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A Computational Study of Conformations and Conformers of 1,3-Dithiane (1,3-Dithiacyclohexane)

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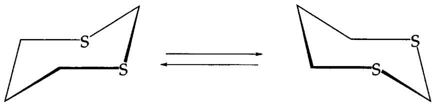
Ab initio molecular orbital theory with the 6-31G(d), 6-31G(d,p), 6-31+G(d), 6-31+G(d,p), and 6-311+G(d,p) basis sets and density functional theory (BLYP, BP86) including the hybrid density functionals B3LYP, B3P86, and B3PW91 have been used to investigate stereoelectronic hyperconjugative interactions and relative energies of the chair, 1,4-twist, and 2,5-twist conformers of 1,3-dithiane (1,3-dithiacyclohexane). The HF/6-31G(d) energy difference (ΔE) between the chair conformer and the 1,4-boat transition state was 5.53 kcal/mol, and the B3LYP/6-311+G(d,p) energy difference between the chair conformer and the 2,5-boat transition state was 5.42 kcal/mol. Intrinsic reaction coordinate (IRC, minimum energy path) calculations have been used to connect the enantiomers of the 1,4-twist conformer via the 2,5-boat transition state. The B3LYP/6-311+G(d,p) calculated energy difference between the 1,4-twist conformer and the 2,5-boat transition state was 0.80 kcal/mol. The HF/6-31G(d) energy difference (ΔE) between the chair conformer and the 2,5-twist conformer was 4.24 kcal/mol, and the 2,5-twist conformer was 0.48 kcal/mol lower in energy than the 1,4-twist conformer. The chair−1,4-twist free energy difference (ΔG°_{c-t}) is 4.42 kcal/mol, and the chair−2,5-twist ΔG°_{c-t} is 4.27 kcal/mol. IRC calculations connected the chair conformer and 2,5-twist conformer on the potential energy surface by a path that passes through the transition state [**TS-1**]‡ between them. IRC reaction path computations also connected transition state [**TS-2**]‡ to the chair conformer and the 1,4-twist conformer. The transition state [**TS-2**]‡ between the chair and the 1,4-twist conformers is 9.89 kcal/mol higher in energy than the chair conformer, and the transition state [**TS-1**]‡ between the chair and the 2,5-twist conformers is 10.44 kcal/mol higher in energy than the chair conformer. The C2−Hax, C4−Hax, and C6−Hax bond lengths are longer than the corresponding C−Heq bond lengths in the chair conformer ($LP_S \rightarrow \sigma^*_{C-Hax}$, $\sigma_{C-Hax} \rightarrow \sigma^*_{C-Hax}$). In contrast, the C5−Heq bond in the chair conformer is longer than the C5−Hax bond ($\sigma_{S-C} \rightarrow \sigma^*_{C5-Heq}$, W effect, or homoanomeric $LP_S \rightarrow \sigma^*_{C5-Heq}$). The importance of geometrical considerations in stereoelectronic hyperconjugative interactions is shown in the twist conformers and transition states of 1,3-dithiane. Unlike the chair conformer, in the 2,5-twist conformer, the respective C−H bond lengths at each carbon are equal and the C2−Hiso bond lengths are shorter than the C5−Hiso bond lengths. In the 1,4-twist conformer, the respective C−H bond lengths at C2, C4, and C6 are equal and the C5−Heq bond length is longer than the C5−Hax bond length ($\sigma_{S-C} \rightarrow \sigma^*_{C5-Heq}$, W effect, or homoanomeric $LP_S \rightarrow \sigma^*_{C5-Heq}$).

Introduction

Knowledge of the conformers, conformations, and structural properties of carbocycles and heterocycles and their stereoelectronic interactions is of considerable interest because of the important roles that they play in many areas of science.[1−9] Derivatives of cyclohexane (**1**, Figure 1) serve as models for more complex systems, and derivatives of 1,3-dioxane (1,3-dioxacyclohexane, **2**, Figure 1) and 1,3-dithiane (1,3-dithiacyclohexane, **3**, Figure 2, eq 1) have been employed in a wide variety of organic reactions. Studies of stereoelectronic effects in carbocycles and heterocycles are useful because of their rigid cyclic geometry, which keeps interacting orbitals in a well-defined geometry. The differences in stereoelectronic interactions and conformational properties among heterocycles are also useful for comparative purposes. For example, the stereoelectronic behavior of X−C−Y-containing systems (X, Y = OR, NR$_2$, Hal), which is known as the anomeric effect, tends to be stronger in O−C−O relative to the S−C−S segment.



3

(1)

There is a large body of information on the chair conformers of substituted saturated six-membered heterocycles[9−13] but only a few ab initio theory and density functional theory (DFT) studies on the mechanisms of conformational interconversions in unsubstituted heterocyclohexanes.[14−17] The investigations on substituted saturated six-membered heterocyclohexanes have almost exclusively dealt with possible chair conformers in order to obtain their geometries, degree of puckering, and, in particular, energy differences between axially and equatorially substituted structures.[11] The energetics and structural properties of 1,3-dithiane (**3**), 2-phenyl-1,3-dithiane, and their corresponding 2-lithio derivatives have been studied,[18−21] and the conformational free energies (ΔG°) of substituted 1,3-dithianes have been reviewed.[13] The question as to whether a single axial methyl group may be sufficient to cause substituted 1,3-dithianes to adopt twist forms has led to different sets of conformational

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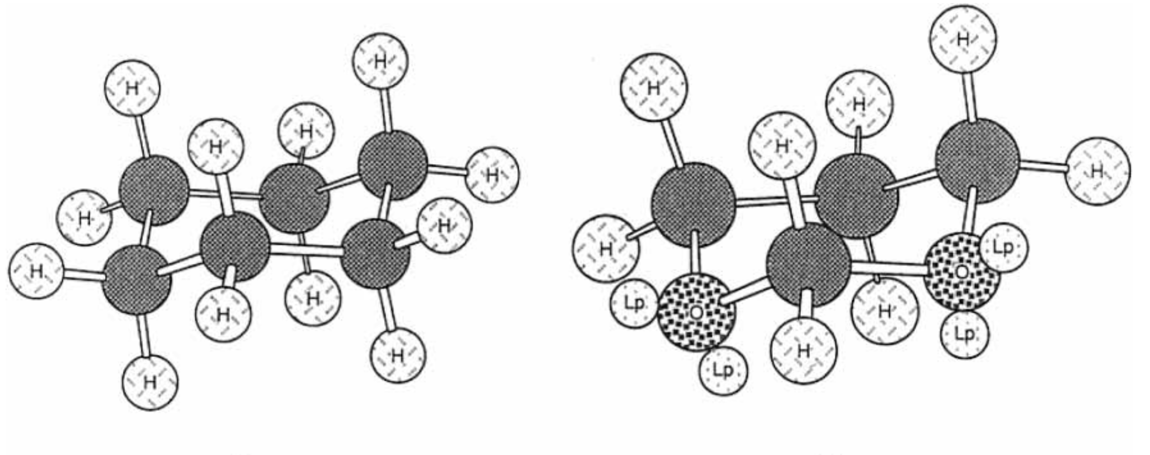
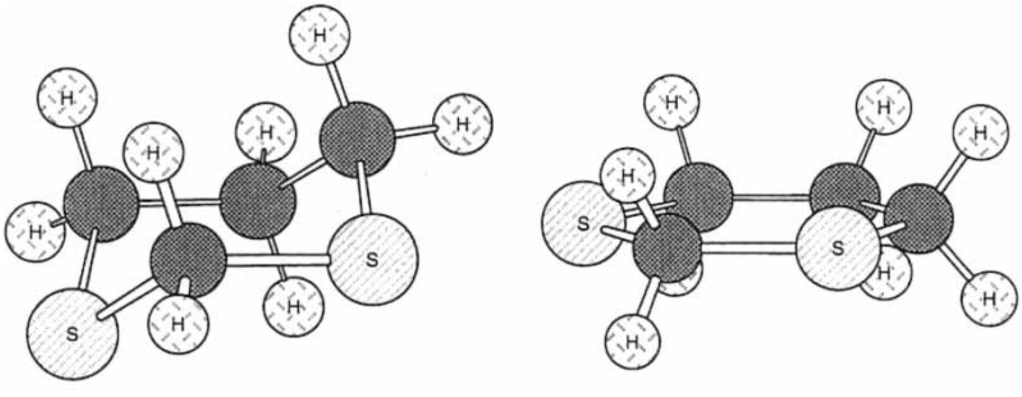


1 **2**

Figure 1. Chair conformers of cyclohexane (**1**) and 1,3-dioxane (**2**).



3 **8**

Figure 2. Chair conformer (**3**) and planar conformation (**8**) of 1,3-dithiane.

