Pure Appl. Chem., Vol. 80, No. 3, pp. 533–546, 2008.
doi:10.1351/pac200880030533

Nonplanar aromatic compounds. Part 10: A strategy for the synthesis of aromatic belts—all wrapped up or down the tubes?*,**

Tieguang Yao, Hao Yu, Rudolf J. Vermeij, and Graham J. Bodwell‡

Department of Chemistry, Memorial University, St. John's, NL A1B 3X7, Canada

Abstract: A strategy for the synthesis of cyclophenacene-type aromatic belts (or armchair nanotube segments) that relies upon a valence isomerization/dehydrogenation reaction is described, and progress toward achieving this goal is presented.

Keywords: cyclacenes; cyclophenacenes; cyclophanes; valence isomerization; aromatic belts; nonplanar aromatics; pyrene; aromaticity.

INTRODUCTION

A belt is an object that has two continuous, nonintersecting edges and a width that is small in relation to its circumference, i.e., **1** (Fig. 1). On the molecular level, belt and belt-like structures are not uncommon [1], but belts having surfaces consisting entirely of a polycyclic aromatic framework are. Such systems, which are commonly referred to as "aromatic belts", have been the subject of both synthetic and theoretical interest for many years, dating back well before the dawn of the fullerene/carbon nanotube era. The emergence of the new forms of carbon has only heightened interest in aromatic belts.

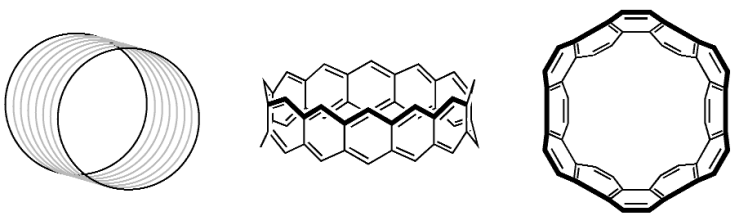


Fig. 1 Aromatic belt motifs.

Being substructures of single-walled carbon nanotubes (SWCNTs), aromatic belts can be categorized according to the same roll-up motifs [2]. However, since the consideration of aromatic belts predates that of SWCNTs, they have different names. Thus, a cyclacene, e.g., [12]cyclacene **2**, corresponds

*Paper based on a presentation at the 12th International Symposium on Novel Aromatic Compounds (ISNA-12), 22–27 July 2007, Awaji Island, Japan. Other presentations are published in this issue, pp. 411–667.
Part 9: B. Zhang, G. P. Manning, M. A. Dobrowolski, M. K. Cyranski, G. J. Bodwell. *Org. Lett.* **10, 273 (2008).
‡Corresponding author

to a zigzag SWCNT, specifically a (12,0) nanotube, and a cyclophenacene, e.g., [12]cyclophenacene **3**, corresponds to an armchair SWCNT, specifically a (6,6) nanotube. Chiral belts are also possible, but these will not be discussed here.

From a theoretical perspective, [*n*]cyclacenes have received a great deal of attention [3]. They are expected to be reactive systems consisting of two bond-equalized trannulene [4] ribbons connected by a series of single bonds. [*n*]Cyclacenes with odd-numbered values of *n*, which have [4*n*+2] π-electrons in each ribbon, are predicted to be more stable than those with even numbered values of *n.*

Synthetic work aimed at the synthesis of [12]cyclacene was reported by Stoddart [5]. The synthetic strategy relied upon a double Diels–Alder reaction to form the required carbon framework. The synthesis ultimately failed because a partially saturated precursor **4** (Fig. 2) could not be dehydrogenated. Meaningful progress toward [8]cyclacene derivatives was achieved by Cory, who also employed a double Diels–Alder reaction to assemble the carbon skeleton [6]. Again, the inability to dehydrogenate and/or aromatize various belt precursors (e.g., **5**) was the stumbling block in this work. Klaerner also reported the synthesis of some molecular belts (e.g., **6**) using a double Diels–Alder approach [7], but their aromatization to give [12]-, [13]-, and [14]cyclacenes would require multiple C–C bond scissions, and work in this direction has not been reported. Organometallic belts (e.g., **7**) related to the [*n*]cyclacenes have been reported by Gleiter [8], who very elegantly exploited a cobalt-mediated [2+2] cycloaddition. Also closely related to the [*n*]cyclacenes is the "double-stranded cycle" **8**, which Schlüter appears to be very close to preparing [9]. The approach to this system, which maps onto the equator of D_2-C_{84}, again involves a double Diels–Alder reaction followed by aromatization. The challenging part of this approach is again the aromatization process. Prior to this work, Schlüter reported the synthesis of potential precursors to [6]-, [9]-, and [18]cyclacenes [11] using the now familiar Diels–Alder strategy. A fundamentally different approach to [*n*]cyclacenes, which is based on the reversible [4+2] cycloaddition of C_{60} to [*n*]acenes, has recently been described by Miller, and reports of progress towards this goal are eagerly awaited [12].

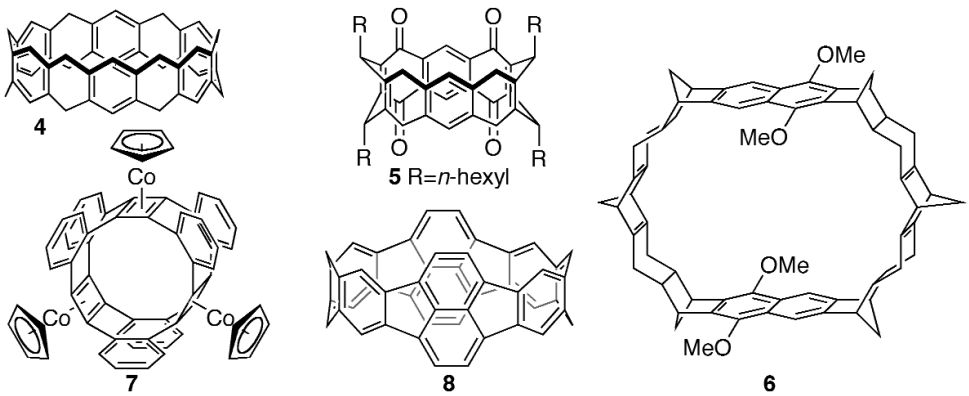


Fig. 2 Selected molecular belts and Schlüter's target **8**.

The [*n*]cyclophenacenes have been predicted to be more stable than the corresponding [*n*]cyclacenes, much as [*n*]phenacenes are more stable than the corresponding [*n*]acenes [13]. [*n*]Cyclophenacenes and related systems have been targeted synthetically by several groups. Nakamura's work stands out because it has produced the only known [*n*]cyclophenacene derivative, **9** (Fig. 3) [14]. The unique synthetic approach involved two separate fivefold nucleophilic additions to the polar caps of C_{60}, which revealed the preexisting [10]cyclophenacene system around the equator. Free-standing (i.e., uncapped) systems have been approached by Iyoda [15] and Scott [16], but these too

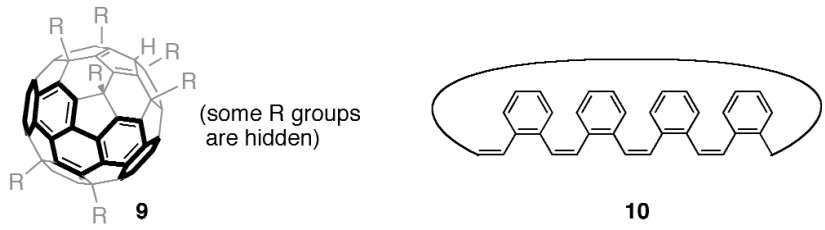


Fig. 3 Nakamura's [10]cyclophenacene derivative and Iyoda's [8]cyclophenacene precursor.

failed at a late stage. In these cases, belt formation was attempted by way of cyclodehydrogenation of relatively unstrained starting materials (e.g., **10**).

