Molecular Orbital Studies of Methoxy-1,3,5-cycloheptatriene Isomers: Results from Semiempirical, ab Initio, and Density Functional Theory Calculations

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The fully optimized structures and relative energies of all possible methoxy-1,3,5-cycloheptatriene (MCHT) isomers have been determined by semiempirical, ab initio, and density functional theory (DFT) molecular orbital calculations. All methods identify the boat conformation of 1-methoxy-1,3,5-cycloheptatriene as the most stable species in this group of compounds. In order to evaluate boat interconversion barriers, optimizations of the planar isomers were also performed. For comparison purposes, we applied the same computational methodologies to boat and planar conformations of 1,3,5-cycloheptatriene (CHT). Among the semiempirical methods, the SAM1 approximation was found to best reproduce the ab initio and DFT results. Examination of rotational energy profiles allowed for identification of the factors controlling the preferred orientations of the methoxy group in these compounds. The calculations predict that methoxy substitution has little influence on the preferred conformation of the seven-membered ring and only a minor impact on the energy required for interconversion of boat conformations through a planar transition structure. Inclusion of electron correlation makes little difference on the calculated relative energies of the MCHT isomers and optimized geometries but significantly improves the computed reaction barriers involved in the CHT hydrogen transfer transition structures.

Introduction

Methoxy substitution of 1,3,5-cycloheptatriene gives rise to four structural isomers capable of interconversion when heated. Interestingly, the most stable isomer is 1-methoxy-1,3,5-cycloheptatriene (1-MCHT), a compound that is a potent lachrymator, but the other isomers display considerably less activity as lachrymators. While cycloheptatriene (CHT), the parent compound of these isomers, has been well characterized by many techniques including electron diffraction,[1] microwave,[2] infrared,[3] and NMR spectroscopies,[4,5] and by computational chemistry methods,[6−8] the methoxy-substituted compounds have not yet received similar attention. This is surprising inasmuch as the synthesis and characterization of transition metal complexes involving CHT are active research topics[9] as is the study of other CHT derivatives such as 5-hydroxytropolone.[10,11]

Past computational studies of CHT show that a variety of computational methodologies[6−8] are in accord with the most reliable experimental data for geometries[2] and energies.[4,5] Early CHT work revealed that this system adopts a boat conformation in the ground state that can
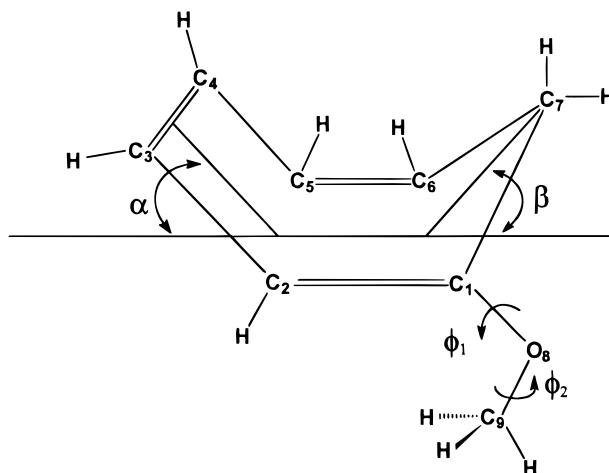
Figure 1. Definition of nonplanarity angles α and β, dihedral angles ϕ_1 and ϕ_2, and atom numbering scheme for 1-methoxy-1,3,5-cycloheptatriene. Omitting the methoxy side chain gives the atom numbering scheme used for calculations on CHT.

interconvert to another boat conformation through a planar structure with a barrier of about 6 kcal/mol.[4,5] Additionally, quantitative estimates of the deviation from planarity of the equilibrium boat conformation have been expressed in terms of α and β angles of approximately 30° and 50°, respectively.[2] Figure 1 provides the definitions of these angles as well as those describing the orientation of the methoxy side chain, ϕ_1 and ϕ_2, and the numbering scheme employed for the MCHT isomers.

The investigations of ter Borg and Kloosterziel[12,13] demonstrated that the thermal isomerizations of 7-deu-

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tero-1,3,5-cycloheptatriene and 7-phenyl-1,3,5-cycloheptatriene occur according to successive transannular 1,5 shifts of hydrogen together with shifts of two double bonds. Temperature studies revealed activation energies of 31−32 kcal/mol for this process and no evidence for any other shifts. On the basis of these results, a schematic representation of the transition structure for the 1,5 shift was proposed[12,13] and was tentatively confirmed with INDO calculations.[14] The availability of this compelling experimental data and preliminary computational data presents an opportunity to examine the ability of modern computational methods to describe the transition state structures involved in the thermal isomerization reactions of CHT.

Recent advances in computational chemistry methods include the introduction of the semi-ab-initio-model 1 Hamiltonian (SAM1)[15−17] and the popularization of density functional theory.[18−22] Both of these methods appear very promising, but they differ considerably in both their cost and their theoretical basis. Hence, it is of interest to determine how they perform compared to one another and to conventional Hartree−Fock-based methods. Our objective in the present paper is to examine the conformational energies of planar and boat methoxy-1,3,5-cycloheptatriene isomers according to these different computational methodologies. Attention is directed toward understanding the influence of the methoxy group on ring geometries and energies so as to gain insights into the factors affecting the preferred conformations of the various isomers. As a gauge of the reliability of the present methods, we also include experimental and calculated data for CHT. Additionally, consideration is also given to determining the preferred geometries and relative energies of the possible transition structures involved in the thermal isomerization reactions of CHT.

Methods

All semiempirical calculations were accomplished with the AMPAC5.0 program,[23] while all ab initio and DFT calculations were implemented with the Gaussian92/DFT program suite.[24] For the semiempirical molecular orbital calculations, we used the AM1,[25] PM3,[26] and SAM1[15] Hamiltonians, including the PRECISE and GNORM=0.01 keywords to ensure well-converged results. Planar and boat conformations of CHT and all possible MCHT isomers were studied. The nature of all stationary points thus located was confirmed through FORCE calculations.