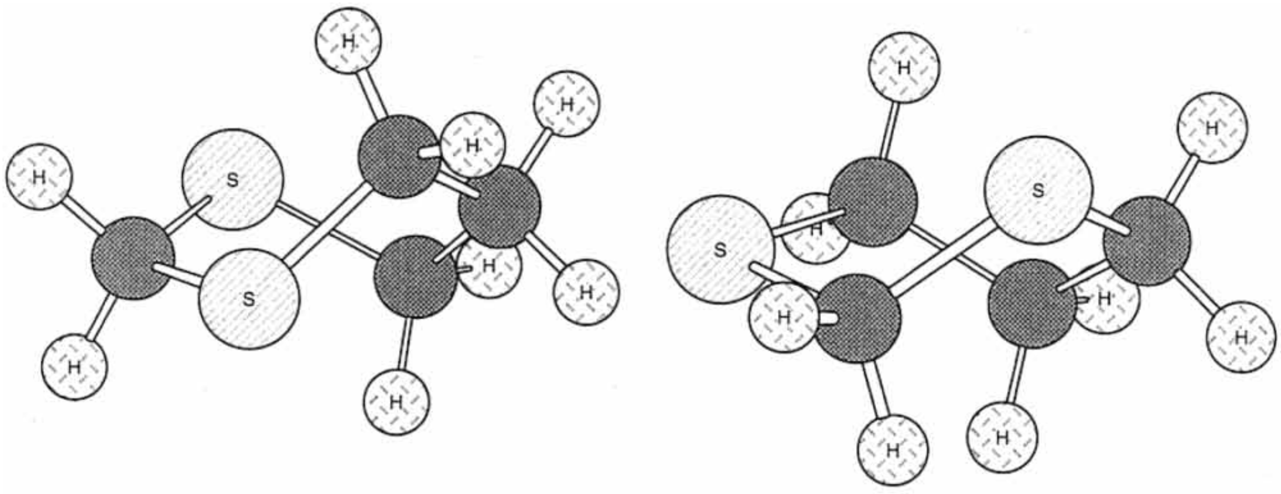
free energy ($\Delta G°$) values for alkyl substituents at various positions on 1,3-dithianes.[13]

There are numerous computational studies on stereoelectronic hyperconjugative interactions in the chair conformers of diheterocyclohexanes[2,4−7,22−27] but only a few computational studies [1,3-dioxane (**2**),[16] 1,4-dioxane,[14] and 1,2-oxathiane[17]] on the mechanisms of conformational interconversion. Thus, in contrast to cyclohexane (**1**), there is a paucity of detailed information dealing with the chair−chair and twist−twist conformational interconversions of unsubstituted heterocyclohexanes.[14−17]

Although the energy differences ($\Delta G°_{c-t}$) between the chair and the twist conformers of simple monoheterocyclohexanes seem not to be known,[9,15] it has been estimated experimentally from substituted 1,3-dioxanes that the twist conformer of 1,3-dioxane (**2**) is of higher energy relative to its chair conformer than that in cyclohexane (**1**).[9,28−32] It has also been estimated experimentally from substituted 1,3-dithianes that the $\Delta G°_{c-t}$ for 1,3-dithiane (**3**) is smaller than that for cyclohexane (**1**) and other saturated six-membered rings.[9,13,33−35]

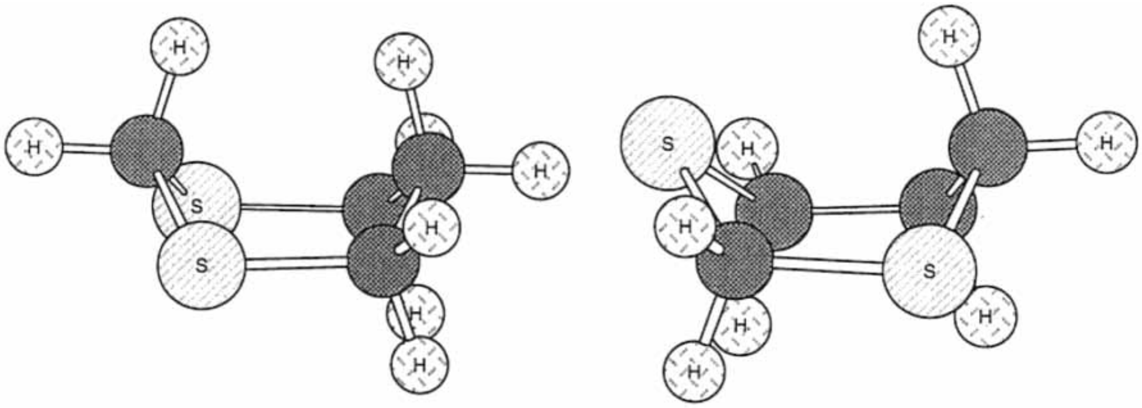
One bond NMR spin−spin coupling constants have been used as a probe for stereoelectronic hyperconjugative effects.[2,6,7] For example, in cyclohexane, the direct $^1H-^{13}C$ coupling constants are larger for equatorial hydrogens than for the axial hydrogens. This observation, which is referred to as the Perlin effect,[36] results from a hyperconjugative interaction with the participation of antiperiplanar C−H bonds ($\sigma_{C-Hax} \rightarrow \sigma^*_{C-Hax}$).[2,6,7,26,27] This results in a longer and weaker axial C−H bond. Although axial protons in a cyclohexane ring resonate upfield of the corresponding equatorial ones,[37] different behavior has been observed in 1,3-dioxanes and 1,3-dithianes. In 1,3-dioxane (**2**), C5−Hax is downfield from C5−Heq and in 1,3-dithiane (**3**) C2−Hax is downfield from C2−Heq.[2,6,7] In *cis*-4,6-dimethyl-1,3-dioxane,[24] a normal Perlin effect ($^1J_{C-Hax} = 157.4$ Hz $< {}^1J_{C-Heq} = 167.5$ Hz) was observed at C2, but *cis*-4,6-dimethyl-1,3-dithiane[25] exhibits a reverse Perlin effect ($^1J_{C-Hax} = 157.4$ Hz $> {}^1J_{C-Heq} = 144.9$ Hz).[2,6,7,36−44] A $LP_O \rightarrow \sigma^*_{C5-Heq}$ interaction though a W arrangement (the W effect) of orbitals was proposed to explain the NMR coupling (reverse Perlin effect) in 1,3-dioxane (**2**, Figure 7).[41−44] The hyperconjugative interactions between the equatorial σ-orbitals and the antiperiplanar C−S σ-orbitals ($\sigma_{S-C} \rightarrow \sigma^*_{C-Heq}$) were used to account for the reverse Perlin effect for all carbon atoms in the chair conformation of 1,3-dithiane (**3**).[7,23] It was also suggested that the $\sigma_{O-C} \rightarrow \sigma^*_{C-Heq}$ interaction could be present in 1,3-dioxanes and that the W effect might also be important in 1,3-dithianes.[2,6,7,23] It is possible that the normal or reverse Perlin effect is related to the C−H bond lengths and the longer C2−Hax bond lengths in the chair conformers of 1,3-dioxanes and 1,3-dithianes may be the result of the interplay of several stereoelectronic hyperconjugative interactions, including homoallylic participation.[45,46]

This study was undertaken in order to explore the ability of modern ab initio molecular orbital theory and DFT to investigate possible stereoelectronic hyperconjugative interactions in various conformers (**3**, **4a**, **4b**) and transition states of 1,3-dithiane, to calculate the energy differences among these conformers and transition states, and to explore the mechanisms of conforma-



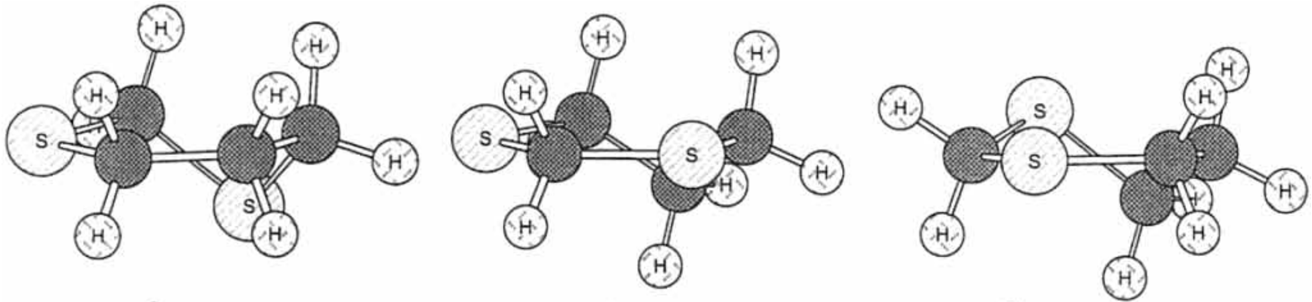
4a **4b**

Figure 3. 2,5-twist (**4a**) and 1,4-twist (**4b**) conformers of 1,3-dithiane.