Aromatic belts of the general structure **12** (Fig. 4), which also fall into the cyclophenacene/armchair SWCNT category, were identified by Vögtle as interesting targets as early as 1983 (two years before the discovery of C_{60}) [17]. The synthetic approach stands out from the others in that it exploits classical cyclophane chemistry [18]. The idea was to construct a macrocyclic, belt-like cyclophane **11** and then convert it into the corresponding aromatic belt through ring contraction and then valence isomerization/dehydrogenation [19]. The obstacle to success in this work was the difficulty of generating the required macrocyclic cyclophanes from their ribbon-like precursors. Cyclophanes **13** and **14** were synthesized, but they would not be expected to give stable belts because of their small size. In any event, no report of their further elaboration has appeared. Larger cycles, which are potential precursors to larger, more stable belts, could only be detected using mass spectrometry [19f].

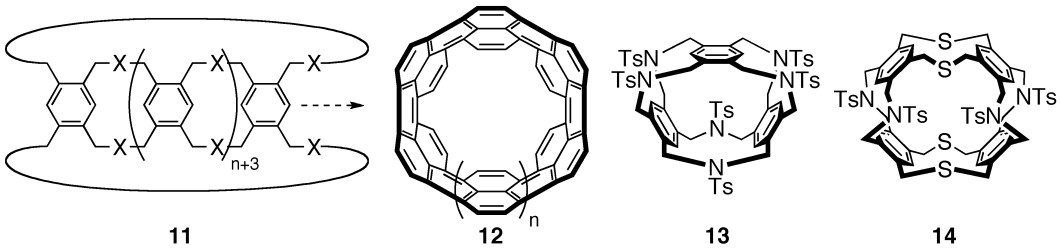


Fig. 4 Vögtle's proposed belts and potential precursors.

A key structural feature of aromatic belts is the presence of radially oriented *p* orbitals [20]. Other systems with radially oriented *p* orbitals, e.g., Oda and Kawase's nanorings **15** (Fig. 5), have been reported [21], but the intersection of the two edges at the ethynylene linkages disqualifies them as aromatic belts. However, it doesn't detract from their novelty, appeal, and importance.

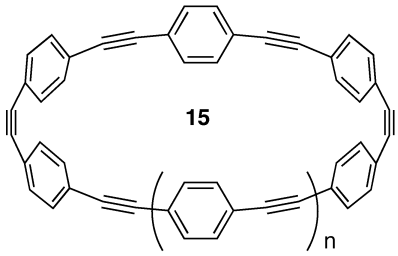
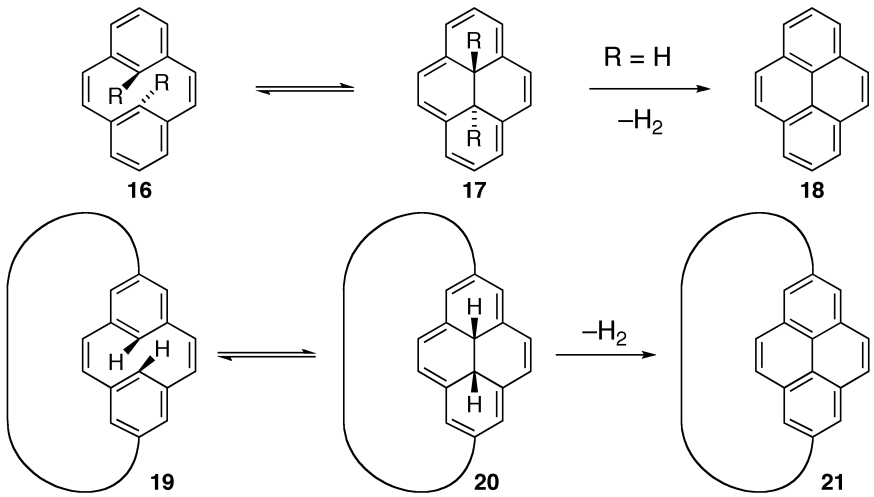


Fig. 5 Oda and Kawase's nanorings.

A common thread in the unsuccessful attempts to generate aromatic belts is the late-stage failure of reactions (mainly eliminations and dehydrogenations) of relatively unstrained systems to give fully aromatic, but considerably more strained belts. In this regard, the interplay of strain and aromaticity is clearly of critical importance. A successful approach to stable, free-standing aromatic belts will clearly have to proceed through a key reaction that brings with it a sufficient energetic driving force, such as aromatic stabilization energy (ASE), to combat the build-up of strain.

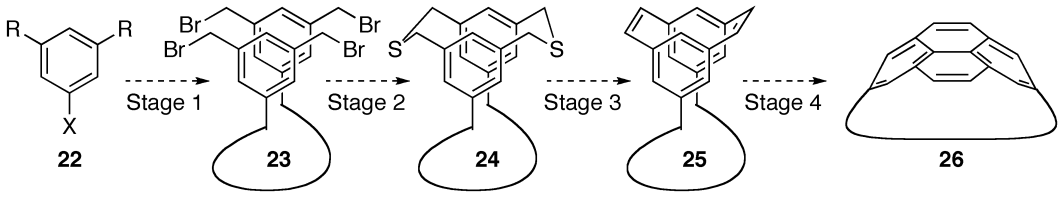
PYRENOPHANE CHEMISTRY: BACKGROUND WORK FOR AN APPROACH TO AROMATIC BELTS

Our entry into the synthesis of nonplanar aromatic systems was founded upon the observation that *trans*-10b,10c-dihydropyrene (**17**), a valence isomer of *anti*-[2.2]metacyclophanediene (**16**), undergoes facile dehydrogenation to give pyrene (**18**) (Scheme 1) [22]. By bridging the 5 and 13 positions of the [2.2]metacyclophane-1,9-diene structure (i.e., **19**), it was envisaged that the ensuing processes of valence isomerization and dehydrogenation (VID) would lead to the formation of [*n*](2,7)pyrenophanes **21**. In contrast to the parent transformation (**16** to **18**), the presence of the long bridge in **19** constrains the [2.2]metacyclophane-1,9-diene unit to adopt the *syn* conformation instead of *anti.* As a result, the valence isomerization changes from being a thermally disfavored antarafacial [4*n*+2] electrocyclic ring closure (**16** to **17**) to a thermally favored suprafacial [4*n*+2] electrocyclic ring closure (**19** to **20**) [23]. Furthermore, the resulting *cis*-10b,10c-dihydropyrene skeleton is innately saucer-shaped due to the presence of an eclipsed ethano unit embedded within the [14]annulene [24]. The adoption of this geometry was expected to go some way toward accommodating shorter tethers and thus provide a stepping stone *en route* to the more strained [*n*](2,7)pyrenophanes. The dehydrogenation of dihydropyrenophanes **20** to afford the corresponding [*n*](2,7)pyrenophanes **21** was anticipated to be accompanied by an increase in strain energy, but it was also expected that this would be counterbalanced by a concomitant increase in ASE. However, at the time, we had no firm numbers to assess the extent of this effect and we pressed on blithely with our synthetic work. Whether due to great intuition, sheer luck, or some happy medium between the two, this naïve assessment now appears to have been quite correct. As outlined below, the VID methodology has proved be a very powerful way of generating severely bent pyrene systems.