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Profiles of energy vs methoxy group rotation (ϕ_1) from −180° to 180° in 15° increments were derived for planar and boat conformations of MCHT isomers using the SAM1 Hamiltonian. For the conventional ab initio studies, we utilized the Hartree-Fock method with the 6-31G* basis set (HF/6-31G*). Complete geometry optimizations were performed at this level of theory as well as optimizations constraining the seven-membered ring to planarity. Frequency calculations at this level were used to confirm the nature of the stationary points and to provide zero-point vibrational energies (ZPVEs). To include electron correlation effects, we also evaluated single-point energies with second-order frozen-core Møller−Plesset[27] perturbation theory at the HF/6-31G* geometries (MP2/6-31G*//HF/6-31G*). For the density functional theory calculations, we selected Becke's three-parameter hybrid method[28,29] using the Lee−Yang−Parr correlation functional[30,31] denoted as Becke3LYP or B3LYP in conjunction with the 6-31G* basis set. This functional has proven to be among the most successful in providing reliable structures and energies.[20,32] Single-point energy evaluations (Becke3LYP/6-31G*//HF/6-31G*), full energy optimizations (Becke3LYP/6-31G*//Becke3LYP/6-31G*), and vibrational frequencies were determined using this DFT functional. For the calculations identifying the hydrogen transfer thermal isomerization transition state structures, it was convenient to employ the HF/3-21G level of theory initially and to refine the located structures at the HF/6-31G* and Becke3LYP/6-31G* levels.

Most of the data describing the geometries of optimized structures were obtained directly from the program output. However, to obtain the α and β values defined in Figure 1, we employed standard methods[33] to calculate the plane equations of interest from the x-, y-, and z-coordinates of appropriate atoms and the angle between these planes.

Results

Figures 2 and 3 provide the lowest energy structures located and the numbering scheme employed for the boat and planar conformations of the MCHT isomers considered in this study at the HF/6-31G* level. Table 1 presents the total and relative energies of these structures as well as those of CHT according to several computational methods. It is immediately apparent that all methods are unanimous in identifying the **1-B** isomer as the most stable MCHT species. Furthermore, most of the methods are in agreement about the order of isomer stability: **1** > **3** > **2** > **7**. The only exception is AM1 where **7-EXO** and **2-B** are predicted to have similar energies.

Taking the B3LYP/6-31G*//B3LYP/6-31G* results as a standard, the HF/6-31G* level of theory slightly underestimates the relative energy differences of the MCHT isomers, while MP2/6-31G*//HF/6-31G* calculations overestimate these differences. The HF/6-31G* geometries are not significantly modified by optimizations

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Table 1. Total and Relative Energies of Boat and Planar Conformations of 1,3,5-Cycloheptatriene and Methoxy-1,3,5-cycloheptatriene Isomers[a]

str[b]	AM1	PM3	SAM1	HF//HF[c]	MP2//HF[d]	B3LYP//HF[e]	B3LYP//B3LYP[f]
CHT-B	38.30 (0.00)	42.51 (0.00)	40.82 (0.00)	−269.682 330 (0.00)	−270.566 399 (0.00)	−271.506 462 (0.00)	−271.509 539 (0.00)
CHT-P	41.12 (2.82)	46.44 (3.93)	44.40 (3.58)	−269.675 532 (4.27)	−270.552 674 (8.61)	−271.499 146 (4.65)	−271.501 192 (5.24)
7-EXO	0.43 (2.75)	7.73 (5.00)	9.05 (6.66)	−383.559 588 (5.48)	−384.748 652 (7.36)	−386.021 115 (8.56)	−386.025 307 (8.36)
7-P	4.12 (6.44)	12.29 (9.56)	12.49 (10.10)	−383.553 116 (9.54)	−384.739 076 (13.37)	−386.016 538 (11.50)	−386.020 136 (11.60)
7-ENDO	4.39 (6.71)	10.93 (8.20)	12.25 (9.86)	−383.554 840 (8.46)	−384.745 603 (9.27)	−386.019 044 (9.86)	−386.023 322 (9.61)
1-B	−2.32 (0.00)	2.73 (0.00)	2.39 (0.00)	−383.568 324 (0.00)	−384.760 377 (0.00)	−386.034 761 (0.00)	−386.038 629 (0.00)
1-P	1.53 (3.85)	7.72 (4.99)	7.50 (5.11)	−383.561 314 (4.40)	−384.746 643 (8.62)	−386.027 337 (4.66)	−386.030 711 (4.97)
2-B	0.61 (2.93)	4.73 (2.00)	6.95 (4.56)	−383.563 182 (3.23)	−384.753 852 (4.09)	−386.027 641 (4.47)	−386.031 809 (4.28)
2-P	3.65 (5.97)	8.86 (6.13)	10.54 (8.15)	−383.555 975 (7.75)	−384.740 430 (12.52)	−386.021 021 (8.62)	−386.023 908 (9.24)
3-B	−0.11 (2.21)	4.16 (1.43)	5.56 (3.17)	−383.564 789 (2.22)	−384.756 005 (2.74)	−386.029 948 (3.02)	−386.034 011 (2.90)
3-P	2.69 (5.01)	8.08 (5.35)	9.03 (6.64)	−383.558 540 (6.14)	−384.743 293 (10.72)	−386.023 894 (6.82)	−386.026 987 (7.31)

