranilamides that self-assemble into highly stable planar and straight molecular ribbons with controlled strength in both solution and solid state as a result of strong intramolecularly three-centered hydrogen bonding.[6−8]

Compounds **1**−**5**, which possess one to seven aromatic units, respectively, have been designed and synthesized.

---

(1) Martin, R. E.; Diederich, F. *Angew. Chem., Int. Ed.* **1999**, *38*, 1350. (b) Tour, J. M. *Acc. Chem. Res.* **2000**, *33*, 791. (c) Bunz, U. H. F. *Acc. Chem. Res.* **2001**, *34*, 998.

(2) (a) Fyfe, M. C. T.; Stoddart, J. F. *Acc. Chem. Res.* **1997**, *30*, 393. (b) Fujita, M. *Chem. Soc. Rev.* **1998**, *27*, 417. (c) Leininger, S.; Olenyuk, B.; Stang, P. J. *Chem. Rev.* **2000**, *100*, 853. (d) Dinolfo, P. H.; Hupp, J. T. *Chem. Mater.* **2001**, *13*, 3113.

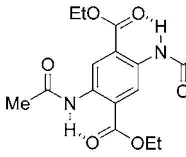
(3) Okuyama, K.; Hasegawa, T.; Ito, M.; Mikami, N. *J. Phys. Chem.* **1984**, *88*, 1711.

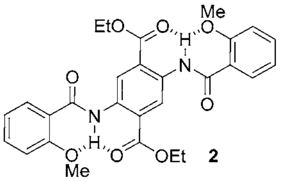
(4) (a) Bassani, D. M.; Lehn, J.-M.; Baum, G.; Fenske, D. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1845. (b) Seebach, D.; Matthews, J. L. *Chem. Commun.* **1997**, 2015. (c) Gellman, S. H. *Acc. Chem. Res.* **1998**, *31*, 173. (d) Nowick, J. S. *Acc. Chem. Res.* **1999**, *32*, 287. (e) Cheng, R. P.; Gellman, S. H.; Degrado, W. F. *Chem. Rev.* **2001**, *101*, 3219. (f) Hill, D. J.; Mio, M. J.; Prince, R. B.; Hughes, T. S.; Moore, J. S. *Chem. Rev.* **2001**, *101*, 3893. (g) Cubberley, M. S.; Iverson, B. L. *Curr. Opin. Chem. Biol.* **2001**, *5*, 650. (h) Sanford, A. R.; Gong, B. *Curr. Org. Chem.* **2003**, *7*, 1649. (i) Zhao, D.; Moore, J. S. *Chem. Commun.* **2003**, 807.

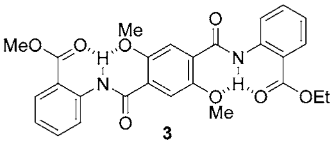
(5) For recent examples of intramolecular hydrogen bonds for stablizing the planarity of π-conjugated folded systems, see: (a) Cary, J. M.; Moore, J. S. *Org. Lett.* **2002**, *4*, 4663. (b) Yang, X.; Brown, A. M.; Furukawa, M.; Li, S.; Gardinier, W. E.; Bukowski, E. J.; Bright, F. V.; Zheng, C.; Zeng, X. C.; Gong, B. *Chem. Commun.* **2003**, 56. (c) Ernst, J. T.; Becceril, J.; Park, H. S.; Yin, H.; Hamilton, A. D. *Angew. Chem., Int. Ed.* **2003**, *43*, 535.

