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Gauche/Trans Equilibria of 2,2′-Bi-1,3-dioxanyl, 2,2′-Dimethyl-2,2′-bi-1,3-dioxanyl, 2,2′-Bi-1,3-dithianyl, and 2,2′-Dimethyl-2,2′-bi-1,3-dithianyl in Different Media. Theory and Experiment

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The gauche/trans conformational equilibria of 2,2′-bi-1,3-dioxanyl (**1**), 2,2′-dimethyl-2,2′-bi-1,3-dioxanyl (**2**), 2,2′-bi-1,3-dithianyl (**3**), and 2,2′-dimethyl-2,2′-bi-1,3-dithianyl (**4)** dissolved in carbon tetrachloride and benzene are studied through dipole moment determination. Analyses of the relative permittivity data show that the dioxa system favors the trans form at 25 °C. Replacement of the oxygen atoms in **1** with sulfur completely reverses the gauche/trans equilibrium in carbon tetrachloride such that **3** exists predominantly in the gauche form. However, **4** exists mainly in the trans conformation in carbon tetrachloride solution and both **3** and **4** favor the trans form in benzene. X-ray crystallographic determination revealed that **1**−**4** favored the trans conformation in the solid state. Ab initio and DFT calculations were performed to examine the structural features of **1**−**4** and study the effects of solvent on these molecules. The calculated gauche/trans equilibria of **3** in different media are in excellent accord with the experimental findings. The observed difference in conformational preference of **3** in CCl_4 and benzene can be explained in terms of the specific solvation effect of benzene. CH···X (X = O or S) are important to understand the structures and relative energies of these 1,3-diheteroane systems.

Introduction

Molecular conformational equilibrium is a central concept in the structural chemistry of many biological and chemical systems. This equilibrium is affected by environmental conditions such as temperature, pressure, and solvents, and systematic studies of these effects are therefore required to better understand the influence of intermolecular interactions on molecular structures and their properties. The conformational equilibria of small molecules are of particular interest as they serve as prototypes for more complex systems, and the results obtained from these studies may be used as benchmarks for testing theoretical approximations.[1−3]

In recent years, much attention has also been paid to the interactions involving CH groups and electronegative atoms X.[4,5] These interactions have been found to contribute an important role in the stabilization of particular conformations of isolated single molecules.[6,7] To elucidate the effect of solvents on CH···X interactions, we have studied the conformations of 2,2′-bi-1,3-dioxolanyl, 2,2′-dimethyl-2,2′-bi-1,3-dioxolanyl, 2,2′-1,3-dithiolanyl, and 2,2′-dimethyl-2,2′-1,3-dithiolanyl[8] by dipole moment determination, X-ray crystallography, and density functional calculations. In these studies, we have shown that these compounds, except 2,2′-1,3-dithiolanyl, prefer the gauche conformer in the gas phase due to favorable CH···X (X = O, S) interactions. However, a solvent reaction field has a larger stabilization effect on the less polar trans form such that the gauche/trans equilibrium is reversed on going from the gas phase to a polar dielectric medium. To gain further insight to the implications of solvent on CH···X interactions, we have investigated, in this work, the conformations of 2,2′-bi-1,3-dioxanyl (**1**), 2,2′-dimethyl-2,2′-bi-1,3-dioxanyl (**2**), 2,2′-bi-1,3-dithianyl (**3**), and 2,2′-dimethyl-2,2′-bi-1,3-dithianyl (**4)** (Figure 1) by dipole moment determination, X-ray crystallography and density functional calculations.

Experimental Procedure

Compounds **1**−**4** were prepared by the acid-catalyzed condensation of α-diketone with 1,3-dipropandiol or 1,3-propanedithiol.[9,10]