5a **5b**

Figure 4. 2,5-boat (**5a**) and 1,4-boat (**5b**) conformations of 1,3-dithiane.



6a **6b** **6c**

Figure 5. Half-chair conformations (**6a**−**c**) of 1,3-dithiane.

tional interconversions of the chair conformer (**3**), the 2,5-twist conformer (**4a**, Figure 3), and the 1,4-twist conformer (**4b**, Figure 3). Although the chair−chair conformational interconversion for 1,3-dithiane (**3**) might be expected to be similar to that for cyclohexane, differences are also expected because of the changes in bond angles, bond lengths, and the presence of lone pairs. Among the structures to be considered for the conformational interconversion mechanisms of the chair conformer of 1,3-dithiane (**3**, C_s symmetry) are the 2,5-twist conformer and its enantiomer (**4a**, C_2 symmetry), the 1,4-twist conformer and its enantiomer (**4b**, C_1 symmetry), the 2,5-boat transition state ([**5a**]‡, C_s symmetry, Figure 4), the 1,4-boat transition state ([**5b**]‡, Figure 4), and the structures resembling the 1,4-half chairs (**6a**,**b**, Figure 5), the 2,5-half-chair (**6c**, Figure 5), the 1,4-sofa (**7b**, Figure 6), the 2,5-sofas (**7a**, C_s symmetry, and **7d**, C_s symmetry), and the 3,6-sofa (**7c**). The hypothetical high energy planar form (**8**, C_{2v} symmetry, Figure 2) is not expected to be involved in the conformational interconversion mechanisms. In contrast to the chair conformer of 1,3-dithiane (**3**), with only the axial and equatorial positions available for substituents, the twist conformer has three possible positions. These are the pseudoaxial (ψ_{ax}), pseudoequatorial (ψ_{eq}), and isoclinal (iso, Chart 1).

Computational Methods and Calculations

The geometry optimized structures and the energy calculations were carried out with the MacSpartan Pro,[47] Spartan,[47] and

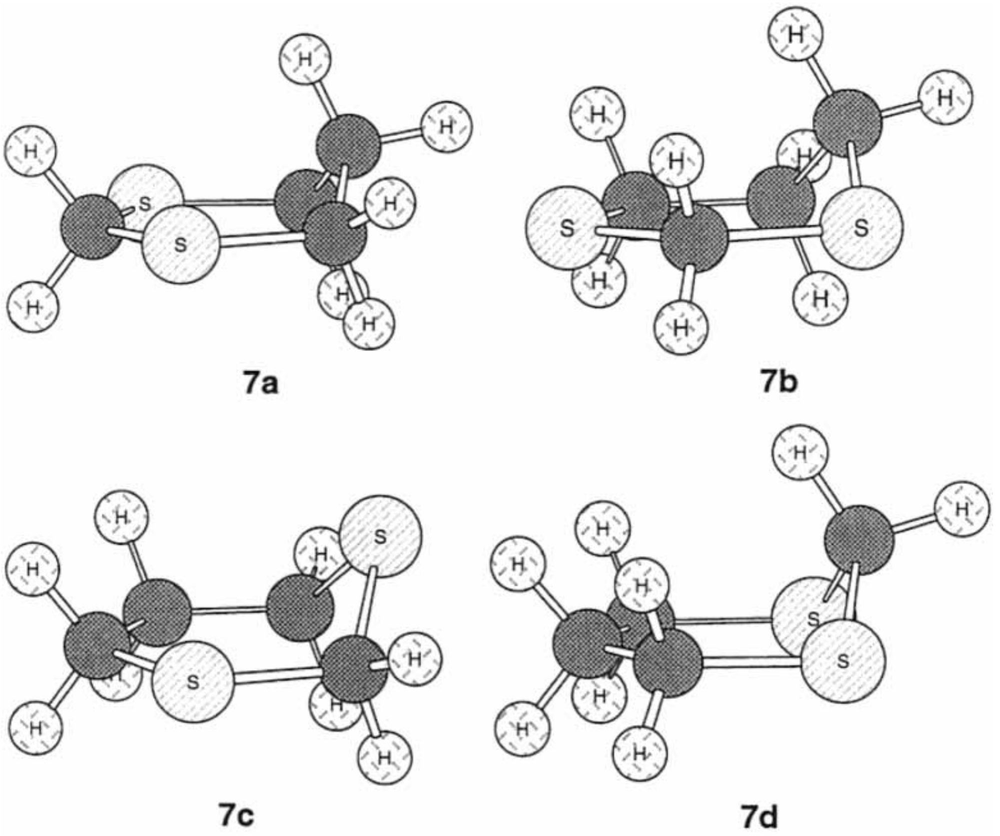
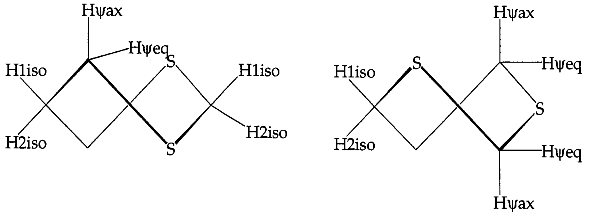


Figure 6. Sofa conformations (**7a**−**d**) of 1,3-dithiane.

CHART 1



4a

4b

Gaussian[48] computational programs. The HF/6-31G(d) geometry optimized structures were used as starting points for the other geometry optimization calculations and MP2 single point energy calculations. MP2 single point energy calculations were done on the respective geometry optimized structures. MP2 and DFT provide electron correlation, which is often important in conformational studies.[49,50] Basis sets with diffuse functions are important for molecules with lone pair electrons, and the 6-31+G(d), 6-31+G(d,p), and 6-311+G(d,p) basis sets take into account the relative diffuse nature of lone pairs.[50] Basis sets with polarization functions have been useful in computational studies involving hyperconjugative stereoelectronic interactions[1,2,6,7,15−17,23,51] and involving structures containing third row elements.[17,52]

Frequency calculations were computed on the HF/6-31G(d), BLYP/6-31G(d), B3LYP/6-31G(d), B3P86/6-31G(d), and B3PW91/6-31G(d) geometry optimized structures at 203, 298.15, or 330 K and 1 atm of pressure. The zero point vibrational energies (ZPE) were scaled for HF/6-31G(d) (0.9135), BLYP/6-31G(d) (1.0119), and B3LYP (0.9804).[50,53−59] The HF/6-31G(d), BLYP/6-31G(d), BP86/6-31G(d), B3LYP/6-31G(d), B3P86/6-31G(d), and B3PW91/6-31G(d) vibrational frequencies were scaled by 0.8929, 0.9945, 0.9914, 0.9614, 0.9558, and 0.9573, respectively.[50,53−59] Total energies are given in hartrees (1 H = 1 atomic unit (au) = 627.5095 kcal/mol), and the other energies (energy difference (ΔE), free energy difference ($\Delta G°$), ZPE, and thermal energy) are in kcal/mol. The dipole moments are given in debyes (D), and the entropies are given in entropy units (eu).

Structures **5**−**7** were used as starting points for exploration of the potential energy surface (PES). To maintain the desired structural integrity during partial geometry optimizations in the preliminary screening process, torsional angles (τ) were constrained in the 2,5-boat (**5a**, C2−S1−C6−C5 = C2−S3−C4−C5 = 0°), 1,4-boat (**5b**, S1−C2−S3−C4 = S1−C6−C5−C4 = 0°), half-chair (**6a**, S3−C4−C5−C6 = 0°, S3−C4−C5−C6 = 57.3 or 58.9°; **6b**, C2−S1−C6−C5 = 0°, S3−C4−C5−C6 = 57.3°; **6c**, C2−S3−C4−C5, = 0°, S3−C4−C5−C6 = 57.3°), sofa (**7a**, C4−S3−C2−S1−C6 are coplanar; **7b**, S1−C2−S3−C4−C5 are coplanar; **7c**, C2−S3−C4−C5−C6 are coplanar; **7d**, S3−C4−C5−C6−S1 are coplanar), and planar (**8a**, ring atoms are coplanar) structures. The constraints were removed from each of the optimized constrained structures (**5**−**7**) after the prescreening partial geometrical optimization step, and it was submitted for transition structure search/optimization and then a subsequent frequency calculation.

