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En Route to Archimedene: Total Synthesis of C_{3h}-Symmetric [7]Phenylene

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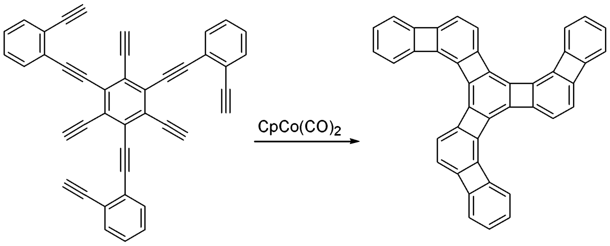
ABSTRACT



The total synthesis of C_{3h}-symmetric [7]phenylene has been accomplished by triple cobalt-catalyzed cycloisomerization of an appropriate nonayne. Its spectral data are in accord with the expectations for a triply angularly fused system, but its calculated heat of formation suggests the presence of a destabilizing σ effect relative to its D_{3h} isomer. The molecule constitutes the largest substructure of archimedene hitherto synthesized.

The icosahedral fullerene archimedene, C_{120} (Figure 1), endowed with the contour of one of the 13 archimedean solids, the truncated icosidodecahedron, and containing 12 [10]annulene, 20 benzene, and 30 cyclobutadiene rings, has so far been the subject of solely theoretical estimates.[1] Thus, it should be considerably more energetic than C_{60}, with a comparable HOMO−LUMO gap, primarily due to the presence of the four-membered rings, and it should exhibit considerable resonance stabilization. Archimedene may be regarded as a spherical phenylene,[1b,c,2] the synthesis of which presents a considerable challenge, partly alleviated by the ready deformability of such systems,[3] rendering curvature a lesser problem than for normal fullerenes. Our approach to this molecule is similar to that to the latter,[4] namely the gradual buildup of strategic substructures, eventually to be annealed to the final target. In this connection, it is noteworthy that fullerenes containing fused or incorporated four-membered rings are known.[5] We have reported on the

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[1] See, inter alia: (a) De La Vaissière, B.; Fowler, P. W.; Deza, M. *J. Chem. Inf. Comput. Sci.* **2001**, *41*, 376. (b) Schulman, J. M.; Disch, R. L. *Chem. Phys. Lett.* **1996**, *262*, 813. (c) Schulman, J. M.; Disch, R. L. *J. Am. Chem. Soc.* **1996**, *118*, 8470. (d) Kurita, N.; Kobayashi, K.; Kumahora, H.; Tago, K.; Ozawa, K. *Chem. Phys. Lett.* **1992**, *188*, 181. (e) Kovačević, K.; Graovac, A. *Int. J. Quantum Chem., Quantum. Chem. Symp.* **1987**, *21*, 589. (f) Coulombeau, C.; Rassat, A. *J. Chim. Phys.* **1987**, *84*, 875. (g) Fowler, P. W.; Woolrich, J. *Chem. Phys. Lett.* **1986**, *127*, 78. (h) Haymet, A. D. J. *Chem. Phys. Lett.* **1985**, *122*, 421.

[2] Vollhardt, K. P. C.; Mohler, D. L. In *Advances in Strain in Organic Chemistry*; Halton, B., Ed.; JAI: London, 1996; pp 121−160.

[3] Holmes, D.; Kumaraswamy, S.; Matzger, A. J.; Vollhardt, K. P. C. *Chem. Eur. J.* **1999**, *5*, 3399.

