JOC Article

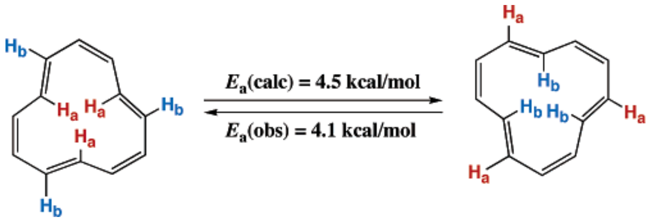
Computational Evaluation of the Evidence for Tri-*trans*-[12]Annulene

Claire Castro,* William L. Karney,* Catherine M. H. Vu, Stephen E. Burkhardt, and Miguel A. Valencia

Department of Chemistry, University of San Francisco, 2130 Fulton Street,
San Francisco, California 94117-1080

castroc@usfca.edu; karney@usfca.edu

Received November 17, 2004



Automerization in tri-*trans*-[12]annulene (**1**) was investigated by DFT, MP2, and coupled-cluster methods. Using the highest level of theory employed here, CCSD(T)/cc-pVDZ//BHandHLYP/6-311+G(d,p), we located two low-energy pathways for degenerate conformational change from the lowest-energy conformer of **1** (**1a**): one with $E_a = 4.5$ kcal/mol that interconverts the three inner trans hydrogens with the three outer trans hydrogens and one with $E_a = 2.7$ kcal/mol that interconverts the three inner hydrogens with each other. These results are consistent with the experimental results of Oth and co-workers on [12]annulene **1a** (Oth, J. F. M.; Röttele, H.; Schröder, G. *Tetrahedron Lett.* **1970**, 61). The conformational exchange of the inner trans hydrogens with the outer ones is predicted to occur via a one-step process involving a C_2-symmetric transition state and not via the D_3-symmetric transition state (**1b**) that was postulated earlier. Conformer **1b** was found to be a shallow minimum 6.7 kcal/mol above **1a** with a barrier of 0.4 kcal/mol for conversion to **1a**. Finally, GIAO-B3LYP/6-311+G(d,p) and BHandHLYP/6-311+G(d,p) computed ^{1}H NMR chemical shifts of **1a** and three other low-lying isomers support Oth's original assignment of observed ^{1}H NMR peaks to **1a** at both low and high temperature.

As a class of compounds, the annulenes have continued to intrigue chemists for many decades.[1] Within this class, the [4n]annulene series has been studied primarily in order to probe (anti)aromaticity.[2] Recent theoretical[3] and experimental[4] work on the [4n] series, however, has focused on the possibility of identifying and isolating Möbius aromatic compounds, which was first suggested by Heilbronner 40 years ago.[5] For example, a Möbius [16]-annulene derivative was prepared recently and characterized fully by Herges et al.[4] However, it appears to be nonaromatic.[6]

Along with cyclobutadiene, [12]annulene is perhaps one of the most elusive of the [4n]annulenes. Tri-trans isomer **1a** (Scheme 1) was reportedly synthesized over 30 years ago by Oth and co-workers,[7] although one [4n]-annulene review casts doubt on the matter,[8] whereas another review devotes only a few sentences to [12]-annulene, stating that "there has been very little recent

---

[1] For reviews of annulenes see: (a) Sondheimer, F. *Acc. Chem. Res.* **1972**, *5*, 81. (b) Kennedy, R. D.; Lloyd, D.; McNab, H. *J. Chem. Soc., Perkin Trans. 2* **2002**, 1601. (c) Balaban, A. T.; Banciu, M.; Ciorba, V. *Annulenes, Benzo-, Hetero-, Homo-Derivatives, and their Valence Isomers*; CRC Press: Boca Raton, FL, 1987; Vol. I., Chapter 4.

[2] (a) For recent reviews on aromaticity see: *Chem. Rev.* **2001**, *101*, May issue. "Aromaticity." (b) Wannere, C. S.; Moran, D.; Allinger, N. L.; Hess, B. A.; Schaad, L. J.; Schleyer, P. v. R. *Org. Lett.* **2003**, *5*, 2983.

[3] (a) Castro, C.; Isborn, C. M.; Karney, W. L.; Mauksch, M.; Schleyer, P. v. R. *Org. Lett.* **2002**, *4*, 3431. (b) Martin-Santamaria, S.; Lavan, B.; Rzepa, H. S. *J. Chem. Soc., Perkin Trans. 2* **2000**, 1415.

[4] Ajami, D.; Oeckler, O.; Simon, A.; Herges, R. *Nature* **2003**, *426*, 819.

[5] Heilbronner, E. *Tetrahedron Lett.* **1964**, 1923.

[6] Castro, C.; Chen, Z.; Wannere, C. S.; Jiao, H.; Karney, W. L.; Mauksch, M.; Puchta, R.; Hommes, N. J. R. v. E.; Schleyer, P. v. R. *J. Am Chem. Soc.* **2005**, *127*, 2425.

[7] (a) Oth, J. F. M.; Röttele, H.; Schröder, G. *Tetrahedron Lett.* **1970**, 61. (b) Oth, J. F. M.; Gilles, J.-M.; Schröder, G. *Tetrahedron Lett.* **1970**, 67. (c) Although the stated barrier in reference 7b is "4.1 ± 0.2 kcal/mol", footnote 11 of reference 7b states: "Systematic errors could be as high as two times the standard errors." (d) For a summary of this work, see, Oth, J. F. M. *Pure Appl. Chem.* **1971**, *25*, 573.

[8] Wiberg, K. B. *Chem. Rev.* **2001**, *101*, 1317.