Each transition state optimized structure with one imaginary frequency was submitted for intrinsic reaction coordinate (IRC, minimum energy path) calculations[50,60,61] since finding one imaginary frequency (saddle point) does not guarantee that one has found a transition structure that is involved in the conformational interconversion mechanism. Although saddle points generally connect two minima on the PES, these minima may not be the structures of interest.[62−67] An IRC calculation examines the reaction path leading down from a transition structure on a PES. The calculation starts at the saddle point and follows the reaction in both directions. Thus, the IRC calculations definitively connect two minima on the PES by a

TABLE 1: Vibrational Frequencies (cm^{-1}) and Assignments for the Chair Conformer (3) of 1,3-Dithiane

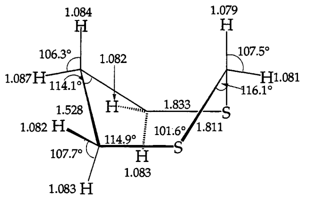
Raman[66,67]	IR[66,67]	HF/ 6-31G(d)	BLYP/ 6-31G(d)	BP86/ 6-31G(d)	B3LYP/ 6-31G(d)	B3PW91/ 6-31G(d)	relative intensity (HF)	Raman activity (HF)	assignment[66,67]
2962 m	2958 ms	2964	2965	2964	2952		0.04	86.2	CH_2 stretch (?*A″*)
2950 s	2940 m	2936	2937	2945	2934	2945	0.49	84.2	CH_2 stretch (?*A″*)
2932 m		2932			2931	2926	0.22	75.8	
2900 vs	2900 vs	2916			2910	2911	0.37	73.5	CH_2 stretch (*A′*)
2859 w	2860 sh	2878					0.15	18.0	CH_2 stretch (*A′*)
	2848 sh	2855					0.59	108.8	2 × 1424 = 2848
	2838 ms								CH_2 stretch (*A′*)
2820 w, br	2818 m								CH_2 stretch (*A′*)
	2760 w								?2 × 1387 = 2774
	1424 vs	1438		1437	1431	1427	0.09	19.4	CH_2 scissors (*A′*)
1419 wm	1419 m, sh	1422	1425		1409	1419	0.05	21.2	CH_2 scissors (*A′*)
1390 wm	1387 ms					1398			CH_2 scissors (*A′*)
1338 vw	1342 vw		1355		1345	1336			?
1290 vw	1285 m	1309	1291	1286	1284	1290	0.45	0.73	CH_2 wag (*A″*)
1272 vw	1274 ms					1278			CH_2 wag (*A″*)
1244 w	1244 ms	1242	1246	1243	1234	1230	0.17	11.9	CH_2 wag (*A″*)
1204 w	1210 wm		1213	1212	1209	1206			CH_2 wag (*A″*)
1200 w	1200 wm								
1180 m		1193	1180	1181			0.27	15.9	CH_2 twist (*A′* or *A″*)
1175 w, sh^r	1172 vs				1176	1175			CH_2 twist (*A′* or *A″*)
1152 vw	1150 w	1158		1154	1147	1145	0.05	0.42	CH_2 twist (*A′* or *A″*)
1090 w	1090 w	1092		1089	1082	1080	0.01	1.19	CH_2 twist (*A′* or *A″*)
1047 wm				1037		1030			?
1009 m	1010 ms	1012	1006	1006	1001	998	0.07	7.25	CH_2 rock (*A′*) + C−C stretch (*A″*)
916 wm	922 vs	920	917	915	910	907	0.27	4.19	C−C stretch (*A′*)
888 w, br	889 ms	868	862	877	865	873	0.06	5.81	CH_2 rock (*A″*)
818 w, br	817 wm	812	814	809	805	799	0.02	0.25	CH_2 rock (*A″*)
798 w	792 w	790	789	788	782	779	0.00	4.09	CH_2 rock (*A′*)
	750 vs	757					0.22	10.3	C−S stretch (*A″*)
738 m						724			?
				698	702				
679 ms	677 s								C−S stretch (*A′* + *A″*)
672 w, sh^r		665	667	657		662	0.04	7.51	
638 vvs	642 wm		637		639				C−S stretch (*A′*)
	620	622	622	621		624	0.06	34.0	
466 w	472 w	458	459	458	456	453	0.00	2.17	ring deformation (*A′*)
332 w		322	327	330	324	325	0.02	4.14	ring deformation (*A′*)
316 m		307	311	314	309	309	0.00	2.22	ring deformation (*A″*)
312 s		306	306	307	305	304	0.01	3.62	ring deformation (*A′*)
	217	191	206	211	200	204	0.04	0.42	ring deformation (*A″*)
		162	169	172	166	168	0.01	0.05	
80 m									ring deformation (*A′*)

path that passes through the transition state between them. However, two minima on a PES may have more than one reaction path connecting them, corresponding to different transition structures through which the reaction passes.[50]

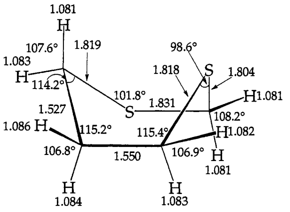
Results and Discussion

Frequency calculations showed that three minima were located, the chair (**3**), 1,4-twist (**4a**), and 2,5-twist (**4b**) conformations, which are related to the chair and twist conformations of cyclohexane. After the transition structure search/optimization and frequency calculations, the constrained 2,5-boat (**5a**) and 1,4-boat (**5b**) geometries afforded the transition structures [**5a**]‡ (HF/6-31G(d) E = −951.141407 au, μ = 2.65 D) and [**5b**]‡ (HF/6-31G(d) E = −951.141275 au, μ = 1.98 D), respectively. Transition structure **TS-1** (HF/6-31G(d) E = −951.1335788 au) was obtained from the half-chair structures **6a**,**c** and from the sofa structures **7c**,**d**, and transition structure **TS-2** (HF/6-31G(d) E = −951.1344865 au) was obtained from the half-chair structure **6b** and the sofa structures **7a**,**b**.

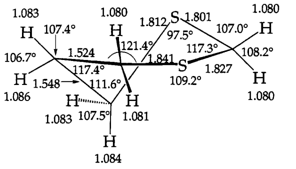
Table 1 shows the HF and DFT calculated and the experimental vibrational and Raman wavelengths and their respective assignments for the chair conformer (**3**) of 1,3-dithiane.[68,69] Because of an absence of electron correlation, vibrational frequencies at the Hartree−Fock level are commonly overestimated quite systematically by about 10%. The DFT methods are in general well-behaved in predicting vibrational frequencies, and deviations from experimental results occur quite systematically.[59] The infrared and Raman spectra of the chair conformation (**3**) of 1,3-dithiane have been discussed.[68−70] Data from vibrational spectroscopy,[68,69] microwave spectroscopy (MW),[71,72]



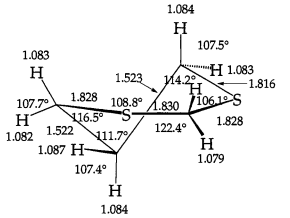
[5a]‡



[5b]‡



[TS-1]‡



[TS-2]‡

TABLE 2: Calculated Bond Lengths (Å) for the Chair Conformer (3) of 1,3-Dithiane

	HF/ 6-31G(d)	MP2/ 6-31G(d)	B3LYP/ 6-31G(d)	B3P86/ 6-31G(d)	B3PW91/ 6-31G(d)
C2−Hax	1.083	1.095	1.095	1.095	1.096
C2−Heq	1.081	1.093	1.093	1.093	1.093
C4−Hax	1.085	1.097	1.098	1.098	1.098
C4−Heq	1.083	1.094	1.094	1.094	1.095
C5−Hax	1.084	1.095	1.096	1.095	1.096
C5−Heq	1.088	1.098	1.100	1.100	1.100
S1−C2	1.810	1.810	1.830	1.816	1.818
S1−C6	1.817	1.815	1.838	1.823	1.825
C4−C5	1.529	1.526	1.533	1.525	1.528

gas electron diffraction (ED),[73] NMR spectra,[74] dipole moments,[74,75] and UV photoelectron spectroscopy/MNDO[76] investigations and calculated structural features[77] are consistent with the chair conformation (**3**) being the most stable form of 1,3-dithiane in solution. The molecular orbital theory calculations in this study agree with the experimental data that the chair (**3**) is the most stable conformer of 1,3-dithiane and that it is lower in energy than the 2,5-twist (**4a**) and 1,4-twist (**4b**) conformers.