10.1021/ol027482z CCC: $25.00

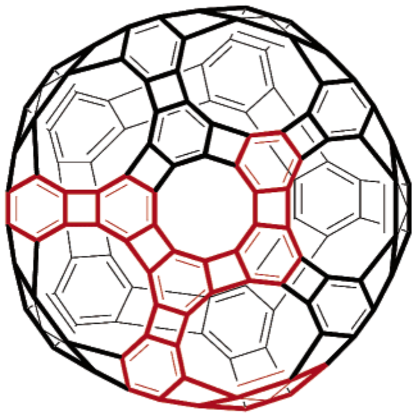
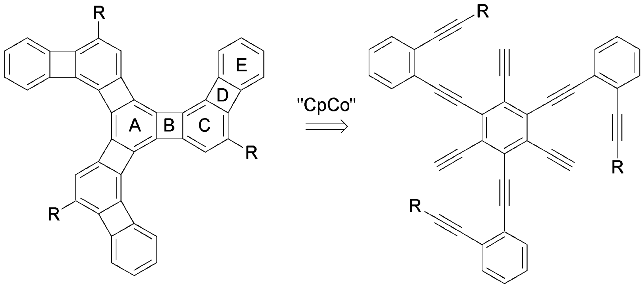


Figure 1. Archimedene, C$_{120}$, and the embedded substructure of C_{3h}-symmetric [7]phenylene **1a**.

construction of several such substructures, the largest so far being triangular [4]phenylene,[6] zigzag [5]phenylene,[7] and angular (helical) [5]phenylene.[8] Strategically, the triangular motif appears most suitable for elaboration to semi-archimedene C$_{60}$ via extension of the terminal benzene nuclei. We report here the beginning of the implementation of this approach through the synthesis of C_{3h}-symmetric [7]phenylene **1a** (see Figure 1, highlighted in red; Scheme 1), in addition to its trihexyl derivative **1b**. These molecules are also of intrinsic interest in comparison to their D_{3h} isotopomer **5** (Figure 2),[9] as well as to their own various substructures, because they provide an opportunity to assess the effect of topology on the physical properties of the higher phenylenes.

Scheme 1



1a, R = H
1b, R = Hex

2a, R = H
2b, R = Hex

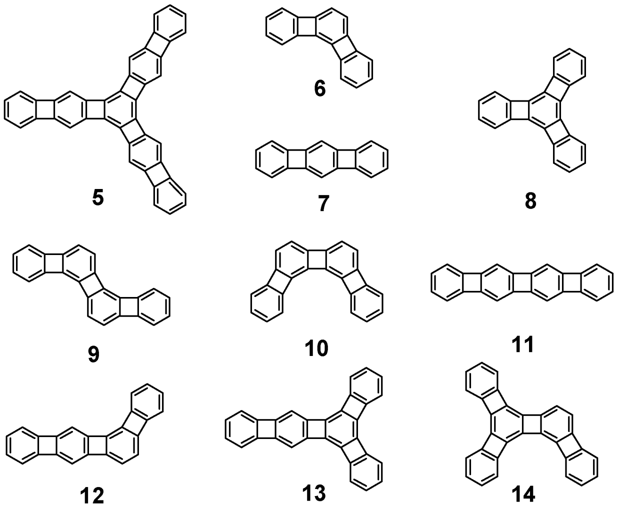


Figure 2. Phenylene structures pertinent to the discussion.

Encouraged by our recent successful execution of triple cycloisomerizations catalyzed by CpCo on route to the heliphenes,[10] the retrosynthetic analysis in Scheme 1 was implemented. From the various approaches to the alternating hexaalkynyl substitution pattern in **2**,[11] we chose the one starting from Rubin's trialdehyde **3** (Scheme 2),[11d] which was readily elaborated to **4**. This material could be subjected to triple coupling with the respective alkynylarene fragments[12] that led to **2a** and **b**. Cobalt-catalyzed cyclization then furnished the desired targets in yet another[10] remarkable transformation that makes nine rings in one step, including all of the component cyclobutadiene units, albeit in low yields.