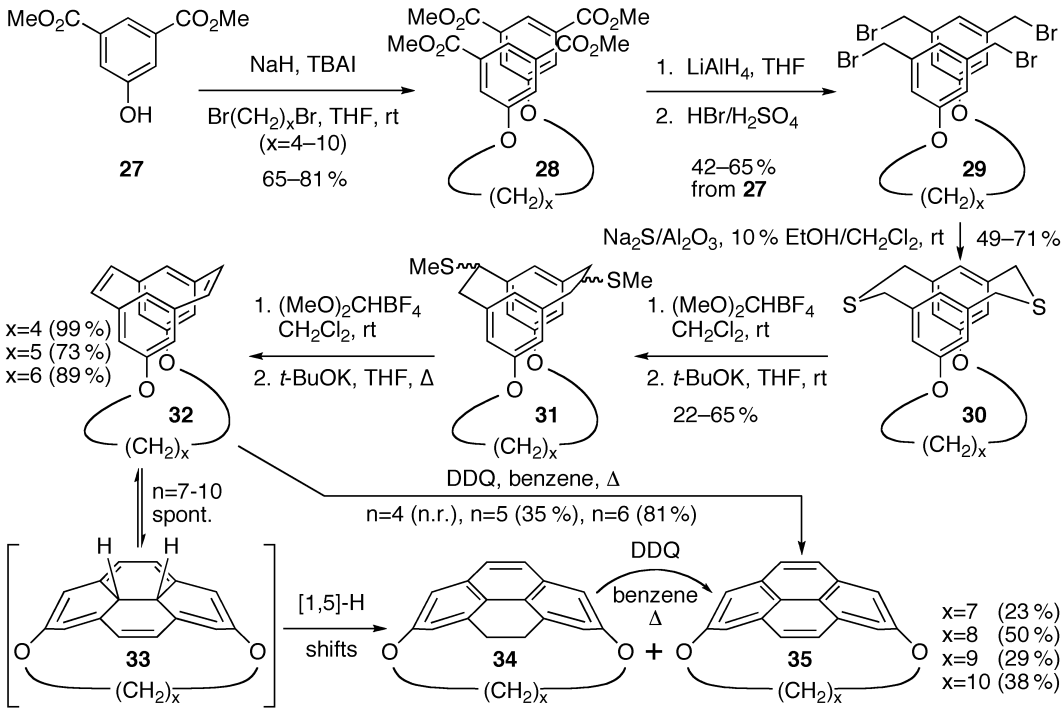
Scheme 1 The evolution of the VID approach to [*n*](2,7)pyrenophanes.

The overall synthetic strategy for the formation of [*n*](2,7)pyrenophanes involves four stages: (1) the tethering of two functionalized aromatic units **22** (molecular plates) and functional group interconversion to give **23**; (2) the formation of a dithiametacyclophane system **24**; (3) generation of a [2.2]metacyclophane-1,9-diene **25**; and (4) application of the VID reaction to generate the nonplanar pyrene system **26** (Scheme 2). A key feature to the success of this approach is that the bent pyrene moiety is generated in its nonplanar conformation, rather than being formed flat and then bent.



Scheme 2 General strategy for the synthesis of [*n*](2,7)pyrenophanes.

The application of this strategy can be exemplified by the syntheses of the 1,*n*-dioxa[*n*](2,7)pyrenophanes **35** [25] (Scheme 3). Esterification of 5-hydroxyisophthalic acid afforded diester **27** in high yield. The tethering of two of these units was accomplished by a Williamson ether synthesis with a series of α,ω-dibromides to afford tetraesters **28**. The completion of Stage 1 was then accomplished through functional group interconversion. Accordingly, tetraesters **28** were reduced with $LiAlH_4$, and the resulting crude tetraols were immediately treated with HBr/H_2SO_4 to furnish tetrabromides **29**. Dithiacyclophanes **30** were formed (Stage 2) upon treatment of **29** with Na_2S/Al_2O_3, which we have found to be a very easily handled, virtually odorless and reliable source of sulfide for such reactions [26].



Scheme 3 Synthesis of the 1,*n*-dioxa[*n*](2,7)pyrenophanes **35**.

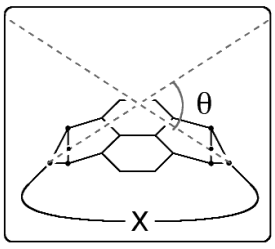
The conversion of the *syn*-[3.3]dithiacyclophane units into the required *syn*-[2.2]metacyclophane-1,9-diene units was achieved using the well-known thia-Stevens rearrangement/Hofmann elimination sequence [18]. Thus, dithiacyclophanes **30** were reacted with the Borch reagent ($(MeO)_2CHBF_4$, dimethoxycarbonium tetrafluoroborate) [27] and the resulting bis(methylsulfonium) tetrafluoroborates were treated with potassium *t*-butoxide to afford ring-contracted cyclophanes **31** as mixtures of isomers. Separation of these isomers was not attempted. Instead, they were subjected to reaction with Borch reagent and the resulting bis(dimethylsulfonium) tetrafluoroborate salts were exposed to base to bring about a Hofmann elimination and thereby create the key *syn*-[2.2]metacyclophanediene unit. The outcome of this reaction was dependent upon the length of the long bridge. For **31** (x = 4–6), the cyclophanedienes **32** (x = 4–6) were isolated in good yield and Stage 3 of the strategy was completed. On the other hand, substrates **31** (x = 7–10) led to the formation of ca. 1:1 mixtures of the desired 1,*n*-dioxa[*n*](2,7)pyrenophanes **35** (x = 7–10) and what were tentatively assigned to be the corresponding 1,*n*-dioxa[*n*](2,7)-4,5-dihydropyrenophanes **34** (x = 7–10). Rather than attempting apparently difficult separations, these mixtures were heated in the presence of dichlorodicyano-*p*-benzoquinone (DDQ) to deliver the desired pyrenophanes **35** (x = 7–10). The formation of **34** (x = 7–10) was explained by the valence isomerization of the cyclophanedienes **32** (x = 7–10) under the conditions of their formation to give 1,*n*-dioxa[*n*](2,7)-10b,10c-dihydropyrenophanes **33** (x = 7–10), followed by a series of three consecutive [1,5]-H shifts. The driving force for this process is presumably the greater ASE in the phenanthrene system compared to that of a *cis*-10b,10c-dihydropyrene and any of the intermediates between them.

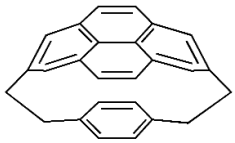
Cyclophanediene **32** (x = 6) reacted smoothly with DDQ in benzene at reflux to afford 1,8-dioxa[8](2,7)pyrenophane **35** (x = 6) in good yield. The next lower homolog, **32** (x = 5), reacted under the same conditions, but the reaction was slower, not as clean, and required careful workup and chromatography to obtain 1,7-dioxa[7](2,7)pyrenophane **35** (x = 5) in modest yield. The smallest member of the series **32** (x = 4) showed no signs of reaction even under considerably more forcing conditions (xylenes, reflux). The capability of the VID reaction certainly appears to have been exceeded at this point.