Dipole Moment Determination. The dipole moment data for compounds **1**−**4** are shown in Table 1. Benzene and carbon tetrachloride were carefully distilled and dried before use. Three concentration dependencies, namely, those of the relative permittivities, densities, and refractive indices ($\alpha\epsilon_1$, βd_1, and γd_1^2), were determined for each solvent at three temperatures. The sample temperature was controlled within ±0.5 °C by circulating thermostated water around the dielectric cell. Relative permittivity was measured with a heterodyne-beat meter,[11] and densities and refractive indices were measured by standard procedures.[12] The physical constants required for the relative permittivity have been given previously.[13,14] Using the least-squares method, the experimental values of the slope $\alpha\epsilon_1$, βd_1, and γd_1^2 (given by eq 1) at infinite dilutions of the compounds

$$\alpha\epsilon_1 = \left(\frac{\delta\Delta\epsilon}{\delta w_2}\right)_{w_2\to 0} \qquad \beta d_1 = \left(\frac{\delta\Delta d}{\delta w_2}\right)_{w_2\to 0}$$

$$\gamma n_1^{\,2} = \left(\frac{\delta\Delta n^2}{\delta w_2}\right)_{w_2\to 0} \qquad (1)$$

(w_2 denoting the solute weight fraction) and the respective molar polarization, refraction and dipole moments were calculated.

By measuring the dielectric effects in extremely dilute solutions of the compounds, we may interpret our system as

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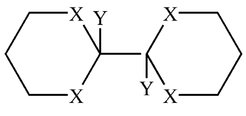
TABLE 1: Molar Polarization, Refractions and Dipole Moments at Infinite Dilution of Compounds 1−4

T/°C	solvent	concn range ($10^5 w_2$)	$\alpha\epsilon_1$	β	γ	P_2/cm^3	R_D/cm^3	μ^a/D
		a. 2,2′-Bi-1,3-dioxanyl (**1**) (R_D = 42.3 cm^3)						
7	CCl$_4$	131−412	3.45	−0.174		98.9		1.58 ± 0.01
25	CCl$_4$	297−652	3.26	−0.219	0.137	99.0	42.6	1.63 ± 0.02
45	CCl$_4$	208−365	3.18	−0.194		99.5		1.70 ± 0.01
7	benzene	270−591	1.54	0.256		92.6		1.49 ± 0.02
25	benzene	254−466	1.74	0.364	0.066	94.7	41.9	1.57 ± 0.01
45	benzene	313−554	1.82	0.390		98.6		1.68 ± 0.02
		b. 2,2′-Dimethyl-2,2′-bi-1,3-dioxanyl (**2**) (R_D = 50.9 cm^3)						
7	CCl$_4$	229−553	2.18	−0.339		94.3		1.37 ± 0.01
25	CCl$_4$	260−618	1.92	−0.459	−0.003	95.2	51.5	1.43 ± 0.01
45	CCl$_4$	204−490	1.94	−0.427		96.5		1.50 ± 0.02
7	benzene	134−357	1.94	0.338		116.4		1.70 ± 0.01
25	benzene	120−370	1.88	0.235	0.026	124.2	52.1	1.86 ± 0.01
45	benzene	120−380	2.51	0.601		127.3		1.96 ± 0.02
		c. 2,2’-Bi-1,3-dithianyl (**3**) (R_D = 66.8 cm^3)						
7	CCl$_4$	122−188	6.06	−0.331		206.2		2.50 ± 0.01
25	CCl$_4$	136−181	5.62	−0.219	0.165	195.1	67.9	2.47 ± 0.01
45	CCl$_4$	107−172	4.86	−0.215		181.5		2.41 ± 0.02
7	benzene	122−200	3.23	0.396		188.3		2.33 ± 0.01
25	benzene	129−200	3.27	0.400	0.106	195.3	66.7	2.47 ± 0.01
45	benzene	88−199	3.25	0.438		197.7		2.58 ± 0.02
		d. 2,2′-Dimethyl-2,2′-bi-1,3-dithianyl (**4**) (R_D = 50.9 cm^3)						
7	CCl$_4$	36−50	3.77	−1.117		205.4		2.40 ± 0.02
25	CCl$_4$	17−37	4.23	−0.827	−0.120	208.6	75.3	2.51 ± 0.01
45	CCl$_4$	22−41	4.44	−0.813		219.7		2.65 ± 0.01
7	benzene	70−90	3.15	0.277		217.4		2.51 ± 0.02
25	benzene	43−237	3.03	0.198	0.034	224.7	75.0	2.66 ± 0.01
45	benzene	64−237	3.31	0.367		231.1		2.81 ± 0.02

[a] $P_D = 1.05R_D$. 1D = 3.337×10^{-30} C m.