Phenylenes **1a** and **b** are air-sensitive, orange solids, quite insoluble in common organic solvents (precluding ^{13}C NMR measurements), and unfortunately not suitable for X-ray analysis. The electronic spectra reveal typical phenylene patterns of a set of relatively strong absorptions at ∼320 nm and another, weaker set extending to ∼460 nm. The latter is noticeably hypsochromically shifted from the chromophore

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(4) For recent reviews, see: (a) Necula, A.; Scott, L. T. *J. Anal. Appl. Pyrolysis* **2000**, *54*, 65. (b) Scott, L. T.; Bronstein, H. E.; Preda, D. V.; Ansems, R. B. M.; Bratcher, M. S.; Hagen, S. *Pure Appl. Chem.* **1999**, *71*, 209. (c) Mehta, G.; Rao, H. S. P. *Tetrahedron* **1998**, *54*, 13325. For most recent work, see, inter alia: (d) Boorum, M. M.; Vasil'ev, Y. V.; Drewello, T.; Scott, L. T. *Science* **2002**, *294*, 828. (e) Bronstein, H. E.; Choi, N.; Scott, L. T. *J. Am. Chem. Soc.* **2002**, *124*, 8870. (f) Marcinow, Z.; Grove, D. I.; Rabideau, P. W. *J. Org. Chem.* **2002**, *67*, 3537. (g) Mehta, G.; Sarma, P. V. V. S. *Tetrahedron Lett.* **2002**, *43*, 6557.

(5) See, e.g.: (a) Nair, V.; Sethumadhavan, D.; Nair, S. M.; Shanmugam, P.; Treesa, P. M.; Eigendorf, G. K. *Synthesis* **2002**, 1655 and references therein. (b) Quian, W.; Bartberger, M. D.; Pastor, S. J.; Houk, K. N.; Wilkins, C. J.; Rubin, Y. *J. Am. Chem. Soc.* **2000**, *122*, 8333. (c) Komatsu, K.; Fujiwara, K.; Tanaka, T.; Murata, Y. *Carbon* **2000**, *38*, 1529. (d) Komatsu, K.; Fujiwara, K.; Murata, Y. *Chem. Commun.* **2000**, 1583. (e) Taylor, R. *Chem. Commun.* **1994**, 1629.

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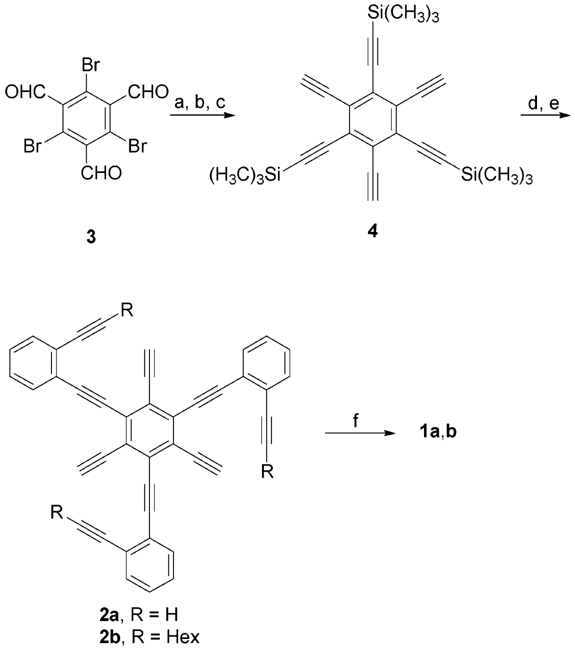
Scheme 2[a]



[a] Reaction conditions: (a) $(CH_3)_3SiC_2H$, $PdCl_2(PPh_3)_2$, CuI, NEt_3, THF, 97%; (b) CBr_4, Zn, PPh_3, CH_2Cl_2, 99%; (c) (i) LDA, THF, −78 °C; (ii) aq NH_4Cl, 95%; for **1a**: (d) 1-iodo-2-(trimethylsilylethynyl)benzene, $PdCl_2(PPh_3)_2$, CuI, *i*-Pr_2NH, THF, 77%; (e) K_2CO_3, MeOH, THF, 61%; (f) $CpCo(CO)_2$, *m*-xylene, $h\nu$, Δ, 2%; for **1b**: (d) 1-(1-octynyl)-2-iodobenzene, $PdCl_2(PPh_3)_2$, CuI, NEt_3, THF, 68%; (e) K_2CO_3, MeOH, THF, 86%; (f) $CpCo(CO)_2$, *m*-xylene, $h\nu$, Δ, 0.24%.