The values of the HF ($\mu = 2.43$ D) and MP2 ($\mu = 2.41$ D) calculated dipole moment (μ) for the chair conformer (**3**) of 1,3-dithane were larger than the experimental values of 2.13 and 2.09 D in tetrachloromethane and benzene, respectively.[74,75] The DFT calculations gave a slightly smaller dipole moment ($\mu = 2.33$ D) for **3** than did HF and MP2. The 2,5-twist conformer (**4a**) had a smaller dipole moment (HF $\mu = 1.35$ D; MP2 and DFT $\mu = 1.25$ D) than the chair (**3**) and 1,4-twist (**4b**, HF $\mu = 2.45$ D; MP2 and DFT $\mu = 2.36$ D) conformers.

HF, MP2, and DFT gave similar values for the torsional angles and bond angles in the chair conformer (**3**) of 1,3-dithiane. The calculated torsional angles in **3** are in better agreement with the ED data[73] than with the MW data.[71,72] Although the HF/6-31G(d) H−C−H bond angles in **3** are slightly smaller than the MW and ED values, the other bond angles are in excellent agreement with the experimental data. These calculations and the experimental data are consistent with each other, indicating that the chair conformer (**3**) of 1,3-dithiane has appreciably greater ring puckering than cyclohexane since the S−C−C, S−C−S, and C−C−C bond angles in **3** are all larger than the C−C−C bond angles in cyclohexane.

Although all levels of theory gave similar geometric parameters for the chair (**3**), 2,5-twist (**4a**), and 1,4-twist (**4b**) conformers of 1,3-dithiane, the MP2 and hybrid density functionals B3LYP, B3P86, and B3PW91 generally gave longer bond lengths than HF.[78,79] The BLYP functional, which systematically overestimates bond lengths, gave the longest bond lengths (Table 2).[80] The C−S bond lengths in **3** are not equal, and B3LYP gave longer C−S bond lengths than HF, MP2, and the other hybrid density functionals. All levels of theory calculated the S1−C2 bond length to be shorter than the S1−C6 bond length in the chair conformer (**3**). The C−S bond lengths have been determined experimentally in tetrahydro-2*H*-thiopyran (C_s symmetry, ED 1.832 Å,[81] MW 1.811 Å[82]), 1,4-dithiacyclohexane (1,4-dithiane, C_{2h} symmetry, ED 1.81 Å,[83] X-ray 1.81[84]),[85] 4-oxa-1-thiacyclohexane (1,4-oxathiane, 1,4-thioxane, ED 1.826 Å,[86,87] MW 1.824 Å[88]), and 1,4-thioselenane (1.81 Å).[83] Thus, the experimental and the HF, MP2, B3P86/6-31G(d), and B3PW91/6-31G(d) calculated S1−C2 and C2−S3 bond lengths in the chair conformer (**3**) of 1,3-dithiane are similar to the observed C−S bond lengths in tetrahydro-2*H*-thiopyran, 1,4-dithiane, and 1,4-thioselenane.

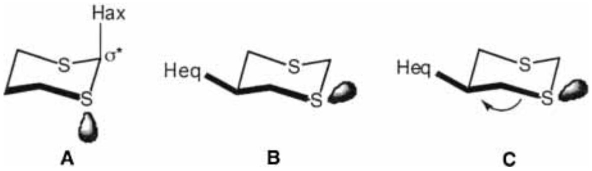


Figure 7. Stereoelectronic interactions proposed for the C−Hax and C5−Heq bonds in the chair conformer of 1,3-dithiane: the anomeric $LP_S \rightarrow \sigma^*$ interaction between the axially directed nonbonding electron pair on sulfur and the antiperiplanar axial C−H bond (A); the W effect or homoanomeric effect ($LP_S \rightarrow \sigma^*_{C5-Heq}$); (C) $\sigma_{S-C} \rightarrow \sigma^*_{C5-Heq}$ (B).

TABLE 3: Bond Lengths (Å) in the 2,5-Twist (4a) and 1,4-Twist (4b) Conformers of 1,3-Dithiane

	HF/ 6-31G(d)	MP2/ 6-31G(d)	B3LYP/ 6-31G(d)	B3P86/ 6-31G(d)	B3PW91/ 6-31G(d)
			2,5-twist (**4a**)		
C2−H1iso	1.081	1.093	1.093	1.093	1.094
C2−H2iso	1.081	1.093	1.093	1.093	1.094
C5−H1iso	1.086	1.096	1.098	1.097	1.098
C5−H2iso	1.086	1.096	1.098	1.097	1.098
C4−Hψax	1.081	1.093	1.093	1.093	1.094
C4−Hψeq	1.083	1.094	1.094	1.094	1.094
S1−C2	1.824	1.826	1.845	1.831	1.833
S3−C2	1.824	1.826	1.845	1.831	1.833
S1−C6	1.817	1.814	1.836	1.822	1.824
S3−C4	1.817	1.814	1.836	1.822	1.824
C4−C5	1.535	1.531	1.540	1.531	1.534
			1,4-twist (**4b**)		
C2−Hψax	1.080	1.093	1.093	1.093	1.094
C2−Hψeq	1.081	1.093	1.092	1.093	1.093
C4−H1iso	1.083	1.094	1.095	1.095	1.095
C4−H2iso	1.083	1.094	1.095	1.095	1.095
C5−Hψax	1.085	1.095	1.096	1.096	1.096
C5−Hψeq	1.087	1.097	1.098	1.098	1.098
C6−Hψax	1.083	1.094	1.095	1.095	1.095
C6−Hψeq	1.083	1.093	1.094	1.094	1.094
S1−C2	1.821	1.823	1.844	1.830	1.832
S3−C2	1.807	1.805	1.824	1.810	1.812
S1−C6	1.825	1.821	1.846	1.830	1.832
S3−C4	1.828	1.825	1.850	1.835	1.837
C4−C5	1.536	1.536	1.540	1.533	1.535
C5−C6	1.528	1.526	1.532	1.525	1.527

Geometry optimizations at all levels of theory showed that the C2−Hax, C4−Hax, and C6−Hax bond lengths in the chair conformer (**3**) were slightly longer ($\Delta r = 0.002-0.004$ Å) than the respective C2−Heq, C4−Heq, and C6−Heq bond lengths ($LP_S \rightarrow \sigma^*_{C-Hax}$, $\sigma_{C-Hax} \rightarrow \sigma^*_{C-Hax}$). In contrast, the C5−Heq bond length in **3**, which is anti to the S−C bond, is longer than the C5−Hax bond length. The S3−C4−C5−Heq and S3−C4−C5−Hax torsional angles (τ) in **3** are 175.0 and 58.1°, respectively, as are the S1−C6−C5−Heq and S1−C6−C5−Hax torsional angles (τ). The longer C5−Heq bond length in **3** may be a manifestation of the $\sigma_{S-C} \rightarrow \sigma^*_{C5-Heq}$ and homoanomeric $LP_S \rightarrow \sigma^*_{C5-Heq}$ stereoelectronic hyperconjugative interactions (Figure 7).[2,6,7,41,42] The S1−C2 and C2−S3 bond lengths in **3** are equal as are the S1−C6 and S3−C4 bond lengths (Table 2). The S1−C2 and C2−S3 bonds are shorter than the S1−C6 and S3−C4 bonds.

The importance of structural considerations on stereoelectronic hyperconjugative interactions in carbon−hydrogen bonds is seen in a comparison of the geometrical parameters for the chair (**3**), 2,5-twist (**4a**), and 1,4-twist (**4b**) conformers of 1,3-dithiane. The C−H bond lengths on the same carbon atom in the 2,5-twist conformer (**4a**) are equal, and the C2−Hiso bond lengths are shorter than the C5−Hiso bond lengths. These equal C−H bond lengths are in marked contrast with the chair conformer (**3**) of 1,3-dithiane, with the chair conformations of other heterocyclohexanes,[2,6,7,15−17,43,44] and with the half-chair conformations of unsaturated six-membered rings[89−92] in which

TABLE 4: HF/6-31G(d) Thermochemical Data for Conformers and Transition States of 1,3-Dithiane

				203 K		298 K		330 K	
	total energy	Δ*E*	ZPE	thermal energy	*S*°	thermal energy	*S*°	thermal energy	*S*°
3	−951.150219		78.142	80.097	70.366	81.869	78.213	82.602	80.748
4a	−951.143460	4.24	78.141	80.222	70.669	82.013	78.595	82.750	81.140
4b	−951.142695	4.72	78.180	80.237	71.679	82.023	79.587	82.759	82.128
[**5a**]‡	−951.141404	5.53	78.178	79.929	68.721	81.523	75.848	82.194	78.186
[**5b**]‡	−951.141275	5.61	78.042	79.863	69.450	81.472	76.635	82.146	78.986
[**TS-1**]‡	−951.133579	10.4	78.059	79.975	71.011	81.596	78.235	82.274	80.577
[**TS-2**]‡	−951.134487	9.87	77.954	79.962	73.150	81.472	78.147	82.243	82.136