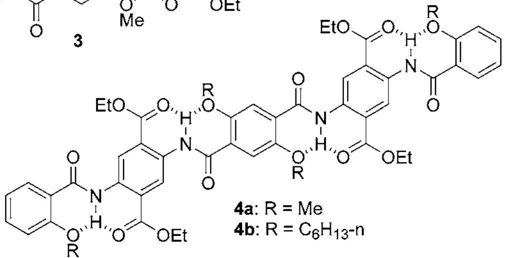
10.1021/ol036108b CCC: $27.50

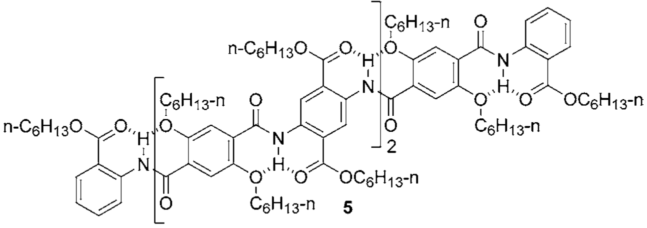
Instead of using 2,5-dialkoxy-1,4-phenylenediamine, which would lead to the formation of five-membered ring hydrogen bonds,[4h,6c] we herein chose to use 2,5-diaminoterephthalate as one of the two key intermediates to construct the ribbon skeletons, since stable six-membered-ring hydrogen bonds would also be expected to be generated.[9]


1


2

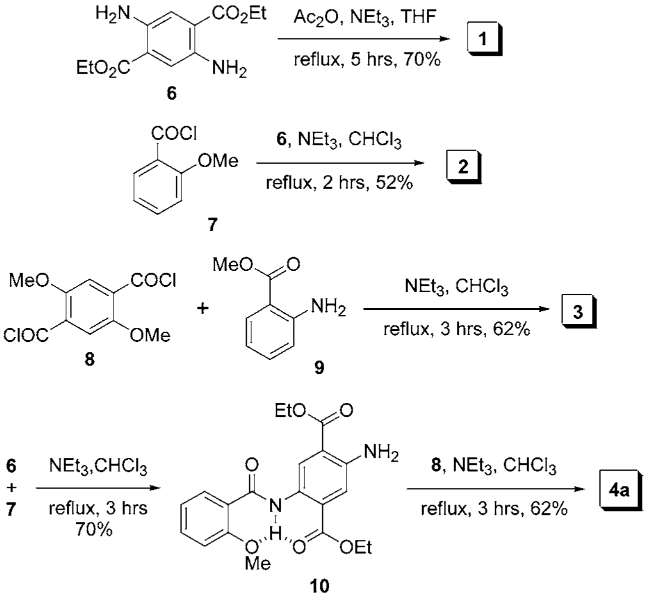

3


4a: R = Me
4b: R = C_6H_{13}-n


5

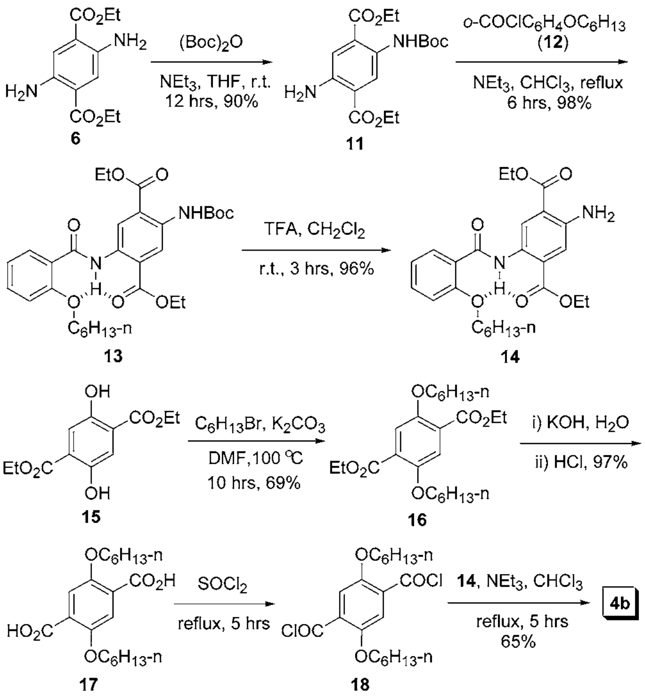
The synthetic routes for **1**−**4a** are presented in Scheme 1. Treatment of diamine **6**[10] with acetic anhydride in the presence of NEt_3 in refluxed THF afforded **1** in 70% yield, whereas the reaction of **6** with acyl chloride **7** in hot chloroform with NEt_3 as base produced **2** in 52% yield. Under conditions analogous to that for **2**, **8**[11] reacted with **9** to afford **3** in 62% yield. For the preparation of **4a**, precursor **10** was first produced in 70% yield by treating **7** with excess of **6** in refluxing chloroform; subsequent reaction of **10** with **8** afforded 5-mer **4a** in 62% yield.