of **5**, which extends to 527 nm.[9] Most informative, in the ^{1}H NMR spectrum of **1a** there are the two doublets for the internal hydrogens at δ = 6.49 and 6.42 ppm (for **1b**, a singlet at δ = 6.25 ppm), close, but slightly shielded relative to the corresponding hydrogens in (hexakistrimethylsilylated) **5** (δ = 6.56 ppm),[9] a trend identical to that observed in angular (**6**; δ = 6.13 ppm) versus linear [3]phenylene (**7**; δ = 6.24 ppm).[2] However, both of the former experience lesser shielding compared to the latter, but for different reasons: in **1**, bond fixation in the central cyclohexatriene ring[6] relieves some of the same in the penultimate benzenes, diminishing the decrease in diatropism observed in the central ring of **6**; in **5**, central bond fixation decreases the paratropism of the adjacent cyclobutadienes relative to that in **7**.

To obtain further information about the pertinent physical properties of **1a** and **5**, DFT calculations were performed at the B3LYP/6-31G* level (see the Supporting Information), a method that has provided remarkably accurate structural information on these systems.[3,6−10,13] Indeed, the calculated structure of **5** is essentially within experimental error identical with that of that determined for a hexasilyl derivative[9] (except for the substituted rings). Thus, by the criterion established previously,[6] its central ring is 92% bond fixed (cf. 8, 97%), the terminal ones 29% (cf. **7**, 32%). In contrast, **1a** reveals only 76% alternation in the central ring, 50% in the penultimate (cf. **6**, 62%), and 24% in the terminal benzenes (cf. **6**, 22%), exactly as predicted taking into account the difference in the effect of angular versus linear annelation. NICS(1.0) data[13,14] corroborate the structural and ^{1}H NMR trends: (proceeding along one "arm" from the inside to the outside, i.e., form ring A to E, Scheme 1) 1**a**, −3.6, −0.3, −5.3, 4.9, −8.8; **5**, −1.4, −2.3, −7.5, 7.6, −7.6 ppm. Thus, the central cyclohexatriene A in the former is more diatropic than that in the latter (and in **8**, −1.1 ppm),[13a] the two respective adjacent cyclobutadienes B are not paratropic (as in **8**), but the remote ones D are, and more so in **5** than in **1a**. Ring C in **1a** is also more diatropic than the analogous moieties in **6** (−3.3 ppm), **9** (−4.7 ppm), **10** (−4.7 ppm), and **12** (−2.9 ppm).[13a]

In line with previous results attesting to the flexibility of the phenylenes,[3,13] we find a weak out-of-plane vibrational mode at 20.4 cm^{-1}. Initially puzzling were the estimates of the heats of formation, established through the homodesmotic reaction **1a**/**5** + 3 × biphenylene → 3 × **6** + **8**, indicating that **1a** (ΔH°_f = 484.6 kcal mol^{-1}) is less stable than **5** (ΔH°_f = 481.9 kcal mol^{-1}) by 2.7 kcal mol^{-1}. This result is at odds with the general expectation[2,13c] that linear phenylene fragments should be destabilized relative to their angular counterparts. For example, the $\Delta\Delta H^\circ_f$ on going from **6** to **7** is +2.4 kcal mol^{-1},[15] and the five [4]phenylene isomers become more energetic along the series **8**, **9**/**10**, **12**, **11** (total $\Delta\Delta H^\circ_f$ = 8.6 kcal mol^{-1}; BLYP/6-31G*).[13c] The rationale for these trends is the destabilizing antiaromaticity associated with the linear fusion, largely removed in the angular topology. Indeed, angular dicylobutadienobenzene is substantially more stable than its linear isomer (17.6 kcal mol^{-1}, SCF/3-21G).[16] On the other hand, there are indications that without the π electronic component, σ strain inverts this order of stability.[16b] In the higher phenylenes of mixed topology, the energy differences between isomers are small enough that this effect may become significant. Thus, the incremental linear destabilization effect in going from **9**/**10** to **12** is much smaller than that calculated on converting **6** to **7**, and in the family of the 12 [5]phenylenes, a number of inversions of the expected stability ordering are noted; e.g., **13** is found to be more stable than **14** (~1.0 kcal mol^{-1}; see the Supporting Information).[13b] To address this issue unambiguously, a calculational experiment was designed in which the additional σ strain on linear and/or angular annelation on the biphenylene nucleus to give **6**, **7**, **9**−**11**, and **12** was