10.1021/jo047955a CCC: $30.25

SCHEME 1

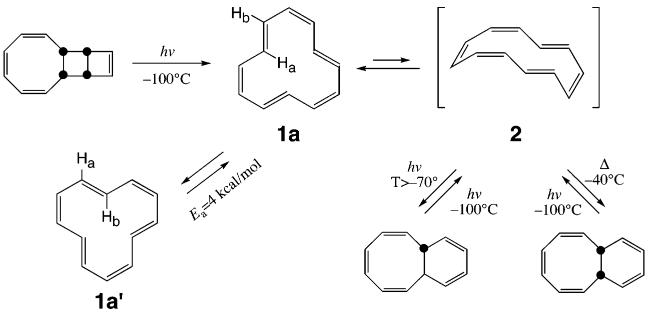
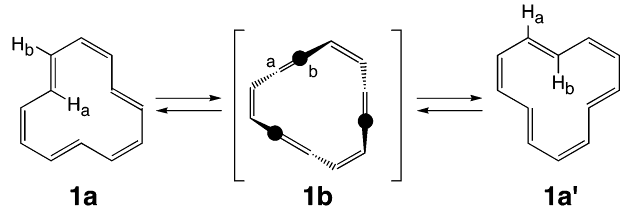


TABLE 1. Experimental ^{1}H NMR Results for [12]Annulene[a] and the [12]Annulene Dianion[b]

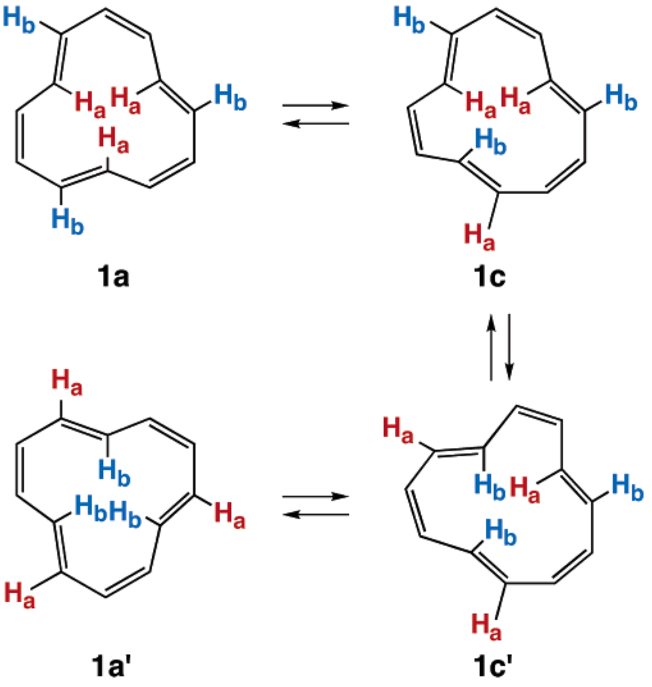
species	temperature	δ (ppm)	integral
[12]annulene	−170°C	7.8	3H
		5.9	9H
	−80°C	6.9	6H
		6.0	6H
[12]annulene dianion	−90°C to 30°C	−4.6	3H
		6.2−7.0	9H

[a] Data from ref 7b. [b] Data from ref 11. Although the chemical shifts as originally reported were referenced to benzene, here we report them relative to tetramethylsilane (TMS).

SCHEME 2



SCHEME 3



work" on it.[1b] Indeed, at the time of both reviews, the most recent experimental work was the report of Stevenson and co-workers, who repeated Oth's synthesis of **1a** to make the corresponding radical anion.[9,10]

Given the paucity of information on [12]annulene, we sought to computationally investigate the tri-*trans*-[12]-annulene hypersurface, with an eye toward critically evaluating Oth's conclusions regarding its existence and conformational mobility.

Background

Oth's original synthesis involved the photochemical ring opening of *syn*-tricyclo[8.2.0.0^{2,9}]dodeca-3,5,7,11-tetraene to form tri-*trans*-[12]annulene (**1a**) at −100 °C (Scheme 1).[7a] The 60-MHz ^{1}H NMR spectrum of **1a** at −170 °C exhibited two peaks at 7.8 and 5.9 ppm (rel ratio, 1:3); these coalesced to two new peaks at 6.9 and 6.0 ppm (rel ratio, 1:1) upon warming to −80 °C (Table 1).[7b] Oth concluded that the [12]annulene ring was distorted from planarity to avoid steric crowding of the three internal hydrogens and it underwent degenerate conformational change, or automerization (**1a** to **1a′**, Scheme 1), with $E_a = 4.1 \pm 0.2$ kcal/mol.[7b] This conformational change interchanges the three inner trans hydrogens with the three outer trans hydrogens.

In addition, he postulated that the isolated bicyclic products resulted from electrocyclic ring closure of the di-*trans*-[12]annulene isomer **2**, which itself formed upon cis/trans isomerization of **1a**. Further evidence for **1a** was that upon catalytic hydrogenation, a modest amount of dodecane was isolated.[7a] Finally, the dianion of **1a** was synthesized and found to be stable to 30 °C.[11] This dianion gave a ^{1}H NMR spectrum consistent with the presence of three shielded inner protons (−4.6 ppm), suggesting an aromatic 14 π-electron ring (Table 1).

Oth suggested that the interconversion of **1a** to **1a′** arises "by simultaneous rotation around all single bonds,"[7b] with the D_3-symmetric conformation (**1b**, all three trans C=C bonds perpendicular to the average ring plane) as a possible transition state (Scheme 2). An alternative mechanism, not mentioned by Oth, is one that involves sequential rotations of the three trans bonds via two equivalent intermediates, **1c** and **1c′** (Scheme 3).

Shortly after Oth's experimental work was published, Allinger and Sprague[12] reported molecular mechanics calculations on **1a**, **1b**, and **2**. They concluded that the energy difference between **1a** and **1b** was consistent with **1b** being a transition state, although it was not "unambiguous". Two other studies used semiempirical methods to evaluate the relative stabilities of [12]annulene isomers. Loos and Leska's semiempirical results contradicted those obtained by Allinger, in that **1b** was found to be the most stable conformation.[13] Later, Hernando and co-workers concluded, based on AM1 calculations, that the most stable conformation of **1a** was that in which

---

(9) Stevenson, G. R.; Concepcion, R.; Reiter, R. C. *J. Org. Chem*, **1983**, *48*, 2777.

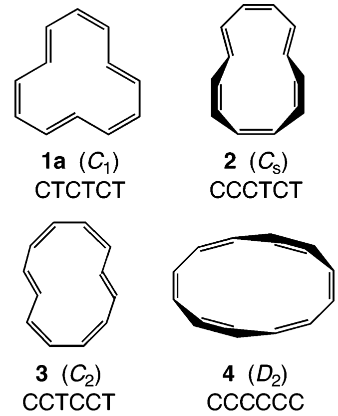
(10) More recently, Stevenson et al. reported the synthesis of the di-*trans*-[12]annulene isomer **3** (see Chart 1) via a different route. Like **1a**, **3** also appears to be very unstable, with characterization inferred from the ESR spectra of the corresponding radical anion. See: Gard, M. N.; Reiter, R. C.; Stevenson, C. D. *Org. Lett.* **2004**, *6*, 393.