Scheme 1



Since compound **4a** is of low solubility in common nonpolar solvents such as chloroform, 5-mer **4b**, which was incorporated with four longer hexyloxyl chains, was also prepared, as shown in Scheme 2. The synthesis began with **6**, which was first monoprotected with $(Boc)_2O$ to produce **11**. Acylation of **11** with **12** in hot chloroform with NEt_3 as base afforded **13**, which was then treated with TFA to give **14**. Diol **15**[12] was then alkylated with *n*-hexyl bromide in the presence of potassium carbonate, and hydrolysis of the product with potassium hydroxide, followed by refluxing in thionyl chloride, produced diacyl chloride **18**. The latter

Scheme 2



---

(6) For three-center hydrogen bonding in folding molecules, see: (a) Hamuro, Y.; Geib, S. J.; Hamilton, A. D. *J. Am. Chem. Soc.* **1996**, *118*, 7529. (b) Hamuro, Y.; Geib, S. J.; Hamilton, A. D. *J. Am. Chem. Soc.* **1997**, *119*, 10587. (c) Parra, R. D.; Zeng, H.; Zhu, J.; Zheng, C.; Zeng, X. C.; Gong, B. *Chem. Eur. J.* **2001**, *7*, 4352. (d) Gong, B.; Zeng, H.; Zhu, J.; Yuan, L.; Han, Y.; Cheng, S.; Furukawa, M.; Parra, R. D.; Kovalevsky, A. Y.; Mills, J. L.; Skrzypczak-Jankun, E.; Martinovic, S.; Smith, R. D.; Zheng, C.; Szyperski, T.; Zeng, X. C. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 11583.

(7) For an example of hydrogen-bond-mediated polyarenes, see: Delnoye, D. A. P.; Sijbesma, R. P.; Vekemans, J. A. J. M.; Meijer, E. W. *J. Am. Chem. Soc.* **1996**, *118*, 8717.

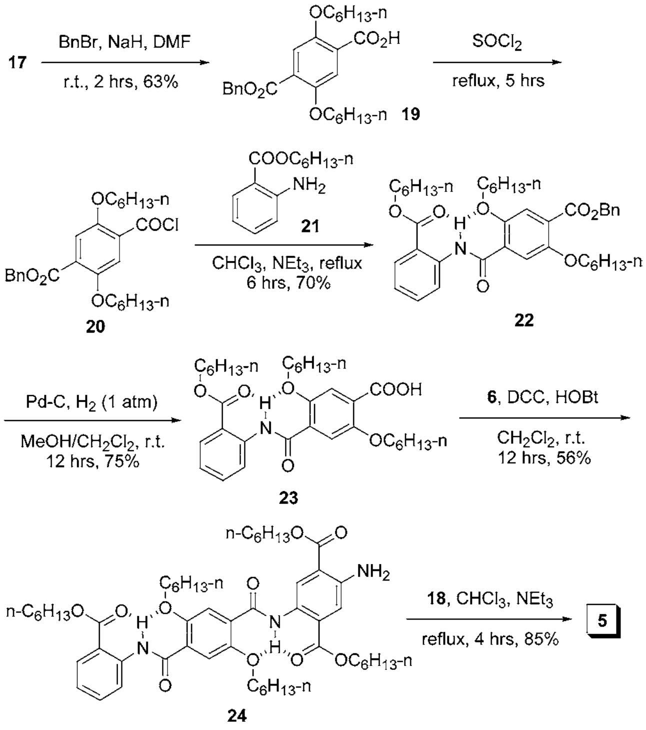
(8) For reviews of covalent bond-mediated molecular ribbons, see: (a) Kohnke, F. H.; Stoddart, J. F. *Pure Appl. Chem.* **1989**, *61*, 1581. (b) Girreser, U.; Giuffrida, D.; Kohnke, F. H.; Mathias, J. P.; Philp, D.; Stoddart, J. F. *Pure Appl. Chem.* **1993**, *65*, 119. (c) Schröder, A.; Mekelburger, H.-B.; Vögtle, F. *Top. Curr. Chem.* **1994**, *172*, 179.