TABLE 5: Total Energies for the Chair (3), 2,5-Twist (4a), and 1,4-Twist (4b) Conformers of 1,3-Dithiane

computational level	chair (**3**)	2,5-twist (**4a**)	1,4-twist (**4b**)
HF/6-31G(d)	−951.150219	−951.143460	−951.142695
MP2/6-31G(d)//HF/6-31G(d)	−951.917149	−951.910929	−951.909663
HF/6-31G(d,p)	−951.162669	−951.155851	−951.155119
MP2/6-31G(d,p)//HF/6-31G(d,p)	−951.982368	−951.976068	−951.974934
HF/6-31+G(d)	−951.152764	−951.145720	−951.145132
MP2/6-31+G(d)//HF/6-31+G(d)	−951.927832	−951.920994	−951.920115
HF/6-31+G(d,p)	−951.164892	−951.157809	−951.157251
MP2/6-31G(d)	−951.918118	−951.912086	−951.910809
B3LYP/6-31G(d)	−953.621602	−953.615225	−953.614262
B3LYP/6-311+G(d,p)	−953.719640	−953.712747	−953.712273
B3P86/6-31G(d)	−954.817577	−954.811428	−954.810257
B3PW91/6-31G(d)	−953.470048	−953.463917	−953.462775

the C−Hax and C−H*ψ*ax bond lengths are longer than the respective C−Heq and C−H*ψ*eq bonds. The equal C−H bond lengths at each carbon in the 2,5-twist (**4a**) suggest an absence of stereoelectronic hyperconjugative interactions involving these bonds. The S3−C4−C5−H1iso and S3−C4−C5−H2iso torsional angles in **4a** are 159.5 and 84.0°, respectively. The C4−S3−C2−H1iso and C4−S3−C2−H2iso torsional angles in **4a** are 92.2 and 150.6°, respectively. The C−C bond lengths in **4a** are longer than those in the chair conformer (**3**). The S1−C2 and C2−S3 bond lengths in **4a** are equal and are longer than the S1−C6 and S3−C4 bond lengths, which are equal. The S1−C2 bond length in **4a** is longer (1.824 Å) than that in the chair conformer (**3**, 1.810 Å) while their S3−C4 bond lengths (1.817 Å) are equal.

Although the respective C−C bond lengths in **3** (1.529 Å) and **4a** (1.535 Å) are equal, in the 1,4-twist conformer (**4b**), the C5−C6 bond (1.528 Å) is shorter than the C4−C5 bond (1.536 Å). A $\sigma_{\mathrm{S1-C6}} \rightarrow \sigma^*_{\mathrm{C5-H\psi eq}}$ stereoelectronic interaction in **4b** should lead to a shorter C5−C6 bond, which should be similar in length to the C−C bond lengths in the chair conformer (**3**, Tables 2 and 3). In the 1,4-twist conformer (**4b**), at positions 2 and 6, the C−H*ψ*ax and C−H*ψ*eq bond lengths are equal as are the C−Hiso bond lengths at position 4. The C5−H*ψ*ax bond length is slightly shorter than the C5−H*ψ*eq bond length ($\sigma_{\mathrm{S-C}} \rightarrow \sigma^*_{\mathrm{C5-H\psi eq}}$ and homoanomeric $\mathrm{LP_S} \rightarrow \sigma^*_{\mathrm{C5-H\psi eq}}$). The S3−C4−C5−H*ψ*ax and S3−C4−C5−H*ψ*eq torsional angles in **4b** are 84.9 and 159.4°, respectively, and the S1−C6−C5−H*ψ*ax and S1−C6−C5−H*ψ*eq torsional angles are 47.4 and 163.5°, respectively. The S1−C2 bond length in the 1,4-twist conformer (**4b**) is the shortest C−S bond among the three conformers (**3** and **4a**,**b**). In the 1,4-twist conformer (**4b**), all of the C−S bond lengths are different. Thus, although the 2,5-twist (**4a**) and 1,4-twist conformers (**4b**) are close in energy (Tables 4−7), their different geometrical features also serve to distinguish between them.

MP2 gave smaller values of the energy differences (Δ*E*) between **3** and **4a** than HF (Table 6), and the 6-31+G(d) basis set gave larger values of Δ*E* than the 6-31G(d) and 6-31G(d,p) basis sets. The B3LYP/6-31G(d) energy difference (Δ*E*) between the chair (**3**) and the 2,5-twist (**4a**) conformers was closer to the HF calculations, and the B3P86/6-31G(d) and B3PW91/6-31G(d) values of Δ*E* were closer to the MP2 values. The HF/6-31G(d) energy difference (Δ*E*) of 4.24 kcal/mol between **3** and **4a** is smaller than the energy differences (Δ*E*) between the chair and the twist conformers of cyclohexane (4.7−6.2 kcal/mol).[9] All levels of theory calculated small energy differences (Δ*E* = less than 1 kcal/mol) between the 2,5-twist (**4a**) and the 1,4-twist (**4b**) conformers with HF and B3LYP giving the smallest energy differences (Δ*E*).

TABLE 6: Thermodynamic Parameters for the 2,5-Twist (4a) and 1,4-Twist (4b) Conformers [Relative to the Chair Conformer (3)] of 1,3-Dithiane

computational level	Δ*E*	Δ*H*°	Δ*G*°
2,5-twist (**4a**)			
HF/6-31G(d)	4.24	4.39	4.27
MP2/6-31G(d)//HF/6-31G(d)	3.92	3.57	4.28
HF/6-31G(d,p)	4.28	4.42	4.31
MP2/6-31G(d,p)//HF/6-31G(d,p)	3.95	3.60	4.31
HF/6-31+G(d)	4.43	4.57	4.46
MP2/6-31+G(d)//HF/6-31+G(d)	4.28	3.93	4.64
MP2/6-31G(d)	3.79	3.93	3.82
B3LYP/6-31G(d)	4.00	4.15	4.03
B3LYP/6-311+G(d,p)	4.33	4.47	4.36
B3P86/6-31G(d)	3.86	4.00	3.89
B3PW91/6-31G(d)	3.85	3.99	3.88
1,4-twist (**4b**)			
HF/6-31G(d)	4.72	4.87	4.46
MP2/6-31G(d)//HF/6-31G(d)	4.72	4.87	4.46
HF/6-31G(d,p)	4.74	4.89	4.48
MP2/6-31G(d,p)//HF/6-31G(d,p)	4.66	4.81	4.40
HF/6-31+G(d)	4.79	4.94	4.53
MP2/6-31+G(d)//HF/6-31+G(d)	4.86	5.01	4.60
MP2/6-31G(d)	4.59	4.74	4.33
B3LYP/6-31G(d)	4.61	4.76	4.35
B3LYP/6-311+G(d,p)	4.62	4.77	4.36
B3P86/6-31G(d)	4.59	4.74	4.33
B3PW91/6-31G(d)	4.56	4.72	4.31

The HF/6-31G(d) chair−twist free energy difference ($\Delta G^\circ_{\mathrm{c-t}}$ = 4.27 kcal/mol) between the chair (**3**) and the 2,5-twist structure (**4a**) is smaller than the estimated experimental $\Delta G^\circ_{\mathrm{c-t}}$ for cyclohexane (4.7−4.9 kcal/mol at 298 K),[9,28,93−96] larger than the estimated experimental value of 2.9 kcal/mol