[a] Heats of formation (kcal/mol) are listed for the semiempirical calculations; total energies in Hartrees are given for the ab initio and DFT calculations. Relative energies are given in parentheses in kcal/mol, where the values for **CHT-P** are relative to those for **CHT-B** and the values for the MCHT isomers are relative to those for **1-B** for each computational method listed. [b] Structure—see Figures 2 and 3. [c] HF/6-31G*//HF/6-31G*. [d] MP2/6-31G*//HF/6-31G*. [e] B3LYP/6-31G*//HF/6-31G*. [f] B3LYP/6-31G*//B3LYP/6-31G*.
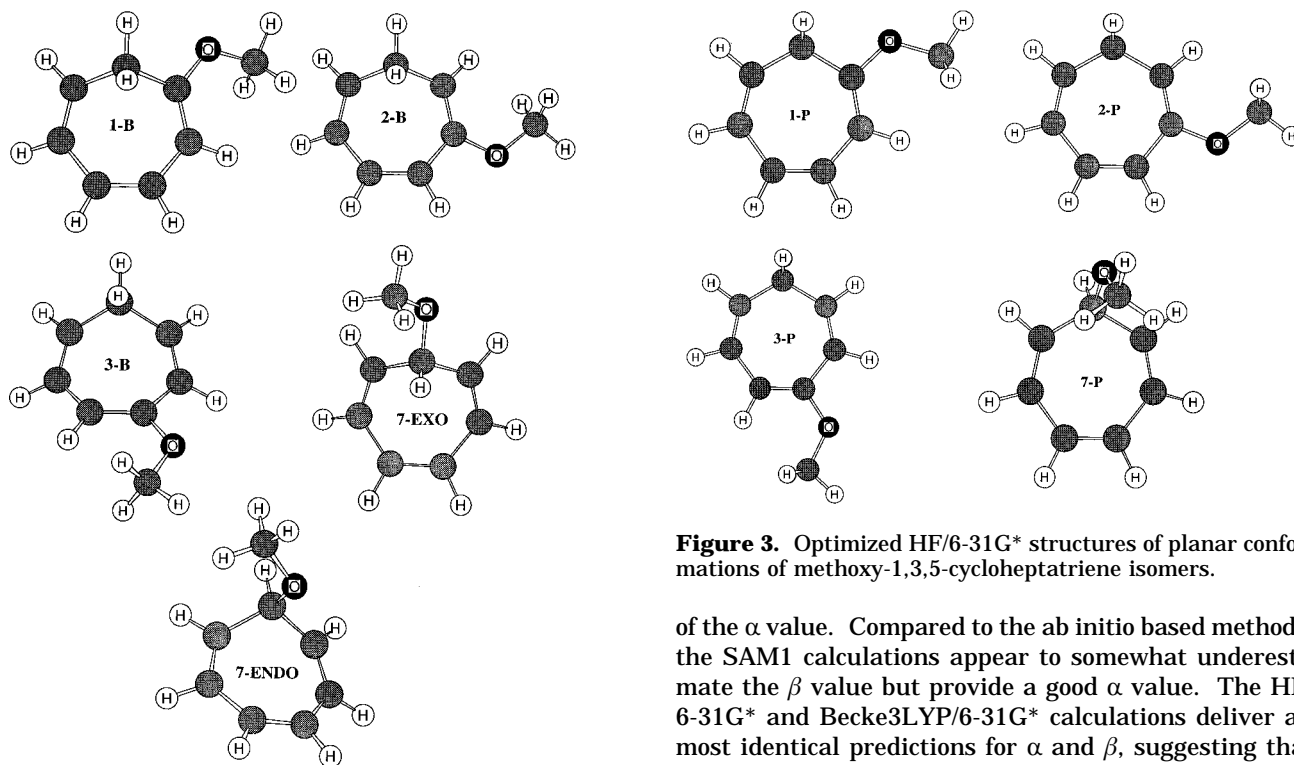
Figure 2. Optimized HF/6-31G* structures of boat conformations of methoxy-1,3,5-cycloheptatriene isomers.

**Figure 3.** Optimized HF/6-31G* structures of planar conformations of methoxy-1,3,5-cycloheptatriene isomers.

using the B3LYP hybrid functional, hence the good results obtained by the B3LYP/6-31G*//HF/6-31G* calculations. Among the semiempirical methods, SAM1 is the most successful in reproducing the DFT values. In view of the impressive performance of this model in conjunction with its computational efficiency, we chose to examine full rotational profiles of each isomer at this level. The results of this exercise are shown in Figures 4 and 5 for the boat and planar conformations, respectively.

Table 2 lists selected geometrical data for the boat and planar conformations of CHT as calculated at the SAM1, HF/6-31G*, and B3LYP/6-31G* levels of theory. As expected for a seven-membered ring, the sum of the internal angles of the planar conformation is 900°. For the boat conformations, the sum of these same angles ranges from 855° to 863°. A more direct measure of the nonplanarity of the boat conformations is provided by angles α and β. Here all three methods are in general agreement, with the β values approximately double that

of the α value. Compared to the ab initio based methods, the SAM1 calculations appear to somewhat underestimate the β value but provide a good α value. The HF/6-31G* and Becke3LYP/6-31G* calculations deliver almost identical predictions for α and β, suggesting that electron correlation has only a small affect on these angles, slightly increasing the difference between them while keeping the sum of the values constant. Hence, our best estimate of these angles for CHT is $\alpha = 25°$ and $\beta = 53°$. Our calculated α and β values are in good agreement with previous computations and the experimental values of Butcher,[2] who obtained $\alpha = 29 \pm 4°$ and $\beta = 50 \pm 5°$ from microwave studies. Although Traetteberg[1] reported very different values of $\alpha = 40.5 \pm 2°$ and $\beta = 36.5 \pm 2°$ on the basis of the sector electron diffraction method, it is interesting to note that the sum of these α and β values (77°) is in close accord with the sum of the α and β values obtained by Butcher[2] and the computational studies.