(9) Etter, M. C. *Acc. Chem. Res.* **1990**, *23*, 120.

(10) Sinnreich, J. *Synthesis* **1980**, 578.

(11) Marvel, K. *J. Org. Chem.* **1953**, *18*, 707.

Scheme 3



reacted with **14** in refluxing chloroform to produce **4b** in 65% yield. As expected, compound **4b** is highly soluble in nonpolar solvents such as chloroform and dichloromethane.

The 7-mer compound **5** was then prepared, as shown in Scheme 3. Diacid **17** first reacted with benzyl bromide in DMF with sodium hydride as base to produce **19** in 63% yield. Acid **19** was then converted to **20** with hot thionyl chloride. The reaction of **20** with amine **21**[6a] also in hot chloroform afforded **22** in 70% yield. Subsequent deprotection of the carboxylic acid group by Pd-catalyzed hydrogenation gave **23** in 75% yield. DCC-mediated coupling reaction of **23** with **6** in dichloromethane with HOBt as catalyst was then carried out to produce **24** in 56% yield. Finally, **24** reacted with **18** in hot chloroform with NEt_3 as base to afford **5** in 85% yield.

Single crystals of **1**−**3** were grown by slow evaporation of the chloroform solution at room temperature. Figure 1a shows the crystal structure of **1**. As expected, two six-membered ring hydrogen bonds (NH···O distance = 1.81 Å) between the adjacent amide NH and ester C═O groups are formed, which lead to a perfectly planar conformation. Evidence for the straight and planar features of the linear molecules are provided by the X-ray structures of 3-mer **2** and **3**. As shown in Figure 1b,c, both **2** and **3** possess four six-membered-ring hydrogen bonds (NH···O distances = 1.81 and 1.82 Å). All three benzene units and the amide groups in both compounds share one plane due to the presence of these strong three-center intramolecular hydrogen bonds (see the packing diagrams of **2** and **3** in the Supporting Information), whereas all the side methyl and ethyl groups point away from the central aromatic skeleton. Since the longer oligomers **4** and **5** also possess the identical repeated structural feature, it is reasonable to consider that these longer oligomers should also adopt similar planar and straight conformations. A CPK model of planar 7-mer **5**, with a length of 4.30 nm, is shown in Figure 2.