As summarized in Fig. 6, a series of other (2,7)pyrenophanes have been synthesized using this general strategy, including the parent [*n*](2,7)pyrenophanes **36** [28]. The angle θ [29], which is used to quantify the degree of nonplanarity of the pyrene system (Fig. 6, inset), has been determined crystallographically for most of the pyrenophanes. AM1 calculations predict values that are, at least in the intermediate to upper range of bend, consistently 4–7° greater than the measured values. This being the case, they can and have been used predictively with a fair degree of confidence. In general, an AM1-calculated value under 110° indicates that the VID reaction will very likely be capable of generating the system in question without any difficulty. For calculated bend angles in the range of 110–120°, it can be expected that the VID reaction may or may not be able to deliver the product and that the product will likely have to be handled with care. Compounds **38** (θ_{calc} = 108.3°), **39** (θ_{calc} = 100.4°) and **40** (θ_{calc} = 106.6°) were prepared after their bend angles were calculated and they all proved to be well-behaved. By the same token, pyrenophane **37** (θ_{calc} = 117.2°) was found to form only very slowly from its direct precursor and it could not be isolated in pure form. It was obtained only as a minor impurity in recovered starting material [29].

As expected, the value of θ increases as the number of atoms in the bridge decreases. Beyond that, a fine-tuning of the bend in the pyrene unit can be achieved by varying the nature of the bridge. More specifically, the replacement of carbon atoms in the tether with oxygen atoms has the effect of slightly shortening the tether due to the $C(sp^3)$–$O(sp^3)$ bond (1.43 Å) being shorter than the $C(sp^3)$–$C(sp^3)$ bond (1.53 Å) [30]. In the case of n = 7, it can be seen that a range of 12.6° is spanned upon going from [7](2,7)pyrenophane **36** to 1,4,7-trioxa[7](2,7]pyrenophane **37.** This is well over half of the difference in bend angle between [7](2,7)pyrenophane and [8](2,7)pyrenophane (17.6°).

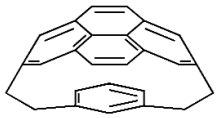
An evaluation of the aromaticity of the pyrene systems in the 1,*n*-dioxa[*n*](2,7)pyrenophanes using geometric (harmonic oscillator model of aromaticity (HOMA)) and magnetic (nucleus-independ-





39

$\theta_{x\text{-ray}}$ = 89.7°
θ_{calc} = 100.4°



40

$\theta_{x\text{-ray}}$ = 97.0°
θ_{calc} = 106.6°

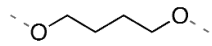
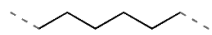
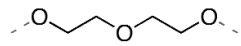
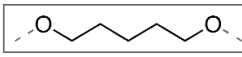
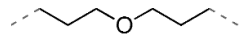
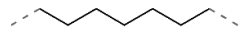
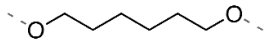
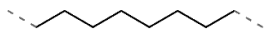
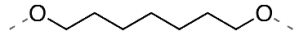
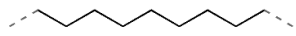
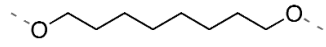
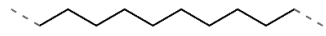
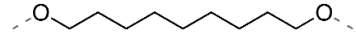
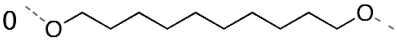
Compound	Tether	(n)	$\theta_{x\text{-ray}}$ (°)	θ_{calc} (°)
35 x=4		6		132.1
36 n=6		6		122.9
37		7		117.2
35 x=5		7	109.2	113.3
38		7	102.9	108.3
36 n=7		7	–	104.6
35 x=6		8	87.8	94.9
36 n=8		8	80.8	87.0
35 x=7		9	72.9	77.8
36 n=9		9	62.4	70.3
35 x=8		10	57.7	61.2
36 n=10		10	46.4	54.4
35 x=9		11	39.9	42.2
35 x=10		12	34.6	33.1

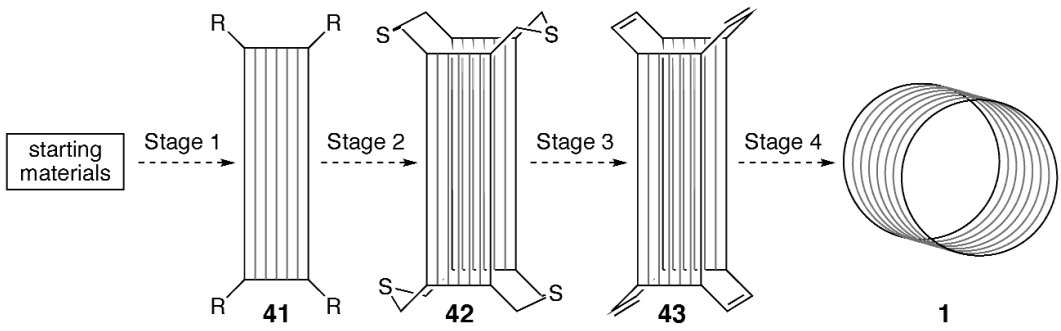
Fig. 6 Bend angles of the [*n*](2,7)pyrenophanes.

ent chemical shift (NICS)) criteria led to the conclusion that the aromaticity drops as the pyrene unit becomes increasingly distorted from planarity, but that 80–90 % of the aromaticity present in the planar system is still present in the most severely bent pyrene, i.e., the one present in 1,7-dioxa[7](2,7)pyrenophane **35** ($x = 5$) ($\theta_{X\text{-ray}} = 109.2°$) [25b]. In other words, aromaticity is robust when it comes to bending the pyrene system away from planarity. This may well be generally true for aromatic systems other than pyrene and for aromatic systems that have been distorted from planarity by pyramidalization (e.g., buckybowls) or by twisting (e.g., helicenes). Of course, the appropriate work will have to be done before this can be stated with confidence. Whatever the case, the most germane aspect of this work is that the VID methodology owes its ability to create severely bent pyrenes to its ability to bring with it most of the ASE of planar pyrene [31], even in the upper register of bend.

RESULTS AND DISCUSSION

A repeating pyrene unit can be identified in the surface of the Vögtle belts **12**. As stated earlier, the possibility of using cyclophane chemistry to synthesize such molecules is very appealing. However, Vögtle's approach fell foul of the conformational preferences of the various [3.3]metacyclophane units in his molecular ribbons, which effectively prevented the crucial macrocyclization event from occurring efficiently [19].