(11) Oth, J. F. M.; Schröder, G. *J. Chem Soc. (B)* **1971**, 904.

(12) Allinger, N. L.; Sprague, J. T. *J. Am. Chem. Soc.* **1973**, *95*, 3893

(13) Loos, D.; Leska, J. *Collect. Czech. Chem. Commun.* **1980**, *45*, 187

CHART 1



1a (C_1)
CTCTCT

2 (C_s)
CCCTCT

3 (C_2)
CCTCCT

4 (D_2)
CCCCCC

two of the internal protons are on one face of the carbon skeleton and the other is on the opposite face.[14]

In our prior study of searching for potentially stable aromatic [4n]annulenes with Möbius topology, we evaluated the energies of not only **1a** but also of several other configurations (Chart 1).[3a] At the B3LYP/6-31G* level, the all-cis isomer (**4**) is slightly more stable than **1a**, whereas all of the other isomers are higher in energy than **1a**. At this level of theory, **1b** is found to be neither a minimum nor a transition state but rather a third-order saddle point.[15]

Choosing the appropriate computational method for the study of [12]annulene is potentially problematic, on the basis of recent [10]annulene studies. Although [10]-annulene was synthesized more than forty years ago,[16] the task of reproducing the observed ^{13}C NMR chemical shifts computationally[17] and obtaining trustworthy relative energies of the C_s-symmetric "heart" and C_2-symmetric "twist" isomers has only been achieved recently. B3LYP and MP2 predict the bond-equalized heart structure to be more stable,[18] but CCSD(T) energies using the B3LYP or MP2 optimized structures predict the bond-alternating twist to be more stable,[18,19] which is a result further supported by high-level CCSD(T)//CCSD(T) energies.[19,20]

Recent work by the Schleyer group[21] has shown that for [10]-, [14]-, [18]-, and [22]annulene, BHandHLYP[22] and KMLYP,[23] density functional methods that incorporate more HF character than B3LYP does, predict that bond-alternating structures for these [4n + 2]-π-electron annulenes are lower in energy than their bond-equalized counterparts.[24] Moreover, BHandHLYP and KMLYP give molecular geometries that yield ^{1}H NMR chemical shifts that are in good agreement with the experimental results. In contrast, for these [4n + 2]annulenes, B3LYP gives overly delocalized geometries with consequently distorted ^{1}H chemical shifts.

Unlike the case of [10]annulene, [12]annulene (except for Möbius topology conformations) should not suffer from competing bond-equalized and bond-alternating structures. All of the structures are expected to be bond-alternating. In addition, although CCSD(T)/DZd geometry optimizations were possible for [10]annulene isomers with at least one symmetry element,[19] similar calculations on [12]annulene isomers with no symmetry (e.g., **1a**) are prohibitively time-consuming. We thus anticipated that BHandHLYP optimized geometries would give us reliable CCSD(T) single-point energies and ^{1}H NMR shifts.

Because of its conformational mobility and the fact that it is the smallest [4n]annulene that can easily accommodate trans double bonds, [12]annulene serves as a useful model for understanding conformational and configurational isomerism in the higher [4n]annulenes. Moreover, given the resurgence of interest in Möbius aromaticity in hydrocarbons,[3,4,6] a more complete understanding of [4n]annulene dynamic processes is desirable. Herein, we report the results of DFT and ab initio calculations aimed at testing the validity of Oth's claim to have synthesized tri-*trans*-[12]annulene **1a**. Specifically, we are interested in (1) determining the mechanism for the proposed automerization of **1a** to **1a′** to rationalize the observed NMR spectra, and (2) comparing computed proton NMR data for **1a** and other low-lying isomers with the data obtained by Oth.

Computational Methods

The geometries of the stationary points were optimized using several different methods, including B3LYP,[25] BHandHLYP,[22] and second-order Møller–Plesset perturbation theory (MP2)[26] with the frozen-core (fc) approximation.[27] Optimizations initially employed the 6-31G* basis set (henceforth denoted as "DZ") and then the 6-311+G(d,p) triple-ζ basis set[28] (henceforth denoted as "TZ"), which includes one set of d functions on each carbon, one set of p functions on each hydrogen, and one set of diffuse functions on each carbon. Vibrational frequency analyses were performed at the same levels as the optimizations (except for MP2/TZ) in order to verify that stationary points were either minima or transition states and to obtain zero-point energies (ZPEs) for the correction of relative energies.

To obtain more reliable relative energies, we computed single-point energies at the BHandHLYP/TZ optimized geom-

---

(14) Hernando, J. M.; Enríquez, F.; Quirante, J. J. *J. Mol. Struct.: THEOCHEM* **1993**, *287*, 131.

(15) Mauksch, M. Dissertation, University of Erlangen, Nuremberg, Germany, 1999.

(16) (a) van Tamelen, E. E.; Burkoth, T. L. *J. Am. Chem. Soc.* **1967**, *89*, 151. (b) Masamune, S.; Hojo, K.; Hojo, K.; Bigam, G.; Rabenstein, D. L. *J. Am. Chem. Soc.* **1971**, *93*, 4966.

(17) Price, D. R.; Stanton, J. F. *Org. Lett.* **2002**, *4*, 2809.

(18) Sulzbach, H. M.; Schaefer, H. F.; Klopper, W.; Lüthi, H. P. *J. Am. Chem. Soc.* **1996**, *118*, 3519.

(19) King, R. A.; Crawford, T. D.; Stanton, J. F.; Schaefer, H. F. *J. Am. Chem. Soc.* **1999**, *121*, 10788.

(20) Upon scrutiny of the data in reference 19, it appears that it is important to compute the energies at the CCSD(T) level using a basis set that includes polarization functions on both carbon and hydrogen (e.g., cc-pVDZ, DZP, or the equivalent).