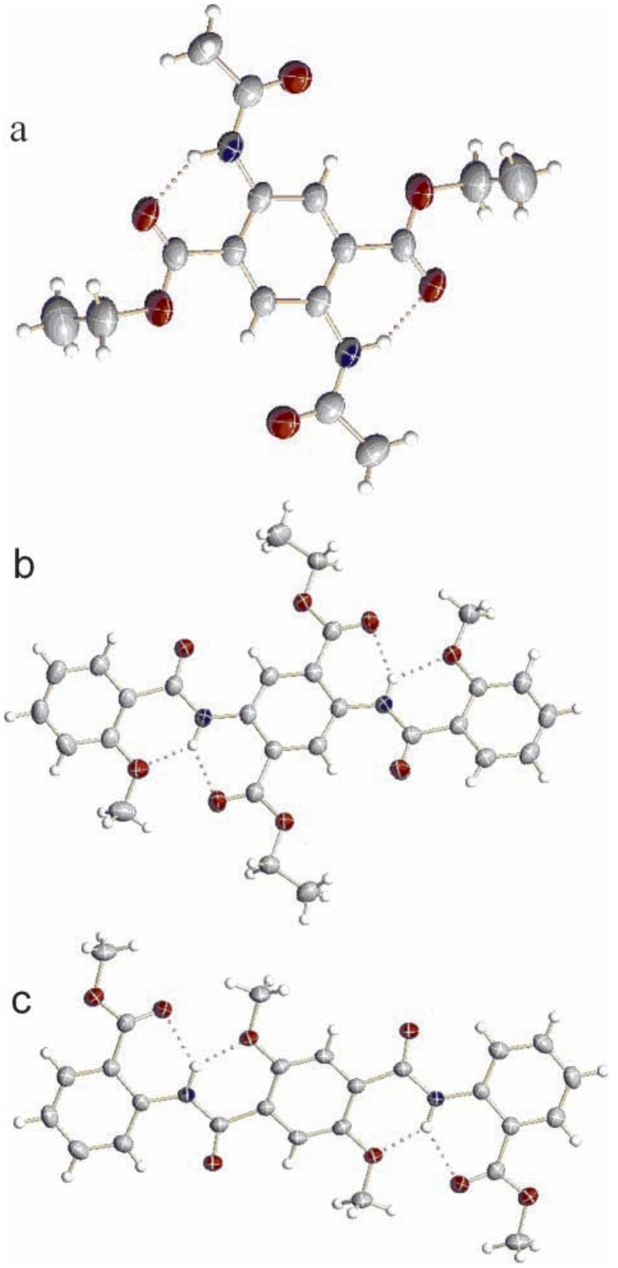


Figure 1. Crystal structures of **1** (a), **2** (b), and **3** (c). All the molecules adopt perfectly flat conformations, and both **2** and **3** possess straight π-extended skeletons, due to the strong six-membered ring hydrogen bonds.

The amide NH signals of the ^1H NMR spectra of all compounds **1**−**5** in chloroform-*d* appeared at downfield positions (Table 1). The results provide strong evidence to support that strong six-membered ring hydrogen bonds are

---

(12) Itami, K.; Palmgren, A.; Thorarensen, A.; Bäckvall, J.-E. *J. Org. Chem.* **1998**, *63*, 6466.

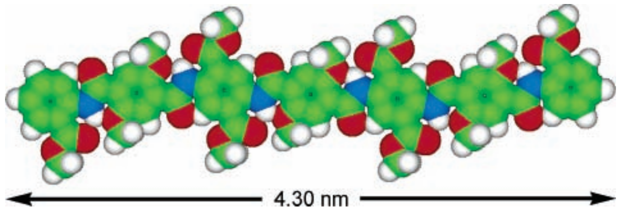


Figure 2. CPK model of 7-mer **5**, produced with AccuModel 1.1 (the hexyl group were replaced with methyl group for clarity).

also formed in solution for the molecules. Moreover, 2D-NOESY ^{1}H NMR experiments for **4b** (10 mM) in chloroform-*d* revealed NOE connections of moderate strength between the NH signals and the adjacent OCH_2 and OCH_2CH_2 signals. Further support for the intramolecularly hydrogen-bonded π-extended structures in solution comes from variable-temperature investigations of the amide NH resonances in chloroform-*d* (Table 1), which revealed rather small chemical shift changes with the temperature ($\leq 4.5 \times 10^{-3}$ ppm/K). This is consistent with their involvement in the formation of intramolecular hydrogen bonds in solution.[13] Dilution experiments (from 40 to 2 mM) in chloroform-*d* revealed no great change of the NH signals (<0.03 ppm) for **1**−**5**, indicating the absence of intermolecular hydrogen bonding. This result also excludes the possibility of important intermolecular $\pi-\pi$ stacking.[14] In addition, when the solvent was changed from chloroform-*d* to DMSO-d_6 (10 mM, 25 °C), the NH signal of **2** displayed a small change (0.17 ppm). In sharp contrast, a very large change (2.47 ppm) was observed for the NH of *N*-phenyl benzamide when the solvent was changed from chloroform to DMSO.[6c] This result also strongly suggests that stable intramolecular hydrogen bonds are formed in the oligomers.

The NH stretching frequencies (ν) of compounds **1**−**5** were measured in $CHCl_3$ (3 mM) and with the KBr disk method by IR spectroscopy (Table 2), which provides additional evidence to support the formation of intramolecular hydrogen bonds in both solution and solid state. For all molecules, intramolecularly hydrogen bonded N−H stretch peaks were observed (<3310 cm^{-1}), but no typical peaks were displayed in the free N−H stretch region (3400−3500 cm^{-1}).[15] In addition, the NH stretching frequencies in chloroform are independent of concentration changes. These observations, similar to the above NMR results, also indicate that **1**−**5** should adopt intramolecularly hydrogen-bonded planar conformations.