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(12) (a) 1-Iodo-2-(trimethylsilylethynyl)benzene: Baxter, P. N. *J. Org. Chem.* **2001**, *66*, 4170. (b) 1-Iodo-2-(1-octynyl)benzene was made from 1-bromo-2-iodobenzene; see the Supporting Information.

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(14) Schleyer, P. v. R.; Maerker, C.; Dransfeld, A.; Jiao, H.; Van E. Hommes, N. J. R. *J. Am. Chem. Soc.* **1996**, *118*, 6317.

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mimicked by gradual single- or double-pairwise bending of the respective ortho hydrogens away from HCC angles of 120° toward 90° and recording the corresponding energy changes relative to optimized biphenylene (Table 1).[17] The results show that, while the effect is subtle, indeed, linear distortion is less costly than its angular counterpart for bond angles larger than 90°. As the effective "bent" bond angles are larger than this value,[17a,18] the observed trends are meaningful and are likely to play a significant contributing role to the heats of formation of larger systems where they become cumulative. Thus, extending these estimates to **1a** and **5**, by computing the appropriate triply pairwise angular and linear HCC angle changes on **8** (Table 2), corroborates these findings and provides a rationale for the relative stability of **5**.

Table 1. Energy (kcal/mol, Relative to Optimized Biphenylene) of Multiple HCC Angle Bending in Biphenylene, Leading to the Topologies of the Phenylenes in the Top Row

angle (deg)	**6**	**7**	**9/10**	**11**	**12**
120	0.0	0.0	0.1/0.1	0.1	0.1
115	1.0	0.7	2.0/2.0	1.5	1.7
110	4.1	3.7	8.3/8.3	7.4	7.8
105	9.6	9.0	19.2/19.2	18.1	18.6
100	17.6	17.1	35.2/35.3	34.2	34.6
95	28.4	28.1	56.8/57.0	56.3	56.4
90	42.2	42.4	84.5/84.7	85.0	84.4

Table 2. Energy (kcal/mol, Relative to **8**) of Multiple HCC Angle Bending in **8**, Leading to the Topologies of **1a** and **5**

angle (deg)	**1a**	**5**	ΔE
120	0.1	0.1	0.0
115	3.2	2.0	1.2
110	12.8	10.5	2.3
105	29.4	26.2	3.2
100	53.7	49.9	3.8
95	86.6	82.4	4.2
90	128.8	124.6	4.2

To summarize, we have implemented a successful synthetic strategy to the framework of **1**, representing the largest hitherto known substructure of archimedene. Calculations have revealed the presence of a subtle effect of the σ frame on the relative stabilities of phenylene isomers. Future work is focusing on improving the yields of the key angular cyclotrimerization reaction and thus enabling a continuation of our strategy toward the target fullerene system.

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Supporting Information Available: Detailed experimental procedures, full characterization of all new compounds, and details of the calculations. This material is available free of charge via the Internet at http://pubs.acs.org.

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