(21) Wannere, C. S.; Sattelmeyer, K. W.; Schaefer, H. F.; Schleyer, P. v. R. *Angew. Chem., Int. Ed.* **2004**, *43*, 4200.

(22) (a) Becke, A. D. *J. Chem Phys.* **1992**, *98*, 1372. (b) Miehlich, B.; Savin, A.; Stoll, H.; Preuss, H. *Chem. Phys. Lett.* **1989**, *157*, 200.

(23) (a) Kang, J. K.; Musgrave, C. B. *J. Chem. Phys.* **2001**, *115*, 11040. (b) The KMLYP functional was specified by including the following keywords in the *Gaussian 98* input files: BLYP iop(5/45 = 10000557) iop(5/46 = 00000443) iop(5/47 = 04481000).

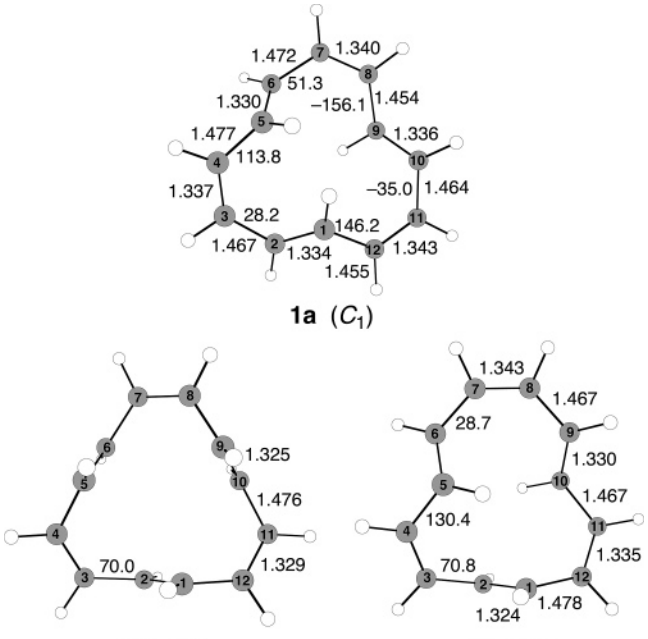
(24) (a) Grimme's SCS-MP2 method[24b,c] also gives energetic results in agreement with the CCSD(T) calculations for [18]annulene. See footnote 31 in reference 21. (b) Grimme, S. *J. Chem. Phys.* **2003**, *118*, 9095. (c) Grimme, S. *J. Comput. Chem.* **2003**, *24*, 1529.

(25) (a) Becke, A. D. *J. Chem. Phys.* **1993**, *98*, 5648. (b) Lee, C.; Yang, W.; Parr, R. G. *Phys. Rev. B* **1988**, *37*, 785.

(26) Møller, C.; Plesset, M. S. *Phys. Rev.* **1934**, *46*, 618.

(27) (a) Some structures were also optimized with the KMLYP method,[23] but these calculations were prone to convergence problems, so a complete set of results was not obtained at this level. (b) Geometries optimized at the various levels are available from the authors on request (castroc@usfca.edu or karney@usfca.edu).

(28) Hariharan P. C.; Pople, J. A. *Theor. Chim. Acta* **1973**, *28*, 213.



1a (C_1)

1b (D_3)

1d (C_2)

FIGURE 1. BHandHLYP/6-311+G(d,p) optimized structures of different conformations of tri-*trans*-[12]annulene **1**. C−C bond lengths (Å) are shown outside the rings, and CCCC dihedral angles (degrees) centered on single bonds are shown inside.

etries using the coupled-cluster theory with single and double substitutions and a perturbative correction for triple excitations [CCSD(T)].[29,30] CCSD(T) calculations employed both the 6-31G* basis set and Dunning's correlation-consistent polarized valence double-ζ basis set (cc-pVDZ), which has polarization functions on both carbon and hydrogen.[31] The BHandHLYP/TZ optimized geometries were used because this optimization method was found to give the best results for the relative energies of the twist and heart [10]annulene isomers,[21] in good agreement with more expensive CCSD(T) calculations. Unless otherwise specified, energies referred to in the text pertain to the CCSD(T)/cc-pVDZ//BHandHLYP/TZ+ZPE level of theory.

To locate transition states for the automerization of **1a**, we performed a series of 2D relaxed potential energy surface (PES) scans at the B3LYP/3-21G level. Three CCCC dihedral angles (d8−7−6−5, d4−3−2−1, and d12−11−10−9; see Figure 1 for numbering), all centered on C−C single bonds, were chosen for manipulation. One of the dihedrals (d8−7−6−5) was held frozen at a set value (e.g., 50.0°), and the other two dihedrals were scanned (e.g., d4−3−2−1 from 20.0 to 110.0°; d12−11−10−9 from −30.0 to −120.0°). The result was a 3D plot of energy versus the dihedrals d4−3−2−1 and d12−11−10−9, for a given fixed value of d8−7−6−5. Next, the d8−7−6−5 dihedral was frozen at a new value, and the other two dihedrals were scanned through the same ranges as before. Values of d8−7−6−5 from 50.0 to 130.0° were investigated.

Magnetic shieldings for the minima were computed using the GIAO method[32] at the B3LYP/TZ and BHandHLYP/TZ levels using geometries optimized with various methods, including B3LYP/TZ, MP2(fc)/TZ, KMLYP/TZ, and BHandHLYP/TZ. Magnetic shieldings were also computed for tetramethylsilane (T_d symmetry) at the same level. Proton chemical shifts were then determined by subtracting the computed isotropic shielding of the proton of interest from that for the TMS protons. All of the calculations were performed using Gaussian 98.[33] Structures were visualized with MacMolPlt.[34]

TABLE 2. GIAO-B3LYP and BHandHLYP Averaged Proton NMR Chemical Shifts for [16]Annulene Using Different Geometries[a]

	B3LYP//B3LYP[b]	B3LYP//BHH[c]	BHH//BHH[c]	exptl[d]
hydrogens	ppm (Δδ)	ppm (Δδ)	ppm (Δδ)	ppm (int)
inner (4H)	16.38 (5.82)	12.24 (1.68)	10.84 (0.28)	10.56 (4H)
outer (12H)	4.42 (−0.95)	5.06 (−0.31)	5.64 (0.27)	5.37 (12H)
all (16H)	7.41 (0.67)	6.85 (0.11)	6.94 (0.20)	6.74 (16H)

[a] Magnetic shieldings were computed using the TZ basis set. BHH = BHandHLYP. ppm = computed chemical shift, obtained by subtracting the isotropic magnetic shielding for the proton of interest from the shielding for protons in tetramethylsilane. See the text for details. Δδ = deviation from experimentally observed chemical shifts ($\delta_{calcd} - \delta_{exptl}$). [b] Shifts computed at the B3LYP/TZ optimized geometry. [c] Shifts computed at the BHandHLYP/TZ optimized geometry. [d] Experimentally observed chemical shifts. "int" = integral. Values from reference 37a.