Tables 3 and 4 provide corresponding geometrical data for the boat and planar conformations of the MCHT isomers studied at the same three levels of theory. The striking observation here is that methoxy substitution apparently has little affect on the α or β values of CHT. The one exception to this generalization is for **7-ENDO** where both the α and β values are somewhat lowered. Nevertheless, in all cases, angle β is approximately twice angle α.
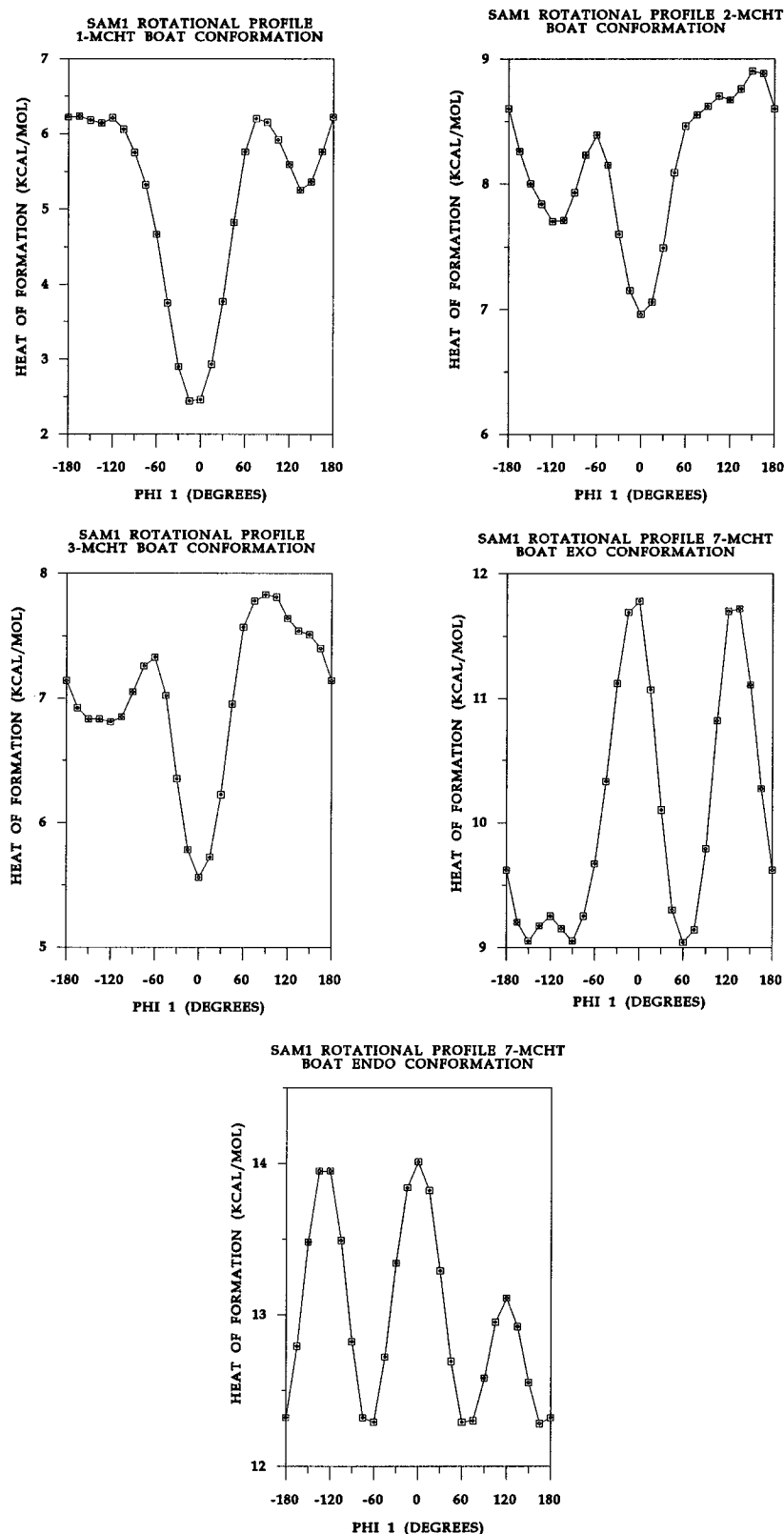
Figure 4. SAM1 plots of energy vs ϕ_1 for boat conformations of methoxy-1,3,5-cycloheptatriene isomers.

Figure 6 presents the B3LYP/6-31G*-optimized CHT hydrogen transfer transition structures **TS1** and **TS2**. This figure clearly shows that **TS1** involves the transfer of hydrogen from C7 to an adjacent carbon, in this case C6. In this instance, the CHT ring is nearly planar while the transferring hydrogen is well out of this plane. Correspondingly, **TS2** involves the transfer of hydrogen from C7 to C4, where the main ring is significantly

puckered. Here, B3LYP/6-31G* calculations predict α' = 59° and β' = 12°. Simply from geometrical consider-ations, we might expect **TS2** to be preferred over **TS1** as it deviates less from the low-energy boat conformation. Table 5 confirms this expectation by listing the energies of **TS1** and **TS2** relative to that of the boat conformation according to the level of theory indicated. We also list these values corrected for ΔZPVEs, as this makes a non-
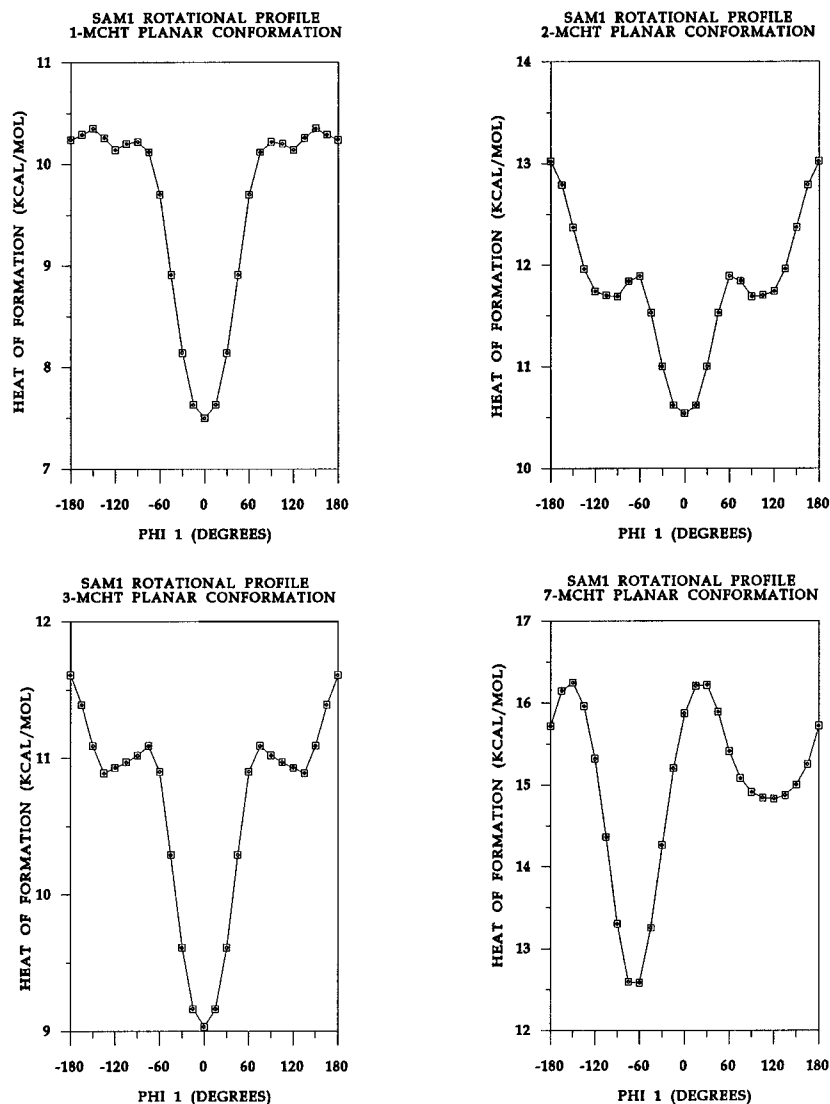
SAM1 ROTATIONAL PROFILE
1-MCHT PLANAR CONFORMATION

SAM1 ROTATIONAL PROFILE
2-MCHT PLANAR CONFORMATION

SAM1 ROTATIONAL PROFILE
3-MCHT PLANAR CONFORMATION

SAM1 ROTATIONAL PROFILE
7-MCHT PLANAR CONFORMATION

Figure 5. SAM1 plots of energy vs ϕ_1 for planar conformations of methoxy-1,3,5-cycloheptatriene isomers.