Table 1. ^{1}H NMR Chemical Shifts (ppm) of the Amide Protons of Compounds **1**−**5** in $CDCl_3$

	30 °C			50 °C			$\Delta\delta$ (ppm)/T ($\times 10^3$)		
1	10.89			10.83			3.00		
2	12.12			12.03			4.50		
3	12.33			12.22			4.50		
4a[a]	12.34	12.18							
4b	12.01	11.88		11.92	11.79		4.50	4.50	
5	12.35	12.14	11.93	12.27	12.08	11.86	4.00	3.00	3.50

[a] Values recorded at 25 °C.

Table 2. Stretching Frequencies (ν, cm^{-1}) of the NH Groups of Compounds **1**−**5** at Ambient Temperature

	$CHCl_3$	KBr		$CHCl_3$	KBr
1	3304	3304	**2**	3225	3225
3	3263	3264	**4a**	3227 2931	3228 2932
4b	3225 2980	3225 2928			
5	3250 3235 2940	3250 3234 2935			

UV−vis experiments in chloroform reveal that the long-wavelength absorption band (**1**, 369 nm; **2**, 370 nm; **3**, 354 nm; **4b**, 399 nm; **5**, 404 nm) shifted bathochromically with the increase of the number of the repeating benzene units. These transitions may also be explained by considering that the longer molecules have stronger amide bond delocalization and increased π-conjugation as a result of the planarity of the straightly arranged repeating aromatic units.[5,7] This is in good agreement with the above X-ray, ^{1}H NMR, and IR results.

In summary, we report the first general approach to constructing highly stable straight and planar molecular ribbons with controlled length by utilizing highly stable intramolecular hydrogen bonds. In the past decade, various secondary interactions had been applied for building a large number of folding structures, the present work demonstrates that straight molecular architectures with controllable length can also be generated from readily available precursors with the help of strong secondary interactions. In principle, longer oligomers of the same skeleton could be readily prepared by simply increasing the number of the repeating aromatic units. By introducing additional functional groups, such as pyridine or acetylene, to the ends of the new skeletons, new generation of extremely long and rigid molecules have been prepared for assembling new giant supramolecular squares or rectangles, which will be reported in due course.

Acknowledgment. We are grateful to the Ministry of Science and Technology (No. G2000078101), the National Natural Science Foundation (No. 20172069, No. 90206005), the Chinese Academy of Sciences, and the State Laboratory of Bioorganic and Natural Products Chemistry of China for financial support of this work.

Supporting Information Available: The experimental procedures and characterizations for **1**−**3**, **4a**,**b**, and **5**, the packing diagrams of **2** and **3** in the solid state, and the X-ray crystallographic data for **1**−**3**. This material is available free of charge via the Internet at http://pubs.acs.org.

OL036108B

---

(13) Kesseler, H. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 512.

(14) (a) Shetty, A. S.; Zhang, J. S.; Moore, J. S. *J. Am. Chem. Soc.* **1996**, *118*, 1019. (b) Hunter, C. A.; Lawson, K. R.; Perkins, J.; Urch, C. J. *J. Chem. Soc., Perkin Trans. 2* **2001**, 651. (c) Tobe, Y.; Utsumi, N.; Kawabata, K.; Nagano, A.; Adachi, K.; Araki, S.; Sonoda, M.; Hirose, K.; Naemura, K. *J. Am. Chem. Soc.* **2002**, *124*, 5350.

(15) (a) Legon, A. C. *Chem. Soc. Rev.* **1990**, *19*, 197. (b) Nowick, J. S.; Powell, N. A.; Martinez, E. J.; Smith, E. M.; Noronha, G. *J. Org. Chem.* **1992**, *57*, 3763. (c) Dado, G. P.; Gellman, S. H. *J. Am. Chem. Soc.* **1994**, *116*, 1054.