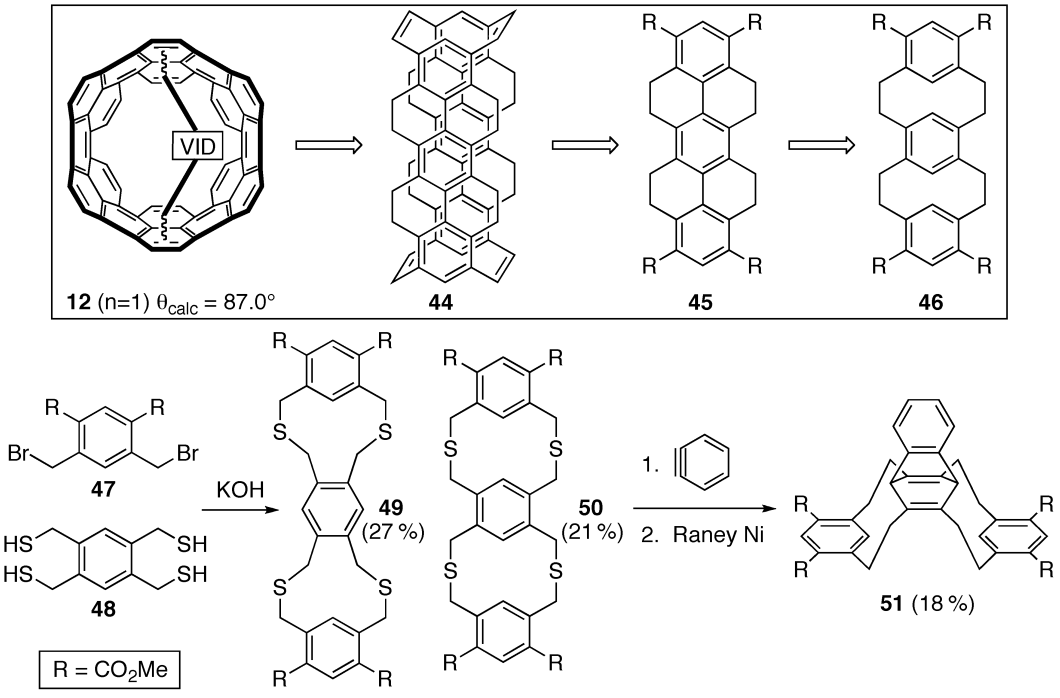
Our approach does not differ greatly from Vögtle's approach. The major difference is that, instead of proceeding through a macrocyclic system consisting of multiple metacyclophane moieties, our plan (Scheme 4) involves the construction of only two such subunits. The stages of our strategy are: (1) the synthesis of an appropriately substituted molecular board **41**; (2) the connection of two such boards to



Scheme 4 A strategy for the synthesis of aromatic belts.

form a tetrathiacyclophane **42**; (3) the conversion of the initial cyclophane into a cyclophanetetraene **43**; and (4) a double VID reaction to give a belt **1**. Two clear advantages of this approach are that the general preference of 2,11-dithia[3.3]metacyclophanes for the *syn* conformation is not at odds with a macrocyclization event (as it was in Vögtle's approach) and that π stacking may even promote it.

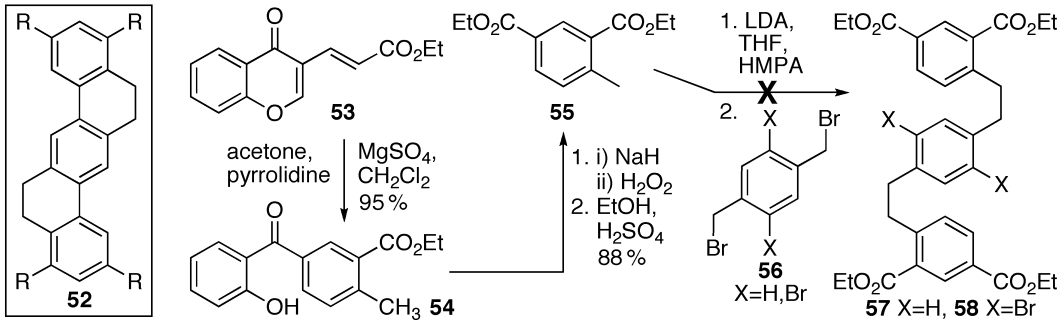
The first belt to receive synthetic attention was the D_{6h}-symmetric Vögtle belt **12** (n = 1). The retrosynthetic analysis (Scheme 5) took **12** (n = 1) back to cyclophanetetraene **44** via a VID transform and then back to board **45** by established cyclophane chemistry [18]. The additional sites of saturation were included in the design to promote solubility throughout the synthesis. It was anticipated that dehydrogenation of these ethano units could be achieved in the final step of the synthesis along with the VID reactions. Encouragingly, literature precedent for the synthesis of the basic skeleton of **45** from cyclophane **46** already existed [32].



Scheme 5 Retrosynthesis and synthetic progress toward Vögtle belt **12** (n = 1).

The modification of the literature synthesis of **46** to include useful functionality (i.e., esters) turned out to be the downfall of this approach. According to Vögtle's procedures, dibromodiester **47** and tetrathiol **48** were synthesized and coupled to afford a mixture of **49** (27 %) and **50** (21 %) [19h,i]. The chromatographic separation of these two isomers was difficult, but a couple of grams of each isomer could be isolated through the investment of sufficient effort. A long list of experiments aimed at achieving a fourfold ring contraction using the Stevens rearrangement, the Wittig rearrangement [18], sulfone pyrolysis [18], photolytic desulfurization [18], and the benzyne Stevens rearrangement [33] all met with disappointment. In general, very complex product mixtures were obtained. The best result was obtained from the attempted benzyne Stevens rearrangement of **50**, which afforded, after subsequent protodesulfurization of the crude reaction mixture with Raney nickel, adduct **51** in poor yield (18 %). It can be inferred from this result that the desired ring contractions did take place to form some of the u,d isomer, but the strained central benzene ring participated in a [4+2] cycloaddition with benzyne.

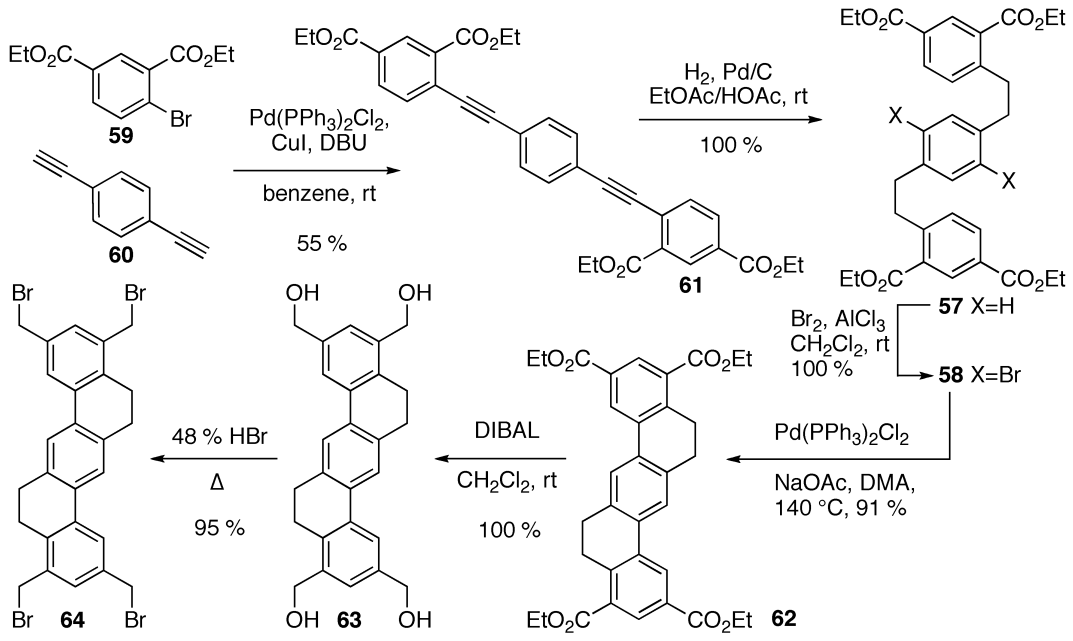
The difficulties associated with the original target caused us to turn our attention to a pared down board motif (**52**) based on dibenzo[*a*,*h*]anthracene (Scheme 6). Again, two elements of unsaturation were incorporated into the boards to promote solubility throughout the synthesis. The first approach to this type of board relied upon an inverse electron demand Diels–Alder (IEDDA) driven domino reaction that we had developed [34]. Reaction of electron-deficient diene **53** with the in situ generated enamine derived from acetone and pyrrolidine afforded 2-hydroxybenzophenone **54** in excellent yield (95 %). Application of the Dakin oxidation gave an isophthalic acid monoester, which was immediately esterified to give isophthalate **55**. Treatment of **55** with strong bases (e.g., LDA) gave deeply colored solutions, but attempts to alkylate the presumed anion with electrophiles **56** failed to give anything more than traces of the desired products **57**, which contain all of the carbon atoms needed to construct board **52**.