Table 2. Comparison of Selected Geometrical Parameters for CHT-B and CHT-P

parameter[a]	CHT-B			CHT-P		
	SAM1	HF/6-31G*	B3LYP	SAM1	HF/6-31G*	B3LYP
C1C2	1.363	1.328	1.351	1.334	1.325	1.344
C2C3	1.465	1.462	1.447	1.443	1.469	1.459
C3C4	1.368	1.338	1.366	1.339	1.328	1.350
C4C5	1.465	1.462	1.447	1.443	1.469	1.459
C5C6	1.363	1.328	1.351	1.334	1.325	1.344
C6C7	1.507	1.510	1.509	1.480	1.507	1.511
C7C1	1.507	1.510	1.509	1.480	1.507	1.511
C1C3	2.517	2.478	2.487	2.512	2.533	2.543
C1C4	3.118	3.076	3.086	3.125	3.144	3.162
C1C5	3.078	3.059	3.053	3.144	3.160	3.172
C1C6	2.476	2.480	2.446	2.582	2.612	2.616
C1C2C3	125.8	125.2	125.4	129.6	130.0	130.2
C2C3C4	125.7	126.1	125.9	128.2	128.3	128.3
C3C4C5	125.7	126.1	125.9	128.2	128.3	128.3
C4C5C6	125.8	125.2	125.4	129.6	130.0	130.2
C5C6C7	124.8	122.8	122.0	132.0	131.6	131.6
C6C7C1	110.4	110.4	108.2	120.4	120.2	120.0
C7C1C2	124.8	122.8	122.0	132.0	131.6	131.6
α	25.8	26.3	25.2	0.0	0.0	0.0
β	45.6	49.6	52.8	0.0	0.0	0.0

[a] See Figure 1 for atom numbering scheme and definitions of angles α and β.

negligible contribution. The detailed listing of the geometries for **TS1** and **TS2** is summarized in Table 6. The distance between the carbon atoms involved in the hydrogen transfer of **TS2** is predicted to be 2.52 Å by all

three levels of theory employed. This value is within the 2.5–2.6 Å range noted by Houk and co-workers[34] but is considerably greater than the INDO prediction of 2.31 Å.[14]

Table 3. Selected Geometrical Parameters of Fully Optimized Boat Conformations of MCHT Isomers According to SAM1, HF/6-31G*, and B3LYP Calculations

parm[a]	1-MCHT			2-MCHT			3-MCHT			7-**EXO**			7-**ENDO**		
	SAM1	6-31G*	B3LYP	SAM1	6-31G*	B3LYP	SAM1	6-31G*	B3LYP	SAM1	6-31G*	B3LYP	SAM1	6-31G*	B3LYP
C1C2	1.379	1.336	1.361	1.374	1.331	1.355	1.360	1.325	1.347	1.362	1.328	1.351	1.361	1.330	1.355
C2C3	1.457	1.459	1.443	1.482	1.468	1.456	1.483	1.466	1.455	1.464	1.461	1.446	1.462	1.456	1.440
C3C4	1.370	1.339	1.366	1.364	1.334	1.360	1.381	1.341	1.369	1.368	1.339	1.367	1.367	1.337	1.365
C4C5	1.462	1.460	1.446	1.465	1.464	1.451	1.461	1.463	1.449	1.464	1.461	1.446	1.462	1.456	1.439
C5C6	1.364	1.328	1.351	1.362	1.326	1.348	1.363	1.327	1.349	1.363	1.328	1.351	1.361	1.331	1.356
C6C7	1.504	1.509	1.510	1.508	1.510	1.511	1.507	1.510	1.511	1.521	1.504	1.503	1.517	1.512	1.509
C7C1	1.525	1.507	1.507	1.506	1.511	1.511	1.506	1.509	1.509	1.521	1.511	1.512	1.517	1.506	1.502
CXO8	1.396	1.343	1.358	1.410	1.356	1.375	1.405	1.352	1.371	1.456	1.399	1.419	1.454	1.406	1.434
O8C9	1.428	1.401	1.421	1.425	1.396	1.415	1.426	1.398	1.417	1.423	1.395	1.414	1.422	1.394	1.414
C1C3	2.493	2.469	2.480	2.567	2.480	2.493	2.506	2.482	2.491	2.518	2.473	2.482	2.527	2.495	2.507
C1C4	3.096	3.083	3.096	3.147	3.079	3.095	3.149	3.077	3.092	3.122	3.064	3.075	3.132	3.095	3.109
C1C5	3.062	3.071	3.071	3.103	3.080	3.080	3.078	3.042	3.043	3.080	3.040	3.035	3.098	3.068	3.069
C1C6	2.469	2.480	2.458	2.490	2.501	2.477	2.478	2.479	2.456	2.485	2.456	2.424	2.509	2.489	2.462
C1C2C3	123.0	124.0	124.4	127.9	124.7	125.0	123.6	125.4	125.5	125.9	124.9	125.1	127.3	127.2	127.6
C2C3C4	127.3	127.7	127.7	123.9	126.4	126.3	127.6	125.6	125.4	125.5	126.0	125.9	126.1	126.5	126.4
C3C4C5	125.6	125.5	125.5	126.6	126.7	126.6	123.4	125.5	125.4	124.4	125.7	125.6	126.0	126.2	126.2
C4C5C6	126.1	124.8	125.3	125.6	124.6	124.9	127.2	126.4	126.6	125.8	125.0	125.3	127.0	127.0	127.3
C5C6C7	124.7	122.5	122.0	124.7	122.5	121.7	124.6	122.4	121.7	123.0	122.4	121.7	126.7	125.1	124.6
C6C7C1	109.2	110.7	109.1	111.4	111.8	110.1	110.6	110.4	108.9	109.5	109.1	107.1	111.6	111.1	109.7
C7C1C2	127.1	122.4	122.2	122.2	122.0	121.2	125.5	123.5	122.7	122.9	122.5	121.9	126.3	125.0	124.3
C9O8CX	118.0	119.6	118.3	117.2	119.3	117.8	117.5	120.2	118.9	113.8	115.1	113.5	114.2	115.3	113.6
α	25.5	26.7	24.5	25.2	26.7	25.6	28.8	26.4	25.0	26.8	26.8	25.3	22.4	21.7	19.7
β	45.7	50.3	52.4	46.9	49.8	52.7	45.2	48.7	51.5	49.2	51.2	54.1	40.8	44.3	47.0
ϕ_1[b]	−8.3	−5.5	−7.6	1.6	2.8	3.1	−5.3	0.0	−1.4	−151.2	−160.9	−165.1	171.2	170.5	172.2
ϕ_2	178.4	175.9	173.1	180.0	177.0	175.8	175.8	180.0	−178.9	177.1	180.0	178.9	−178.0	−175.5	−175.3

[a] Parameter—see Figure 1 for atom numbering scheme. [b] ϕ_1 is defined as dihedral angle C9−O8−C1−C2, C9−O8−C2−C1, C9−O8−C3−C4, and C9−O8−C7−C1 for 1-, 2-, 3-, and 7-MCHT, respectively.