Results and Discussion

Method Validation. Although application of the BHandHLYP/TZ//BHandHLYP/TZ method to the heart and twist isomers of [10]annulene reveals that the twist isomer is 1.0 kcal/mol more stable than the heart,[21] CCSD(T)/cc-pVDZ//BHandHLYP/TZ calculations increase the energy difference between these two isomers to 4.8 kcal/mol, coming much closer to the value of 4.2 kcal/mol that was obtained at the CCSD(T)/TZ2P//CCSD(T)/DZP level.[19]

To validate the use of BHandHLYP optimized geometries for the determination of ^{1}H NMR chemical shifts in [12]annulene, we chose S_4-symmetric [16]annulene[35,36] as a test case because experimental data are available.[37] Although Schleyer et al. showed that this method works well for [4n+2]annulenes with inner hydrogens,[21] this has not been demonstrated for [4n]annulenes. As shown in Table 2, the BHandHLYP/TZ geometry for [16]annulene

---

(29) (a) Bartlett, R. J. *J. Phys. Chem.* **1989**, *93*, 1697. (b) Raghavachari, K.; Trucks, G. W.; Pople, J. A.; Head-Gordon, M. *Chem. Phys. Lett.* **1989**, *157*, 479. (c) Scuseria, G. E. *Chem. Phys. Lett.* **1991**, *176*, 27.

(30) CCSD(T) energies were also computed using the B3LYP/TZ and MP2/TZ optimized geometries. These are available in the Supporting Information.

(31) Dunning, T. H., Jr. *J. Chem. Phys.* **1989**, *90*, 1007.

(32) Wolinski, K.; Hilton, J. F.; Pulay, P. *J. Am. Chem. Soc.* **1990**, *112*, 8251.

(33) 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.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; 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.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B. G.; Chen, W.; Wong, M. W.; Andres, J. L.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*, revision A.11.3; Gaussian, Inc.: Pittsburgh, PA, 1998.

(34) MacMolPlt v.5.3.5: Bode, B. M.; Gordon, M. S. *J. Mol. Graphics Modeling* **1998**, *16*, 133.

(35) Johnson, S. M.; Paul, I. C. *J. Chem. Soc. B* **1970**, 643.

(36) The X-ray crystal structure of [16]annulene is reported to have only "approximate S_4 symmetry."[35] C−C bonds that would be equivalent under strict S_4 symmetry actually have very different lengths in the crystal structure (e.g., 1.326 vs 1.352 Å; 1.443 vs 1.470 Å; and 1.312 vs 1.338 Å). This makes it difficult to draw conclusions regarding which optimization method best matches the experimental geometry.

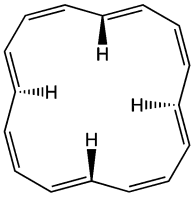
(37) (a) Oth, J. F. M.; Gilles, J.-M. *Tetrahedron Lett.* **1968**, 6259. (b) Stevenson, C. D.; Kurth, T. L. *J. Am. Chem. Soc.* **2000**, *122*, 722.

TABLE 3. Relative Energies (kcal/mol) of Selected [12]Annulene Isomers and Related Transition States[a]

		B3LYP/ TZ		MP2/ TZ[b]		BHandHLYP/ TZ		CCSD(T)/ 6-31G*[c]	CCSD(T)/ cc-pVDZ[c]
species	sym	rel E	NI	rel E	NI[b]	rel E	NI	rel E	rel E
1a	C_1	0.0	0	0.0	0	0.0	0	0.0	0.0
1b	D_3	9.3	2	8.0	0	7.4	0	5.7	6.7
1d	C_2	8.6	0	9.3	0	8.3	0	7.6	7.9
TS1	C_1			7.9	1	7.5	1	6.6	7.1
TS2	C_2	4.8	1	5.3	1	4.7	1	4.6	4.5
TS3	C_1	2.2	1	3.1	1	2.8	1	3.4	2.7
2	C_s	2.8	0	4.0	0	2.8	0	4.2	4.0
3	C_2	1.3	0	−1.0	0	0.5	0	0.5	0.9
4	D_2	−1.2	0	−5.5	0	−0.2	0	0.7	0.0

[a] All energies are given relative to **1a** and are corrected for differences in zero-point energy (ZPE). TZ = 6-311+G(d,p). NI = number of imaginary frequencies. Absolute energies and ZPEs can be found in the Supporting Information. [b] Fully optimized at the MP2(fc)/TZ level but including MP2(fc)/6-31G* ZPE corrections. NI in this column refers to the results of MP2(fc)/6-31G* vibrational analysis. [c] Computed at the BHandHLYP/TZ geometry and including BHandHLYP/TZ ZPE corrections.