Scheme 6 First approach to a dibenzo[*a*,*h*]anthracene-based board.

The second approach to the dibenzo[*a*,*h*]anthracene-based board **52** was reminiscent of our synthesis of [2]paracyclo[2](2,7)pyrenophane **39** [28c]. A Sonogashira cross-coupling reaction between diethyl 4-bromoisophthalate (**59**) [35] and 1,4-diethynylbenzene (**60**) [28c] afforded diynetetraester **61** in 55 % yield (Scheme 7). Catalytic hydrogenation of the triple bonds led to the quantitative formation of tetraester **57**. Reaction of **57** with bromine occurred with complete regioselectivity on the electron-rich central ring to afford dibromotetraester **58** (100 %). An intact board (**62**) was then generated through a double direct arylation reaction [36], which proceeded in high yield (91 %).

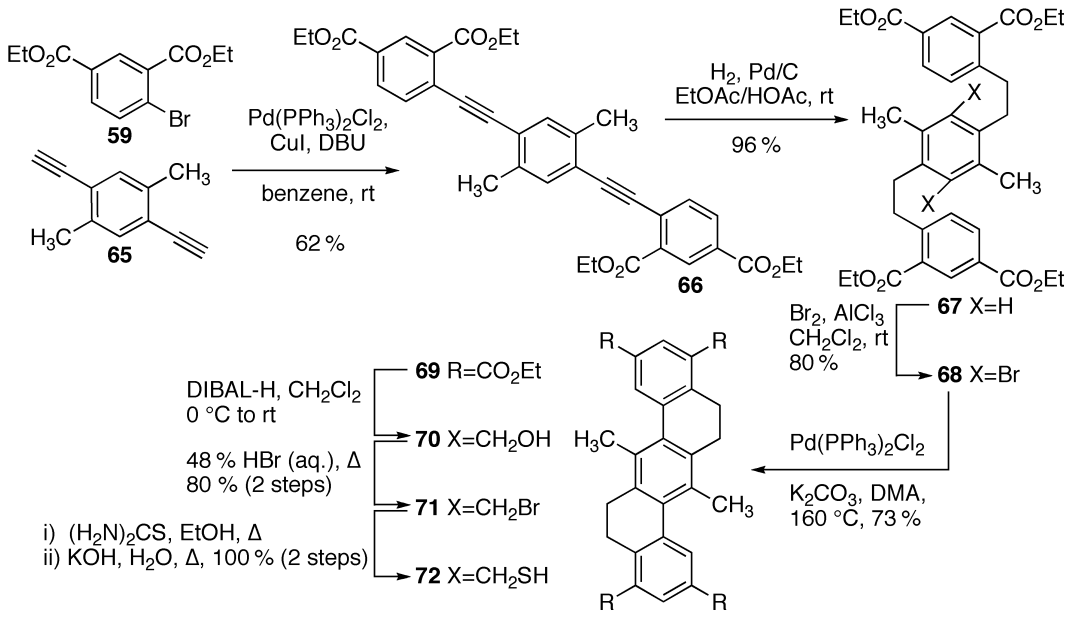
However, the modest solubility of the product in dichloromethane and chloroform was cause for real concern. As feared, the solubility dropped off steeply upon reduction of **62** with $LiAlH_4$ to afford tetraol **63**. Although this compound could be efficiently converted into the desired tetrabromide **62** (95 %) upon treatment with 48 % HBr at reflux, the low solubility of **62** in common organic solvents made it very difficult to work with. This dictated the inclusion of solubilizing groups on the boards.



Scheme 7 Second approach to a dibenzo[*a*,*h*]anthracene-based board.

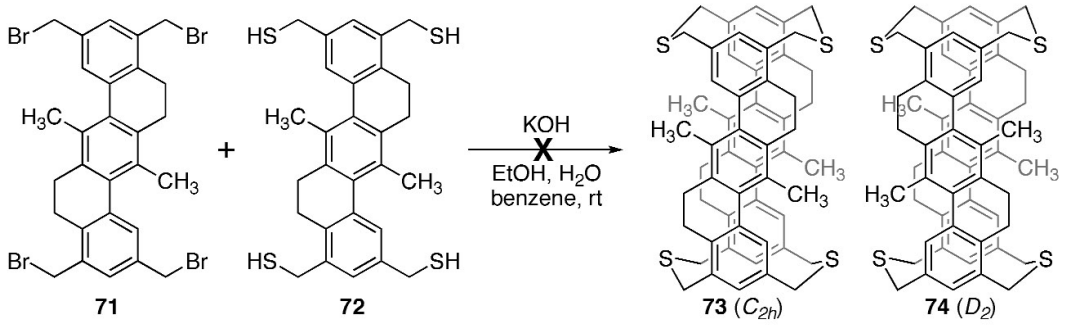
The central part of the board was identified as the best site to add the solubilizing groups because these positions were the furthest from the functional groups, which were slated to be used for the formation and ensuing elaboration of the cyclophane structure. A major concern was that the double direct arylation reaction would now be required to form a hexasubstituted benzene ring, and we were unaware of any precedent for such a reaction. To assess the viability of this approach, it was decided to attach two methyl groups to the central ring.

The synthesis proceeded along the same lines as the previous one (Scheme 8). Diyne **65** was synthesized from p-xylene by a three-step sequence comprised of iodination, Sonogashira cross-coupling with trimethylsilylacetylene, and protodesilylation. Sonogashira cross-coupling of **59** with **65** afforded diynetetrester **66** (62 %), which was hydrogenated to afford **67** (96 %). Bromination of **67** then delivered the substrate for the key double direct arylation reaction, **68** (80 %). Gratifyingly and with very little optimization, the double direct arylation reaction proceeded smoothly to afford the board tetraester **69** (73 %), which was roughly twice as soluble as **62** in chloroform-*d*. Reduction of **69** with diisobutylaluminum hydride (DIBAL-H) afforded poorly soluble tetraol **70**, which was converted without purification into tetrabromide **71** (80 %, 2 steps) upon heating with 48 % aqueous HBr solution. Tetrathiol **72** was then generated quantitatively by reaction of **71** with thiourea, followed by hydrolysis of the resulting tetrakis(isothiouronium) salt.



Scheme 8 Third approach to a dibenzo[*a*,*h*]anthracene-based board.

Attempts to join these precursors to give tetrathiacyclophanes **73** (C_{2h}) and **74** (D_2) were thwarted by insufficient solubility of the starting materials, which crystallized from dilute benzene solutions during addition to the solution of KOH (Scheme 9). No mobile spots were observed in the tlc of the crude reaction mixture. This was not a surprising result considering that methyl groups are not good solubilizing groups. Obviously, more efficient solubilizing groups will be required to carry the strategy through the later stages of the general strategy. However, the demonstration that the double direct arylation reaction smoothly afforded **69** bodes very well for the incorporation of longer alkyl groups such as *n*-decyl groups. Work aimed at achieving this goal is underway.