Table 4. Selected Geometrical Parameters of Optimized Planar Conformations of MCHT Isomers According to SAM1, HF/6-31G*, and B3LYP Calculations

parm[a]	1-MCHT			2-MCHT			3-MCHT			7-MCHT		
	SAM1	6-31G*	B3LYP	SAM1	6-31G*	B3LYP	SAM1	6-31G*	B3LYP	SAM1	6-31G*	B3LYP
C1C2	1.375	1.332	1.353	1.369	1.327	1.347	1.354	1.323	1.341	1.358	1.327	1.349
C2C3	1.454	1.464	1.451	1.480	1.474	1.466	1.480	1.474	1.466	1.459	1.463	1.450
C3C4	1.364	1.329	1.352	1.359	1.325	1.346	1.376	1.332	1.355	1.363	1.330	1.354
C4C5	1.458	1.465	1.454	1.461	1.468	1.459	1.457	1.467	1.456	1.459	1.463	1.450
C5C6	1.357	1.325	1.345	1.359	1.324	1.343	1.358	1.325	1.344	1.358	1.327	1.349
C6C7	1.494	1.504	1.506	1.497	1.505	1.508	1.497	1.505	1.509	1.512	1.508	1.506
C1C7	1.523	1.508	1.514	1.496	1.510	1.513	1.497	1.505	1.508	1.512	1.508	1.506
CXO8	1.407	1.350	1.366	1.417	1.360	1.381	1.409	1.352	1.372	1.455	1.414	1.450
O8C9	1.425	1.399	1.420	1.424	1.395	1.413	1.425	1.397	1.416	1.424	1.400	1.421
C1C3	2.534	2.526	2.536	2.602	2.530	2.544	2.544	2.539	2.549	2.554	2.531	2.540
C1C4	3.162	3.161	3.175	3.201	3.142	3.164	3.200	3.145	3.166	3.177	3.141	3.158
C1C5	3.166	3.181	3.188	3.203	3.177	3.190	3.168	3.131	3.148	3.187	3.150	3.161
C1C6	2.594	2.622	2.622	2.613	2.627	2.630	2.597	2.601	2.606	2.621	2.601	2.600
C1C2C3	127.2	129.3	129.5	131.9	129.1	129.5	127.6	130.3	130.5	130.0	130.2	130.2
C2C3C4	130.0	130.0	129.7	126.4	128.8	128.7	130.5	127.7	127.7	128.3	128.2	128.1
C3C4C5	127.7	127.7	127.6	129.2	129.1	128.8	125.5	127.4	127.3	128.3	128.1	128.1
C4C5C6	129.8	129.5	129.9	129.4	129.2	129.5	131.4	131.7	131.8	130.1	130.2	130.2
C5C6C7	133.0	131.9	131.9	132.2	131.4	131.4	131.7	131.0	130.9	131.5	132.0	132.0
C6C7C1	118.5	121.0	120.5	121.6	121.2	121.1	120.3	119.5	119.6	120.2	119.3	119.3
C7C1C2	133.7	130.7	130.9	129.4	131.2	131.0	133.0	132.3	132.1	131.6	132.0	132.0
C9O8CX	118.4	121.1	119.8	117.7	120.6	119.1	117.7	120.2	118.9	116.0	116.9	115.0
ϕ_1[b]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−67.2	−66.6	−66.2
ϕ_2	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0

[a] Parameter—see Figure 1 for atom numbering scheme. [b] ϕ_1 is defined as dihedral angle C9−O8−C1−C2, C9−O8−C2−C1, C9−O8−C3−C4, and C9−O8−C7−C1 for 1-, 2-, 3-, and 7-MCHT, respectively.

Discussion

Geometries and Energies. Previous investigators have noted that the preferred geometry of CHT is determined by the interaction of ring strain forces, nonbonded interactions, and resonance effects.[6] The finding that CHT adopts a boat rather than planar conformation was taken as evidence that ring strain forces predominate. Table 2 shows that the sp^3 carbon

center in planar CHT has a C−C−C bond angle of about 120°, while the sp^2 carbon centers have C−C−C bond angles ranging from 128° to 132°. Relaxing to the boat conformation reduces these values to 108° and 122−126°, respectively, for the same centers, in better accord with the ideal angles expected of such centers, 109.5° and 120.0°. A review of the data in Table 3 reveals that methoxy substitution has only a minor impact on the C−C−C ring bond angles in the planar and boat conformations. Thus, the ring strain comments made about CHT also apply to the MCHT isomers.

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**Table 5. Relative Energies (kcal/mol) of TS1 and TS2[a]**

	HF/3-21G		HF/6-31G*		B3LYP/6-31G*	
str[b]	ΔE	$\Delta E + \Delta$ZPVE	ΔE	$\Delta E + \Delta$ZPVE	ΔE	$\Delta E + \Delta$ZPVE
TS1	90.60	85.75	81.75	77.24	69.96	65.45
TS2	53.05	49.84	56.49	53.18	40.55	37.24

[a] Relative to that of **CHT-B** at the level of theory indicated. [b] Structure—see Figure 6.