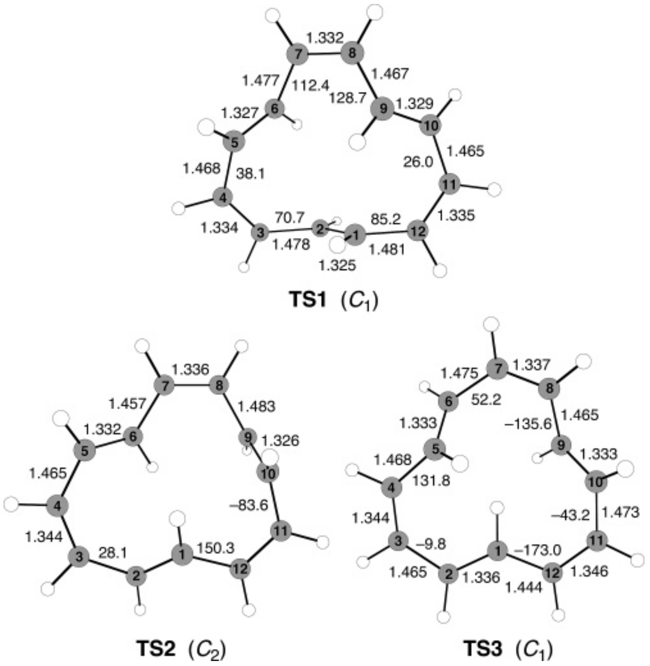
gives computed ^{1}H NMR shifts that agree nicely with the experimental values.[37] In contrast, the B3LYP geometry gives shift values that deviate by more than 5 ppm from the experimental value of 10.56 ppm for the four inner hydrogens. Interestingly, the GIAO-B3LYP//BHandHLYP computed shifts are not as accurate as those obtained using GIAO-BHandHLYP//BHandHLYP.



[16]Annulene (S_4)

Mechanism of Conformational Change. The BHandHLYP/TZ optimized geometry of **1a** is shown in Figure 1, along with two other conformations, **1b** and **1d** (vide infra). In agreement with earlier studies,[12,14] we find that the most stable conformation of tri-*trans*-[12]annulene is that in which two inner hydrogens lie on one face of the average ring plane (Table 3). Conformations **1b** and **1d** are ca. 7−8 kcal/mol less stable than **1a**. Our initial exploration of the interconversion of **1a** to **1a′** focused on the possibility of **1b** behaving as a transition state or intermediate along the reaction path (Scheme 2). The vibrational analyses for **1b** (Table 3) show that the nature of this stationary point is sensitive to the level of theory; **1b** was found to be either a minimum (BHandHLYP, MP2) or a second-order saddle point (B3LYP). These results suggest that the potential surface in the vicinity of **1b** is very shallow. It is important to note, however, that at our highest level of theory, the relative energy of **1b** is ca. 2.5 kcal/mol higher than the ca. 4 kcal/mol energy barrier reported for the **1a** → **1a′** interconversion, diminishing the likelihood of **1b** playing a role in this process.

A pathway connecting **1a** and **1b** was located at the MP2 and BHandHLYP levels. The BHandHLYP/TZ structure of the transition state connecting **1a** and **1b** (**TS1**) is shown in Figure 2. The relative energies in Table 3 reveal that the minimum corresponding to **1b** is shallow with respect to rotation about the single bonds.[38] At the CCSD(T)/cc-pVDZ level, the barrier for **1b** → **1a** is only 0.4 kcal/mol, whereas the reverse process, **1a** → **1b**, has a barrier of 7.1 kcal/mol.



TS1 (C_1)

TS2 (C_2)

TS3 (C_1)

FIGURE 2. BHandHLYPTZ optimized structures of transition states for conformational change in tri-*trans*-[12]annulene **1a**. C−C bond lengths (Å) are shown outside the rings, and CCCC dihedral angles (degrees) centered on single bonds are shown inside.

We also looked for additional local minima around **1b** by following its B3LYP-computed imaginary modes downhill via geometry optimizations. One of these modes led to **1a**, whereas the second led to a new conformational minimum with C_2 symmetry (**1d**, Figure 1) in which one trans bond is essentially orthogonal to the rest of the π system. It is unclear how this conformation is connected to **1a**, but the computed energy of ca. 8 kcal/mol (relative to **1a**) effectively rules out **1d** as a participant in any low-energy conformational change.

Considering that both **1b** and **1d** were not involved in the interconversion of **1a**, we focused on a three-step mechanism via two equivalent intermediates (Scheme 2). All of the attempts to locate a minimum corresponding to **1c** failed; geometry optimizations invariably led to **1a**.

Our next efforts sought a one-step pathway and employed a series of 2D relaxed potential energy surface scans of **1a**. (See the Methods section for details.) Figure 3a shows a contour plot of energy versus two dihedral angles (B3LYP/3-21G). The low-energy pathway from A to B to C corresponds to conformational exchange of the inner and outer trans hydrogens. Focusing on the transition state region (point B) allowed us to locate a C_2-symmetric transition state (**TS2**, Figure 2) for the interconversion of the three inner trans hydrogens with the three outer trans hydrogens.[39] Most noteworthy is that **TS2** lies only 4.5 kcal/mol higher in energy than **1a**

---

[38] At the BHandHLYP/TZ level, the lowest vibrational frequency of **1b** is predicted to be 19.5 cm^{-1}. This very small value also suggests that **1b** lies in a very shallow well.