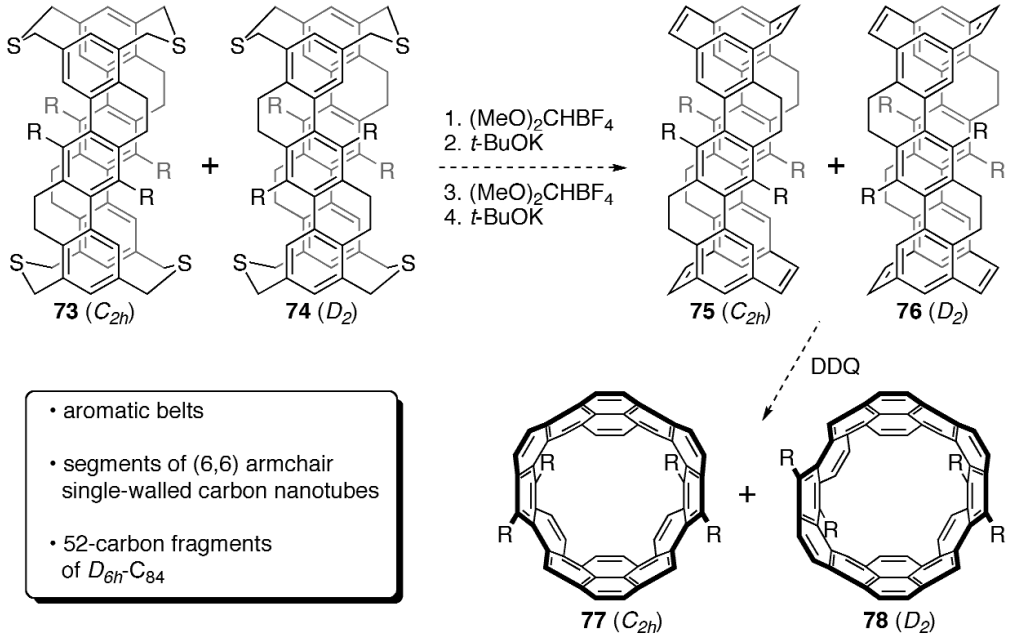


Scheme 9 Attempted union of two boards.

OUTLOOK

Stage 1 of our general strategy has been accomplished, and initial attempts to complete Stage 2 were thwarted by solubility problems, which we expect to solve very soon through the use of better solubilizing groups. Although Stage 3 appears to involve the application of chemistry that we have already employed successfully in the synthesis of numerous pyrenophanes, we are cognizant of the fact that

each step on the way from tetrathiacyclophanes **73** (C_{2h}) and **74** (D_2) to cyclophanetetraenes **75** (C_{2h}) and **76** (D_2) is a fourfold reaction (Scheme 10). As such, yields may be low. With AM1-calculated bend angles of $\theta = 87°$, the VID methodology is expected to be powerful enough to complete the final stage of the synthesis (Stage 4) and deliver aromatic belts **77** (C_{2h}) and **78** (D_2). Hopefully, the fourfold dehydrogenation that must accompany this step will not interfere with this process.



Scheme 10 Remaining steps in the synthesis of aromatic belts **77** (C_{2h}) and **78** (D_2).

REFERENCES AND NOTES

1. For some examples of non-aromatic belt-shaped systems such as cucurbiturils, spherands, cavitands, and crown ether-based belts, see: A. Schröder, H.-B. Mekelburger, F. Vögtle. *Top. Curr. Chem.* **172**, 179 (1994).
2. For a clear explanation of roll-up motifs, see: R. Herges. In *Modern Cyclophane Chemistry*, R. Gleiter, H. Hopf (Eds.), Chap. 13, pp. 337–358, Wiley-VCH, Weinheim (2004).
3. (a) Z. Chen, D. Jiang, X. Lu, H. Bettinger, S. Dai, P. v. R. Schleyer, K. N. Houk. *Org. Lett.* **9**, 5449 (2007); (b) K. Tahara, Y. Tobe. *Chem. Rev.* **107**, 5274 (2007); (c) L. Türker, S. Gümüs. *J. Mol. Struct. (Theochem)* **685**, 1 (2004); (d) K. N. Houk, P. S. Lee, M. Nendel. *J. Org. Chem.* **66**, 5517 (2001); (e) M. Guillaume, B. Champagne, E. A. Perpète, J.-M. André. *Theor. Chem. Acc.* **105**, 431 (2001); (f) K. Tahara, Y. Tobe. *Chem. Rev.* **107**, 5274 (2007).
4. (a) A. A. Fokin, H. Jiao, P. v. R. Schleyer. *J. Am. Chem. Soc.* **120**, 9364 (1998); (b) A. B. McEwen, P. v. R. Schleyer. *J. Org. Chem.* **51**, 4357 (1986).
5. (a) U. Giresser, D. Giuffrida, F. H. Kohnke, J. P. Mathias, D. Philip, J. F. Stoddart. *Pure Appl. Chem.* **65**, 119 (1993); (b) P. R. Ashton, G. R. Brown, N. S. Isaacs, D. Giuffrida, F. H. Kohnke, J. P. Mathias, A. M. Z. Slawin, D. R. Smith, J. F. Stoddart, D. J. Williams. *J. Am. Chem. Soc.* **114**, 6330 (1992); (c) F. H. Kohnke, J. F. Stoddart. *Pure Appl. Chem.* **61**, 1581 (1989).
6. (a) R. M. Cory, C. L. McPhail. *Adv. Theor. Interesting Mol.* **4**, 53 (1998); (b) R. M. Cory, C. L. McPhail. *Tetrahedron Lett.* **37**, 1987 (1996); (c) R. M. Cory, C. L. McPhail, A. J. Dikmans, J. J. Vittal. *Tetrahedron Lett.* **37**, 1983 (1996).