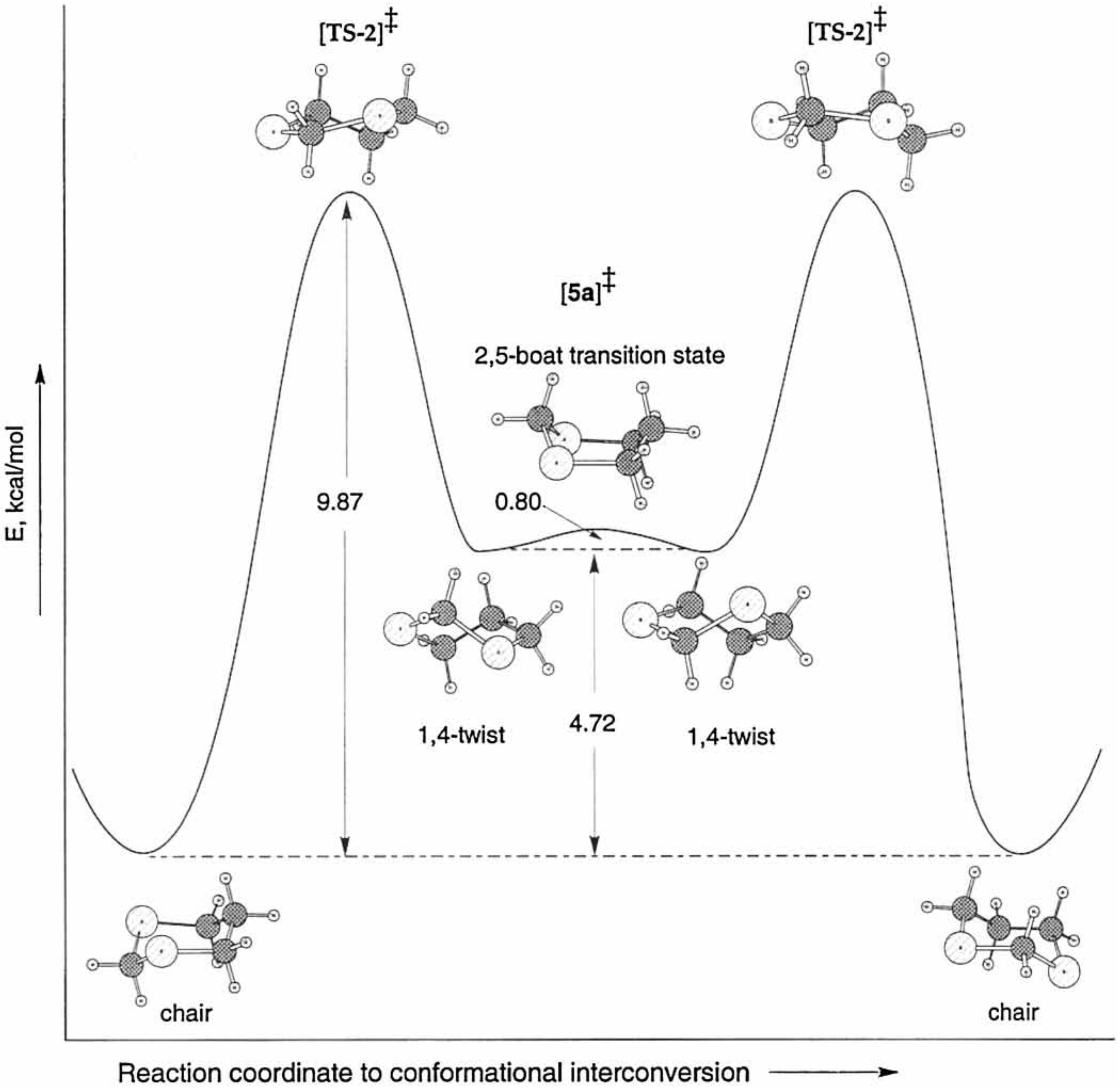


Figure 8. Potential energy diagram for the chair−chair interconversion of 1,3-dithiane (**3**) through [TS-2]‡, the 1,4-twist conformer (**4b**), and the 2,5-boat transition state [**5a**]‡.

from substituted 1,3-dithianes,[9,33−35] and smaller than that estimated value of 5.7 kcal/mol for 1,3-dioxane (**2**) from substituted 1,3-dioxanes.[9,16,28,97−100] The HF/6-31G(d) chair−twist free energy difference (ΔG°_{c-t}) between the chair (**3**) and the 1,4-twist (**4b**) conformers was 4.46 kcal/mol. The longer C−S bonds and the smaller torsional (Pitzer) potential are contributing factors to the smaller estimated experimental ΔG°_{c-t} values for 1,3-dithiane (**3**) from substituted 1,3-dithianes.[9,28]

The C−Hψeq bond lengths are longer than the corresponding C−Hψax bond lengths at C2 and C5 in the 2,5-boat transition state [**5a**]‡, and the C−Hψeq bond lengths are longer than the corresponding C−Hψax bond lengths at C4 and C5 in the 1,4-boat transition state [**5b**]‡. The C5−C6 bond is elongated in the 1,4-boat transition state [**5b**]‡. The respective geometries of the 2,5-boat boat [**5a**]‡ and 1,4-boat [**5b**]‡ transition states were essentially unchanged after attempted IRC calculations at the HF/6-31G(d), HF/6-31+G(d), and HF/6-31+G(d,p) levels of theory. However, IRC calculations at the B3LYP/6-311+G(d,p) level of theory connected the enantiomers of the 1,4-twist conformer through the 2,5-boat boat [**5a**]‡ transition state ($E = -953.710999$ kcal/mol, Figure 8). Although it was not verified by the IRC calculations but based on analogy with cyclohexane conformations, it is reasonable to expect that a structure resembling [**5b**]‡ will be the transition state for the interconversion between the 2,5-twist conformer (**4a**) and its enantiomer. Although it is qualitative, the animated displacements (normal coordinates) at -77 cm^{-1} for [**5b**]‡ suggest that it is the barrier to the interconversion of the enantiomers of the 2,5-twist conformer (**4a**).[101,102] The HF/6-31G(d) energy difference (ΔE) between the chair conformer and the 1,4-boat transition state [**5b**]‡ was 5.53 kcal/mol, and the B3LYP/6-311+G(d,p) energy difference between the chair conformer and the 2,5-boat transition state [**5a**]‡ was 5.42 kcal/mol (Table 4).

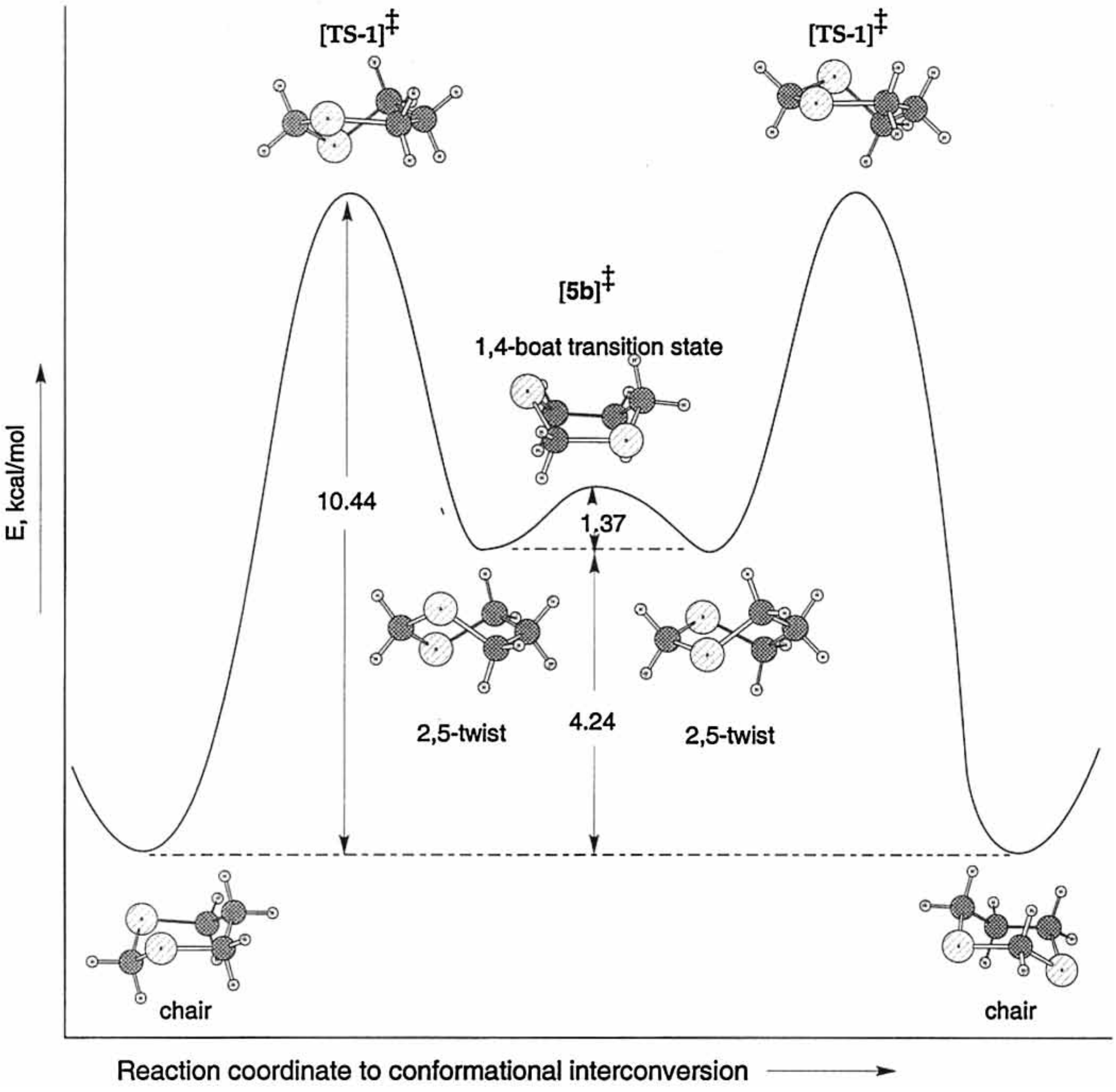


Figure 9. Potential energy diagram of a higher energy path for the chair−chair interconversion of 1,3-dithiane (**3**) through [TS-1]‡, the 2,5-twist conformer (**4a**), and the 1,4-boat transition state [**5b**]‡.