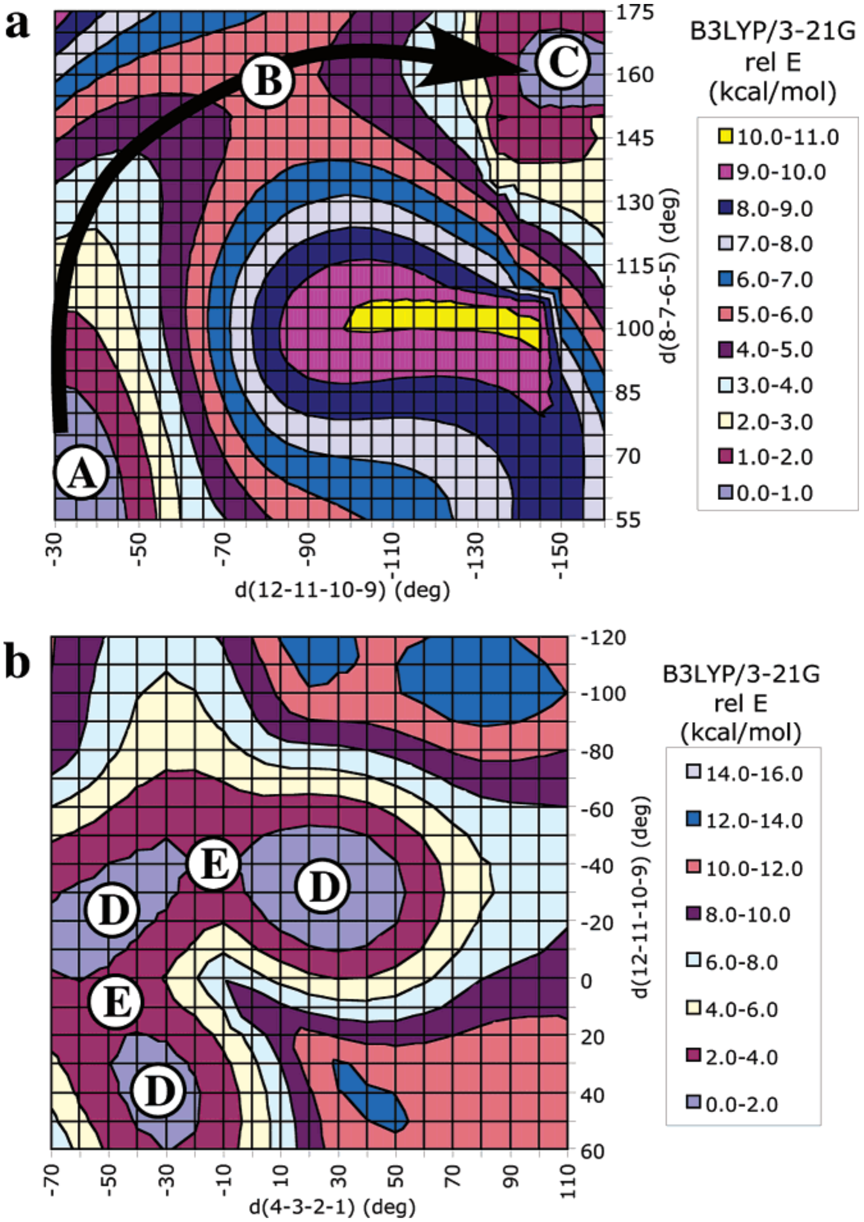


FIGURE 3. B3LYP/3-21G contour plots of energy vs two CCCC dihedral angles for **1a**. (a) A corresponds to the approximate **1a** minimum; B corresponds to the transition state region; C corresponds to a **1a** minimum in which the inner and outer trans hydrogens have traded places (i.e., **1a′**) (b) The D regions correspond to approximate **1a** minima in which the three inner hydrogens exchange roles; the E points are the transition state regions connecting those minima.

(Table 3), a result in close agreement with the experimentally determined barrier of 4.1 ± 0.2 kcal/mol.[40]

In addition, we located a second transition state (**TS3**, Figures 2 and 3b) that serves to interchange the three internal hydrogens with each other via a 2.7 kcal/mol barrier. Overcoming this low energy barrier converts **1a** to its enantiomer.[39] **TS3** is predicted to be only 1.8 kcal/mol below **TS2**, which may explain both the inability of Oth and co-workers to resolve the NMR signals for the three internal protons at −170 °C and the fact that the signal observed was very broad. The energetics of the pathways for automerization in **1a** are summarized in Figure 4.

^{1}H NMR Chemical Shifts. Having determined the mechanism for automerization in **1a**, there remained the issue of whether computed NMR shift values and computed energies would support the existence of **1a**. Given the success of BHandHLYP mentioned earlier, we used BHandHLYP geometries to compute the GIAO chemical shifts.

Regarding the NMR spectrum of [12]annulene,[7] we were particularly interested in evaluating whether the peaks observed by Oth were due solely to **1a**, or if isomers **2**, **3**, or **4** (Chart 1) might have also contributed to the observed spectrum because these species are close in

---

(39) Depictions of the motions involved in the automerization of **1a** can be found in the Supporting Information.

(40) Interestingly, **TS2** can be viewed as having Möbius topology. However, the C7−C8−C9−C10 dihedral angle of −83.6° prevents significant cyclic π delocalization.

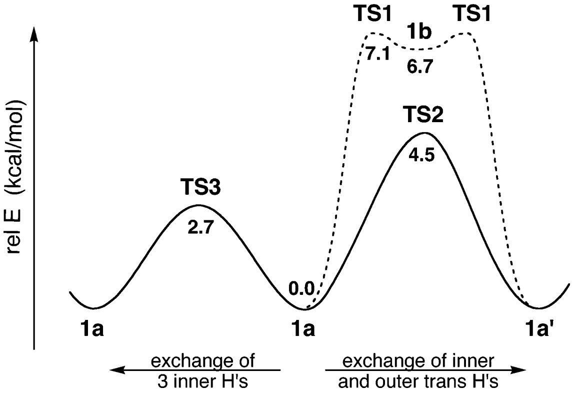
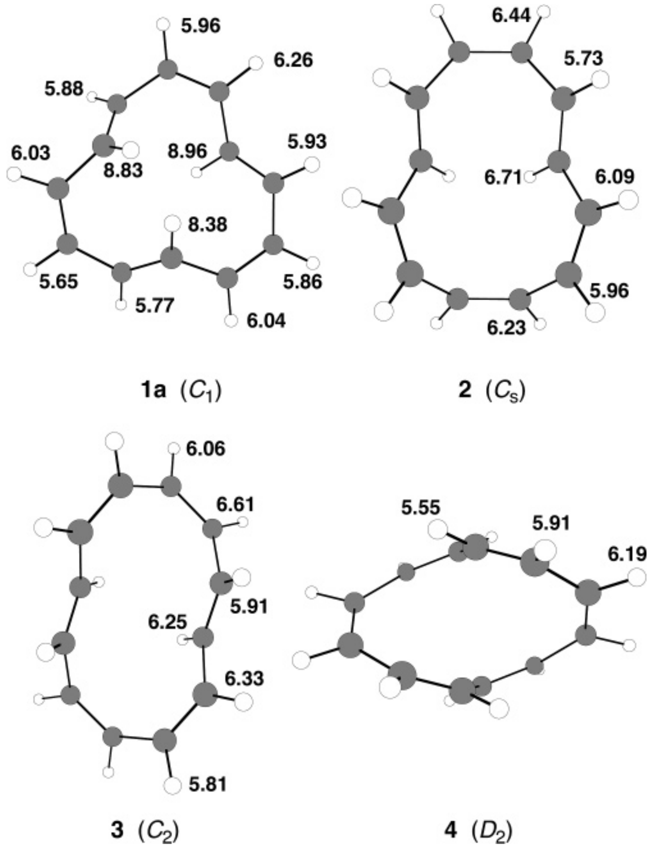


FIGURE 4. Energetics of automerization pathways in tri-*trans*-[12]annulene **1a** at the CCSD(T)/cc-pVDZ//BHandHLYP/TZ level.

energy (i.e., within 4 kcal/mol) to **1a** (Table 3). Di-*trans*-[12]annulene **2** (4.0 kcal/mol above **1a**) is the suggested precursor to the bicyclic products that were finally isolated in Oth's synthesis of [12]annulene. Species **3**, another di-trans isomer reportedly synthesized by the Stevenson group,[10] is only ca. 1 kcal/mol higher than **1a**. The all-cis configuration (**4**) is predicted to be isoenergetic with **1a**, although it is unlikely that it could interconvert with **1a** at low temperature because this requires three cis−trans isomerizations.