Table 6. Selected Geometrical Parameters of TS1 and TS2 According to HF/6-31G, HF/6-31G*, and B3LYP/6-31G*

	TS1			TS2		
parm[a]	HF/3-21G	HF/6-31G*	B3LYP/6-31G*	HF/3-21G*	HF/6-31G*	B3LYP/6-31G*
C1C2	1.374	1.377	1.392	1.385	1.387	1.397
C2C3	1.396	1.401	1.406	1.385	1.387	1.397
C3C4	1.396	1.401	1.406	1.411	1.411	1.424
C4C5	1.375	1.377	1.392	1.506	1.497	1.502
C5C6	1.422	1.433	1.425	1.315	1.317	1.334
C6C7	1.413	1.405	1.417	1.506	1.497	1.502
C1C7	1.423	1.433	1.425	1.411	1.411	1.424
C1C3	2.533	2.542	2.552	2.398	2.397	2.418
C1C4	3.139	3.148	3.159	2.834	2.834	2.850
C1C5	3.203	3.218	3.209	3.044	3.056	3.076
C1C6	2.559	2.564	2.565	2.472	2.486	2.497
C4C7	3.118	3.120	3.140	2.518	2.520	2.520
C7H8	1.467	1.383	1.526	1.456	1.456	1.447
C1C2C3	132.2	132.5	131.6	119.9	119.6	119.7
C2C3C4	125.8	125.6	126.0	121.7	121.9	121.5
C3C4C5	132.2	132.5	131.6	115.8	117.5	117.1
C4C5C6	125.9	125.4	126.1	113.5	113.7	113.2
C5C6C7	129.0	129.2	128.9	113.6	113.7	113.3
C6C7C1	129.0	129.3	129.0	115.8	117.5	117.2
C7C1C2	125.9	125.4	126.2	121.7	121.9	121.5
α'[b]	1.6	1.2	4.5	60.4	58.4	59.2
β'[c]	0.1	2.6	5.6	12.2	12.4	12.0
CH8C[d]	57.6	61.1	55.3	119.7	119.8	121.1
CCH8[e]	61.2	59.4	62.3	30.1	30.1	29.4

[a] Parameter—see Figure 6 for atom numbering schemes of **TS1** and **TS2**. [b] Angle between the planes defined by atoms 1−2−6 and 2−3−4 for **TS1** and by atoms 1−3−4 and 4−6−7 for **TS2**. [c] Angle between the plane defined by atoms 1−2−6 and 1−6−7 for **TS1** and by atoms 1−2−3 and 1−3−4 for **TS2**. [d] Angle C7H8C6 for **TS1**; angle C7H8C4 for **TS2**. [e] Angle C6C7H8 for **TS1**; angle C4C7H8 for **TS2**.
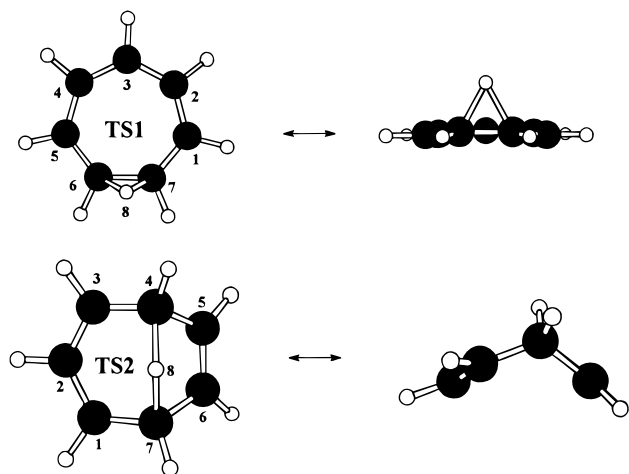
Figure 6. Two views of B3LYP/6-31G*-optimized CHT hydrogen transfer transition structures **TS1** (top) and **TS2** (bottom).

For the cyclic systems considered here, it seems reasonable to expect that the completely relaxed boat conformations with large α and β values will require more energy to pass through a planar conformation to another boat conformation than will relaxed boat conformations with small α and β values. Most of the isomers studied here exhibit very similar interconversion barriers and distortions from planarity. However, for **7-ENDO** the boat structure is closer to planarity than for the other isomer boat conformations as can be seen by the sum of the α and β values: 67° for **7-ENDO** and 75−78° for the

other isomers. Not surprisingly then, the interconversion barrier computed from the data in Table 1 for **7-ENDO** is only about 2 kcal/mol in contrast to the value of 5 kcal/mol that is predicted for the other isomers at the B3LYP/6-31G*//B3LYP/6-31G* level.

Evaluation of ZPVEs for the planar and boat conformations at the HF/6-31G* and Becke3LYP/6-31G* levels reveals that these quantities are relatively consistent. Thus, the ZPVEs for all nine MCHT conformations studied vary over a range of 108.67−109.15 kcal/mol according to the HF/6-31G* calculations and from 100.89 to 101.62 kcal/mol according to the Becke3LYP/6-31G* calculations. Consequently, including ΔZPVE values in the relative energies presented in Table 1 would result in only minor changes to the current values, which do not include ZPVEs. A correction factor of 0.893 is commonly used to scale the vibrational frequencies and ZPVEs computed at the HF/6-31G* level.[35,36] Assuming the validity of this procedure, the Becke3LYP/6-31G* frequencies and ZPVEs require a correction factor of approximately 0.96 to deliver results in accord with the corrected HF/6-31G* values.

Examining the various conformations of the MCHT isomers and their rotational energy profiles reveals that the preferred methoxy group orientations are those where (1) there is minimum overlap between the π electrons of the proximate CC double bond in the ring and the lone pair of electrons on the methoxy group oxygen atom and

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(2) there is minimum overlap between the π electrons of the CC double bond in the ring and the methoxy group hydrogen atoms. The first factor controls ϕ_1 while the second controls ϕ_2. These principles adequately explain the profiles obtained for the 1-, 2-, and 3-MCHT isomers. In all three cases, there is one clearly preferred minimum at $\phi_1 = 0°$ where factor 1 stated above is satisfied. For these systems, a second minimum, corresponding to a staggered structure, is also present, although this conformer is less stable than the $\phi_1 = 0°$ arrangement by approximately 2.5, 0.75, and 1.5 kcal/mol for 1-, 2-, and 3-MCHT, respectively.