7. J. Benkhoff, R. Boese, F.-G. Klärner, A. E. Wigger. *Tetrahedron Lett.* **35**, 73 (1994).
8. (a) B. Esser, J. A. Raskatov, R. Gleiter. *Org. Lett.* **9**, 4037 (2007); (b) R. Gleiter, B. Hellbach, S. Gath, R. J. Schaller. *Pure Appl. Chem.* **78**, 699 (2006); (c) B. Hellbach, F. Rominger, R. Gleiter. *Angew. Chem., Int. Ed.* **43**, 5846 (2004).
9. (a) C. Denekamp, A. Etinger, W. Amrein, A. Stanger, M. Stuparu, A.-D. Schlüter. *Chem.—Eur. J.* **14**, 1628 (2008); (b) M. Stuparu, V. Gramlich, A. Stanger, A. D. Schlüter. *J. Org. Chem.* **72**, 424 (2007); (c) M. Stuparu, D. Lentz, H. Rüegger, A. D. Schlüter. *Eur. J. Org. Chem.* 88 (2007); (d) W. D. Neudorff, D. Lentz, M. Anibarro, A. D. Schlüter. *Chem.—Eur. J.* **9**, 2745 (2003).
10. A. Godt, V. Enkelmann, A.-D. Schlüter. *Angew. Chem., Int. Ed. Engl*. **28**, 1680 (1989).
11. O. Kintzel, P. Luger, M. Weber, A.-D. Schlüter. *Eur. J. Org. Chem.* 99 (1998).
12. G. P. Miller, S. Okano, D. Tománek. *J. Chem. Phys.* **124**, Art. No. 121102 (2006).
13. (a) J. Aihara. *J. Chem. Soc., Perkin Trans. 2* 971 (1994); see also: (b) Y. Matsuo, K. Tahara, E. Nakamura. *Org. Lett.* **5**, 3181 (2003).
14. (a) Y. Matsuo, K. Tahara, K. Morita, K. Matsuo, E. Nakamura. *Angew. Chem., Int. Ed.* **46**, 2844 (2007); (b) Y. Matsuo, K. Tahara, M. Sawamura, E. Nakamura. *J. Am. Chem. Soc.* **126**, 8725 (2004); (c) E. Nakamura, K. Tahara, Y. Matsuo, M. Sawamura. *J. Am. Chem. Soc.* **125**, 2834 (2003).
15. (a) Y. Kuwatani, T. Yoshida, A. Kusaka, M. Oda, K. Hara, M. Yoshida, H. Matsuyama, M. Iyoda. *Tetrahedron* **57**, 3567 (2001); (b) Y. Kuwatani, T. Yoshida, A. Kusaka, M. Iyoda. *Tetrahedron Lett.* **41**, 359 (2000).
16. (a) M. A. Brooks. Ph.D. dissertation, Boston College, Chestnut Hill, MA (1998); (b) St. H. M. Martin-Davis. Ph.D. dissertation, Boston College, Chestnut Hill, MA (2002).
17. F. Vögtle. *Top. Curr. Chem.* **115**, 157 (1983).
18. R. H. Mitchell. *Heterocycles* **11**, 563 (1978).
19. (a) W. Boomgaarden, F. Vögtle, M. Nieger, H. Hupfer. *Chem.—Eur. J.* **5**, 345 (1999); (b) S. Breidenbach, J. Harren, S. Neumann, M. Nieger, K. Rissanen F. Vögtle**.** *J. Chem. Soc., Perkin Trans. 1* 2061 (1996); (c) S. Breidenbach, S. Ohren, F. Vögtle. *Chem.—Eur. J.* **2**, 832 (1996); (d) S. Breidenbach, S. Ohren, R. Herbst-Irmer, S. Kotila, M. Nieger, F. Vögtle. *Liebigs Ann.* 2115 (1996); (e) S. Breidenbach, S. Ohren, M. Nieger, F. Vögtle. *J. Chem. Soc., Chem. Commun.* 1237 (1995); (f) W. Josten, S. Neumann, F. Vögtle, K. Hägele, M. Przybylski, F. Beer, K. Müllen. *Chem. Ber.* **127**, 2089 (1994); (g) W. Josten, D. Karbach, M. Nieger, F. Vögtle, K. Hägele, M. Svoboda, M. Przybylski. *Chem. Ber.* **127**, 767 (1994); (h) A. Schröder, D. Karbach, F. Vögtle. *Chem. Ber.* **125**, 1881 (1992); (i) F. Vögtle, A. Schröder, D. Karbach. *Angew. Chem., Int. Ed. Engl.* **30**, 575 (1991).
20. L. T. Scott. *Angew. Chem., Int. Ed.* **42**, 4133 (2003).
21. (a) T. Kawase. *J. Synth. Org. Chem. Japan* **65**, 888 (2007); (b) T. Kawase, H. Kurata. *Chem. Rev.* **106**, 5250 (2006); (c) T. Kawase, M. Oda. *Pure Appl. Chem.* **78**, 831 (2006).
22. R. H. Mitchell, V. Boekelheide. *J. Am. Chem. Soc.* **92**, 3510 (1970).
23. I. Fleming. *Frontier Orbitals and Organic Chemical Reactions*, John Wiley, New York (1982).
24. G. J. Bodwell, J. N. Bridson, S.-L. Chen, R. A. Poirier. *J. Am. Chem. Soc.* **123**, 4704 (2001).
25. (a) G. J. Bodwell, J. N. Bridson, T. J. Houghton, J. W. J. Kennedy, M. R. Mannion. *Angew. Chem.* **108**, 1418 (1996); (b) G. J. Bodwell, J. N. Bridson, T. J. Houghton, J. W. J. Kennedy, M. R. Mannion. *Angew. Chem., Int. Ed. Engl.* **35**, 1320 (1996); (c) G. J. Bodwell, J. N. Bridson, T. J. Houghton, J. W. J. Kennedy, M. R. Mannion. *Chem.—Eur. J.* **5**, 1823 (1999); (d) G. J. Bodwell, J. N. Bridson, M. Cyranski, J. W. J. Kennedy, T. M. Krygowski, M. R. Mannion, D. O. Miller. *J. Org. Chem.* **68**, 2089 (2003).
26. G. J. Bodwell, T. J. Houghton, H. E. Koury, B. Yarlagadda. *Synlett* 751 (1995).
27. R. F. Borch. *J. Org. Chem.* **34**, 627 (1969).

28. (a) G. J. Bodwell, J. J. Fleming, M. R. Mannion, D. O. Miller. *J. Org. Chem.* **65**, 5360 (2000); (b) I. Aprahamian, G. J. Bodwell, J. J. Fleming, G. P. Manning, M. R. Mannion, B. L. Merner, T. Sheradsky, R. J. Vermeij, M. Rabinovitz. *J. Am. Chem. Soc.* **126**, 6765 (2004); (c) G. J. Bodwell, D. O. Miller, R. J. Vermeij. *Org. Lett.* **3**, 2093 (2001).
29. G. J. Bodwell, J. J. Fleming, D. O. Miller. *Tetrahedron* **57**, 3577 (2001).
30. M. B. Smith, J. March. *March's Advanced Organic Chemistry*, 5th ed., p. 20, John Wiley, New York (2001).
31. The ASE of pyrene has been estimated to be ca. 62 kcal mol^{-1} by George et al., using isodesmic reactions. See: (a) P. George, M. Trachtman, C. W. Bock, A. M. Brett. *Tetrahedron* **32**, 1357 (1976). We feel these estimates are too low and that the real value is in the range of 70–80 kcal mol^{-1}, see: (b) M. K. Cyranski M. A. Dobrowolski, B. L. Merner, G. J. Bodwell, J. Wu, P. v. R. Schleyer. Manuscript under review.
32. (a) T. Umemoto, T. Kawashima, Y. Sakata, S. Misumi. *Tetrahedron Lett*. 1005 (1975); (b) T. Umemoto, T. Otsubo, Y. Sakata, S. Misumi. *Tetrahedron Lett.* 593 (1973).
33. (a) T. Otsubo, V. Boekelheide. *Tetrahedron Lett.* 3881 (1975); (b) T. Otsubo, V. Boekelheide. *J. Org. Chem*. **42**, 1085 (1977).
34. (a) G. J. Bodwell, K. M. Hawco, T. Satou. *Synlett* 879 (2003); (b) G. J. Bodwell, K. M. Hawco, R. P. da Silva. *Synlett* 179 (2003).
35. This compound was synthesized in three steps from m-xylene by the following sequence: (i) bromination with Br_2, (ii) oxidation with $KMnO_4$ and (iii) esterification with EtOH, H_2SO_4.
36. (a) L. C. Campeau, D. R. Stuart, K. Fagnou. *Aldrichim. Acta* **40**, 35 (2007); (b) L. C. Campeau, M. Parisien, M. Leblanc, K. Fagnou. *J. Am. Chem. Soc*. **126**, 9186 (2004).