Computed ^{1}H NMR shift values obtained from the BHandHLYP optimized geometries for **1a**, **2**, **3**, and **4** are presented in Figure 5.[41] The best agreement with the experimental values is found for **1a**; this species shows clear evidence of a paratropic ring current, which is consistent with the observed spectrum.[42] Table 4 provides the average values for the various sets of protons of **1a** using different optimized geometries. The averages for groups of three and nine protons correspond to Oth's −170 °C spectrum, whereas the averages for two groups of six protons correspond to the −80 °C spectrum. Taking both sets of protons (inner and outer, or cis and trans) into account, the KMLYP and BHandHLYP geometries give superior results compared to the B3LYP geometries. In addition, using the BHandHLYP geometry, we found that the B3LYP computed shifts are slightly better than those computed with BHandHLYP, in contrast to the situation for [16]annulene (vide supra). Finally, the data reveal that when studying [4n]annulenes, particularly those with internal protons, it is important to use a geometry optimization method that has significantly more HF character than B3LYP. However, although this is similar to the case of [4n + 2]annulenes,[21] the dependence of chemical shifts on the geometry optimization method is much smaller for [4n]annulenes than for [4n + 2]annulenes. This is understandable because Hückel-type [4n]annulenes are not as susceptible to bond-length equalization.



1a (C_1) **2** (C_s)

3 (C_2) **4** (D_2)

FIGURE 5. B3LYP/TZ//BHandHLYP/TZ GIAO NMR chemical shifts (ppm) of [12]annulene isomers.

TABLE 4. GIAO Averaged Proton NMR Chemical Shifts for [12]Annulene 1a, Computed at Different Optimized Geometries[a]

hydrogens	B3LYP//B3LYP[b] ppm (Δδ)	B3LYP//KMLYP[c] ppm (Δδ)	B3LYP//BHandH[d] ppm (Δδ)	BHandH//BHandH[d] ppm	exptl[e] ppm (int)
inner (3H)	9.87 (2.1)	8.75 (0.9)	8.72 (0.9)	8.56 (0.8)	7.8 (3H)
outer (9H)	6.01 (0.1)	5.87 (0.0)	5.93 (0.0)	6.22 (0.3)	5.9 (9H)
trans (6H)	7.91 (1.0)	7.29 (0.4)	7.29 (0.4)	7.33 (0.4)	6.9 (6H)
cis (6H)	6.04 (0.0)	5.89 (−0.1)	5.97 (0.0)	6.29 (0.3)	6.0 (6H)

[a] All shifts were computed with the TZ basis set. ppm = computed chemical shift, obtained by subtracting the isotropic magnetic shielding for the proton of interest from the shielding for protons in tetramethylsilane. See the text for details. Δδ = deviation from experimentally observed chemical shifts, ($\delta_{calcd} - \delta_{exptl}$). [b] Shifts computed at the B3LYP/TZ optimized geometry. [c] Shifts computed at the KMLYP/TZ optimized geometry. [d] Shifts computed at the BHandHLYP/TZ optimized geometry. [e] Experimentally observed chemical shifts. "int" = integral. Values taken from reference 7b.

Conclusions

Our computational results support the claim that Oth and Schroeder had indeed synthesized tri-*trans*-[12]-annulene **1a**. The conformational exchange of the inner and outer trans hydrogens in **1a** is predicted to occur via a C_2-symmetric transition state, with a barrier of 4.5 kcal/mol at the CCSD(T)/cc-pVDZ//BHandHLYP/6-311+G(d,p) level. This is in good agreement with the reported experimental value of 4.1 ± 0.2 kcal/mol.[7bc] The transition state located for this process rules out earlier suggestions that D_3-symmetric **1b** plays a role in this interconversion.

---

(41) Proton chemical shifts computed for geometries optimized with other methods are available in the Supporting Information.

(42) Although the average chemical shifts of the outer protons are similar in all of these species (5.8−6.2 ppm), **1a** is the only species that has three protons with signals near the experimental value of 7.8 ppm.

BHandHLYP/6-311+G(d,p) calculations suggest that although there is a pathway via **1b** that interconverts the inner and outer trans hydrogens, at the CCSD(T) level this pathway has a 7.1 kcal/mol barrier. Another low energy process (E_a = 2.7 kcal/mol) was located that interchanges the three internal hydrogens so they become magnetically equivalent, potentially rationalizing why Oth was unable to observe separate peaks for these hydrogens at very low temperature.

The computed NMR data reported here also support the original NMR assignment for the peaks attributed to **1a**. The GIAO-B3LYP/6-311+G(d,p) chemical shifts are in good agreement with the experimental values when KMLYP or BHandHLYP geometries are used. Although this work should remove any lingering doubts about the existence of **1a**, it is still unclear how **1a** isomerizes to the di-trans isomer **2** to afford the isolated bicyclic products. We are currently investigating possible mechanisms for this process.

Acknowledgment. We thank Professor Paul von Ragué Schleyer and his group for providing us with a copy of reference 21 prior to publication. This work was supported in part by the USF Faculty Development Fund.

Supporting Information Available: BHandHLYP/6-311+G(d,p) optimized geometries for all species,[27b] absolute energies and zero-point energies, and computed magnetic shieldings and chemical shifts. This material is available free of charge via the Internet at http://pubs.acs.org.

JO047955A