It has been estimated that the boat structure of cyclohexane is about 5.7−7.7 kcal/mol in energy above the chair conformer. [9]

IRC calculations on transition state [**TS-1**]‡ at the HF/6-31G(d), HF/6-31G(d,p), HF/6-31+G(d), and B3LYP/6-31G(d) levels of theory connected the chair (**3**) and 2,5-twist (**4a**) conformers. IRC calculations on transition state [**TS-2**]‡ at the HF/6-31G(d), HF/6-31G(d,p), 6-31+G(d), and B3LYP/6-31G(d) levels of theory connected the chair (**3**) and 1,4-twist (**4b**) conformers of 1,3-dithiane. Thus, transition state [**TS-2**]‡ is the barrier between the chair conformer (**3**) and the 1,4-twist conformer (**4b**). These data are consistent with a mechanism for the chair−chair interconversion that involves a fluxional transition state with a geometry close to those of the half chair and sofa structures. The C5−Hψeq bond lengths are longer than the C5−Hψax bond lengths in transition state [**TS-1**]‡ and transition state [**TS-2**]‡.

Single point energies and geometry optimized energies for **3**, [**TS-1**]‡, and [**TS-2**]‡are given in Table 7. The HF/6-31G(d) energy difference (Δ*E*) between the chair conformer **3** and the [**TS-1**]‡ is 10.44 kcal/mol, and between the chair conformer **3** and the [**TS-2**]‡, it is 9.87 kcal/mol. The energy difference (Δ*E*) between the chair and the half-chair structure of cyclohexane is 10.7−11.5 kcal/mol.[9] The HF/6-31G(d) calculated Δ*G*‡ values for **3** and [**TS-1**]‡ and for **3** and [**TS-2**]‡ were 10.17 and 9.51 kcal/mol, respectively. The conformational interconversion follows the lower energy pathway, and the Δ*G*‡ values are within 2 kcal/mol at all of the levels of theory and are in good agreement with the experimental value of Δ*G*‡ (10.4 ± 0.2 kcal/mol).[30] The differences in the calculated Δ*G*‡ values could reflect differences in the optimized geometries at various levels as much as differences in the levels of theory. The experimental

TABLE 7: Thermodynamic Parameters Relative to the Chair Conformer (3) for Transition State [TS-1]‡ and Transition State [TS-2]‡

computational level	total energy	ΔE	$\Delta H^‡$	$\Delta G^‡$
	[**TS-1**]‡			
HF/6-31G(d)	−951.133579	10.44	10.18	10.17
MP2/6-31G(d)//HF/6-31G(d)	−951.899013	11.38	11.11	11.11
HF/6-31G(d,p)	−951.145979	10.47	10.21	10.20
MP2/6-31G(d,p)//HF/6-31G(d,p)	−951.964261	11.36	11.10	11.10
HF/6-31+G(d)	−951.135916	10.57	10.31	10.30
MP2/6-31+G(d)//HF/6-31+G(d)	−951.909472	11.54	11.27	11.26
B3LYP/6-31G(d)//HF/6-31G(d)	−953.604183	9.97	9.71	9.70
B3P86/6-31G(d)//HF/6-31G(d)	−954.800071	10.38	10.12	10.11
B3PW91/6-31G(d)//HF/6-31G(d)	−953.452606	10.26	10.00	9.99
	[**TS-2**]‡			
HF/6-31G(d)	−951.134487	9.87	9.49	9.51
MP2/6-31G(d)//HF/6-31G(d)	−951.899059	11.35	10.97	10.99
HF/6-31G(d,p)	−951.146921	9.88	9.50	9.52
MP2/6-31G(d,p)//HF/6-31G(d,p)	−951.964379	11.29	10.91	10.93
HF/6-31+G(d)	−951.136706	10.08	9.70	9.72
MP2/6-31+G(d)//HF/6-31+G(d)	−951.909109	11.75	11.37	11.38
B3LYP/6-31G(d)//HF/6-31G(d)	−953.605038	9.44	9.06	9.08
B3P86/6-31G(d)//HF/6-31G(d)	−954.800674	10.00	9.62	9.64
B3PW91/6-31G(d)//HF/6-31G(d)	−953.453204	9.89	9.50	9.52

$\Delta G^‡$ values for 1,3-dioxane (**2**) and 1,3-oxathiane were 9.9 ± 0.2 and 9.3 ± 0.3 kcal/mol, respectively. [30]

Conclusions

Ab initio molecular orbital theory and DFT have been used to calculate the optimized geometries and relative energies of the chair, 1,4-twist, and 2,5-twist conformers of 1,3-dithiane. The C2−Hax, C4−Hax, and C6−Hax bond lengths are longer than the corresponding C−Heq bond lengths in the chair conformer (**3**) of 1,3-dithiane ($\mathrm{LP_S} \rightarrow \sigma^*_{\mathrm{C-Hax}}$, $\sigma_{\mathrm{C-Hax}} \rightarrow \sigma^*_{\mathrm{C-Hax}}$). In contrast, the C5−Heq bond is longer than the C5−Hax bond ($\sigma_{\mathrm{S-C}} \rightarrow \sigma^*_{\mathrm{C5-Heq}}$, W effect, or homoanomeric $\mathrm{LP_S} \rightarrow \sigma^*_{\mathrm{C5-Heq}}$). The importance of geometrical considerations in stereoelectronic hyperconjugative interactions is shown in the chair and twist conformers of 1,3-dithiane. Unlike the chair conformer, in the 2,5-twist conformer, all C−H bond lengths at a carbon atom are equal and in the 1,4-twist conformer all C−H bond lengths are equal except the C5−Heq bond, which is longer than the C5−Hax bond ($\sigma_{\mathrm{S-C}}$ ($\sigma^*_{\mathrm{C5-Heq}}$, W effect, or homoanomeric LPS ($\sigma^*_{\mathrm{C5-Heq}}$). In the 2,5-twist conformer, the C2−Hiso bond lengths are shorter than the C5−Hiso bond lengths.

The B3LYP/6-311+G(d,p) energy difference (ΔE) between the chair conformer (**3**) and the 2,5-boat transition state [**5a**]‡ was 5.42 kcal/mol, and the HF/6-31G(d) energy difference (ΔE) between the chair conformer (**3**) and the 1,4-boat transition state [**5b**]‡ was 5.61 kcal/mol. The B3LYP/6-311+G(d,p) energy difference (ΔE) between the 1,4-twist conformer (**4b**) and the 2,5-boat transition state [**5a**]‡ was 0.80 kcal/mol. The HF/6-31G(d) energy difference (ΔE) between the chair conformer and the 2,5-twist conformer was 4.24 kcal/mol and the 2,5-twist conformer was 0.48 kcal/mol more stable than the 1,4-twist conformer. The chair−2,5-twist free energy difference $\Delta G^{\circ}_{\mathrm{c-t}}$ for 1,3-dithiane was 4.27 kcal/mol and the chair−1,4-twist $\Delta G^{\circ}_{\mathrm{c-t}}$ was 4.46 kcal/mol.

IRC calculations connected the chair and 2,5-twist conformers via transition state [**TS-1**]‡and connected the chair and 1,4-twist conformers via transition state [**TS-2**]‡. The HF/6-31G(d) energy difference (ΔE) between the chair conformer (**3**) and the transition state [**TS-1**]‡ was 10.44 kcal/mol, and between the chair conformer (**3**) and the transition state [**TS-2**]‡, it was 9.87 kcal/mol. The HF calculated $\Delta G^‡$ between the chair conformer (**3**) and the transition state [**TS-2**]‡ was slightly lower but in good agreement with the experimental value ($\Delta G^‡ = 10.4 \pm 0.2$ kcal/mol).[30] These data suggest that the chair-to-chair interconversion of 1,3-dithiane involves a fluxional transition state with a geometry close to those of its half-chair and sofa structures.

Supporting Information Available: Cartesian coordinates of all reported minima and transition states, additional geometrical parameters for the chair and twist conformers, nonbonded distances in the chair and twist conformers, DFT thermochemical data for the chair and twist conformers, and the total energies for the chair and twist conformers. This material is available free of charge via the Internet at http://pubs.acs.org.

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