The situation is different for 7-MCHT, where the exo and endo configurations must be considered. Because the methoxy group is well displaced from the ring in these isomers, interactions between the π electrons of the ring and the oxygen lone pair electrons are not as important. Instead, the rotational profiles are controlled by eclipsing interactions between the methoxy group and the bonds to C7. Three maxima and three degenerate minima are evident along the OCH$_3$ rotational profile for both configurations. Of the maxima, two are degenerate and substantially higher in energy than the third. The high-energy maxima occur when the methoxy group eclipses the C7−C1 and C7−C6 bonds, while the third maximum occurs when the C7−H bond is eclipsed. For **7-EXO**, one minimum is due to a structure of C_s symmetry ($\phi_1 = 60°$), while the other two minima are staggered structures ($\phi_1 = -150°$ and $-90°$), degenerate by symmetry. For **7-ENDO**, a similar situation is observed where the low-energy C_s symmetric structure occurs at $\phi_1 = -60°$ and the staggered structure minima have ϕ_1 values of 60° and 170°. There is no apparent reason for the C_s structure to be degenerate with the staggered structures, so we examined the relative energies of these structures at the HF/6-31G* level, where the C_s structures are found to be less stable than the staggered minima by 3.5 and 0.8 kcal/mol for **7-EXO** and **7-ENDO**, respectively.

It was somewhat surprising to find that the C_s structure for **7-EXO** is 3.5 kcal/mol higher in energy than the minimum energy staggered structure when the maximum energy difference over the entire SAM1 rotational profile is less than 3 kcal/mol. To explore this issue in more detail, we examined the entire HF/6-31G* rotational profile for **7-EXO**, varying ϕ_1 in 30° increments over the range −180° to 180°. Thus, we find that this model predicts a maximum energy variation of 6.5 kcal/mol over the full rotational profile, considerably larger than the 2.8 kcal/mol maximum barrier generated by SAM1. The overall appearance of the profile is similar to the SAM1 profile shown in Figure 4, although obviously the C_s structure is no longer degenerate with the staggered structures.

Hydrogen Transfer Transition Structures. Thermal isomerizations of CHT and related compounds have been extensively discussed in the literature.[37−40] Houk and co-workers have summarized current progress in elucidation of hydrocarbon pericyclic reaction transition structures by computational means in an excellent review article.[34] They point out that while many methods are able to estimate reasonable transition structure geom-

etries, prediction of reaction barriers is considerably more problematic. This is especially true when many electrons migrate in the transition structure as is the case for the systems presently under study. In such cases, neglect of electron correlation results in large errors in the calculated reaction barrier. Even MP2/6-31G** level calculations may be considerably off due to their incomplete treatment of electron correlation. Moreover, characterization of transition state structures is intrinsically more demanding than finding local energy minima.

We began our search for hydrogen transfer transition structures limiting ourselves to the HF/3-21G, HF/6-31G*, and B3LYP/6-31G* levels of theory. For CHT, three different hydrogen transfer transition structures can be envisioned: transfer from C7 to C6 (or C1), from C7 to C5 (C2), and from C7 to C4 (C3). We attempted to characterize all three transition structures but only succeeded in finding the C7 to C6 and C7 to C4 transition structures, denoted **TS1** and **TS2**. Geometrical constraints imposed by the ring system make it difficult for this system to achieve the needed geometry to allow the C7 to C5 transfer to proceed. Indeed, in propene, several workers have calculated a reaction barrier for the [1,3] hydrogen shift of about 90 kcal/mol.[41−44] Jensen[42] has recently commented on the severe angle strain involved in this system, and it is quite probable that the [1,3] hydrogen shift barrier in CHT is even higher. Nevertheless, in base-catalyzed systems, this transition structure has been located by MNDO calculations.[40]

From Table 5, we see that the ZPVE values differ by 3−5 kcal/mol between the optimized CHT boat conformation and **TS1** and **TS2**, depending on the computational model. All methods indicate that **TS2** is strongly preferred to **TS1**, consistent with experimental evidence.[12] Moreover, the methods omitting electron correlation overestimate the reaction barrier quite significantly. Including ΔZPVEs, the B3LYP/6-31G* model gives a value of 37.2 kcal/mol for the reaction barrier that is in reasonable accord with the experimental value of 31−32 kcal/mol, but still somewhat too large. The agreement between experiment and the INDO-calculated reaction barrier for **TS2** must be regarded as fortuitous, particularly in light of the apparent failings of INDO at computing geometries (the C4−C7 distance of **TS2** is 0.2 Å shorter than the B3LYP value) and the ground state energies of CHT.[14] Also noteworthy is the superficial structural similarity of **TS1** to the transition structure of the [1,5] sigmatropic hydrogen shift in cyclopentadiene.[34] Despite the apparent geometrical similarity of these transition structures, the activation barriers are very different: 40 kcal/mol for cyclopentadiene at the HF/3-21G + ΔZPVE level[45] but 86 kcal/mol for **TS1** at the same level. Presumably, the large discrepancy arises from differences in the ring sizes of the two systems resulting in less efficient overlap of the migrating hydrogen's orbitals with those of the carbons in the case of CHT.

In considering the reliability of DFT methods at predicting transition structure geometries and reaction barriers, it should be kept in mind that most DFT studies

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have focused primarily on stable, ground state molecules. Thus, less is known about how reliable these methods are at describing systems away from equilibrium. Indeed, conventional Kohn-Sham methods severely underestimate barrier heights for some simple radical reactions unless "self-interaction corrections" are included.[46] Nevertheless, quite satisfactory DFT barrier heights involving closed shell systems as considered in the present work have been reported for a variety of reactions.[20] In particular, the B3LYP functional has been successful at describing open as well as closed shell systems. Our present results for CHT hydrogen transfer transition structures appear to be another case successfully handled by this useful functional.

Conclusions

This study has shown that all the computational methods employed here deliver relatively consistent predictions for energies and geometries of CHT and MCHT isomers. Of the semiempirical models, SAM1 is the most successful in reproducing the DFT results. In general, the semiempirical models tend to underestimate the energy differences between the MCHT isomers. The calculations also demonstrate that methoxy substitution of the CHT ring has little effect on the degree of ring nonplanarity as measured by angles α and β and little effect on the barrier to interconversion between boat conformations regardless of the position of substitution. Finally, we account for the preferred orientations of the methoxy group in MCHT isomers in terms of repulsion effects between the π electrons in the ring and (1) the lone pair of electrons on oxygen and (2) the methyl group hydrogens. The choice of computational method depends largely on the property of interest. For geometries and relative energies of simple organic compounds, semiempirical methods appear to offer a rapid, reasonably reliable solution. Although many methods may successfully deliver satisfactory hydrogen transfer transition state structures for CHT and related systems, accurate estimation of reaction barriers requires consideration of correlation effects, and current DFT methods may offer a cost-effective solution. Further investigations into isomer interconversion mechanisms for the methoxy-substituted compounds are now appropriate.

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