TABLE 2: Crystallographic Data

compound	1	2	3	4
fw	174.19	202.24	238.43	266.48
wavelength (Å)		0.71073 (Mo Kα)		
cryst syst	orthorhombic	monoclinic	monoclinic	monoclinic
space group	*Pbca*	*P*2(1)/*c*	*P*2(1)/*n*	*P*2(1)/*c*
unit cell dimens				
a (Å)	8.4490(8)	6.1203(5)	4.7989(8)	10.1273(6)
b (Å)	9.7189(9)	7.5931(6)	9.0110(15)	11.6016(7)
c (Å)	10.5415(10)	11.3089(9)	12.772(2)	10.6862(7)
β (deg)	90	103.780(2)	90.490(4)	94.2600(10)
vol (Å^3)	865.62(14)	510.42(7)	552.30(16)	1252.08(13)
Z, calcd dens (g cm^{-3})	4, 1.377	2, 1.316	2, 1.434	4, 1.414
μ (mm^{-1})	0.107	0.100	0.807	0.720
F(000)	376	220	252	568
no. of reflns collected/unique	5622/1043	4141/1477	4500/1612	10304/3643
refinement method		full-matrix least-squares on F^2		
no. of params	56	64	56	129
goodness-of-fit on F^2	1.106	1.070	0.991	0.984
R_1, $wR2$ (all data)	0.0502, 0.1386	0.0529, 0.1422	0.0512, 0.1157	0.0532, 0.0961



1 X = O, Y = H
2 X = O, Y = CH_3
3 X = S, Y = H
4 X = S, Y = CH_3

Figure 1. Structures of **1**−**4**.

consisting of isolated molecules immersed in a well-defined environment. The dipole moments were determined using the method of LeFevre and Vines.[12,15]

Crystallography. Single crystals of **1**−**4** were obtained from hexane solutions. A Siemens SMART CCD system cooled to 223 K in a stream of cold N_2 gas was used for the data collection. Data were collected using three ω-scans on each crystal over a 180° range at a fixed φ value of 54.74° with a 0.30° scan width and 5 s count time per frame and a crystal-to-detector distance of 5.04 cm. Data were corrected for Lorentz and polarization effects with the SMART suite of programs,[16] and for the absorption effects with SADABS.[17] Structural solution and refinement were carried out with the SHELXTL programs.[18] Further crystallographic data and details of the structure determination for the compounds are given in Table 2

Results and Discussion

Dipole Moment Determination. *A. 2,2′-Bi-1,3-dioxanyl (**1**).* Analysis of the data in Table 1 shows that the dipole moment of this compound increases with increasing temperature in both carbon tetrachloride and benzene solutions, indicating that the trans conformer is more stable than the gauche and is higher in population in these solvents. To analyze the dipole moment data more fully, it is necessary to estimate the dipole moment of the gauche conformer. One approach is to use the Lennard-Jones−Pike method of analysis.[19] Application of this analysis to our dipole moment data in carbon tetrachloride yields a ΔG (G_g −

G_t) value of 4.44 kJ mol^{-1} and a gauche conformer dipole moment (μ_g) of 3.25 D.

Crystal structure analysis of **1** show that the molecule exists in the trans configuration with a H−C−C−H torsion angle of 180°. Hence, assuming that the trans conformer dipole moment $\mu_t = 0$ and μ_g is independent of temperature, an estimate of the gauche-conformer population (x%) in solution can be made from eq 2, which on substituting the observed moment and μ_g values yield a population of 25% gauche and 75% trans at 25 °C.

$$x = \frac{100{\mu_{obs}}^2}{{\mu_g}^2} \qquad (2)$$

The Lennard-Jones−Pike analysis of the dipole moment data in benzene gives a ΔG value of 5.31 kJ mol^{-1} and μ_g of 3.62 D. From eq 2, the composition of gauche form in benzene solution was found to be 19% at 25 °C. These values in benzene compare well with the results obtained from carbon tetrachloride solution, which indicate that, unlike 2,2′-bi-1,3-dioxolanyl,[8] there is minimal conformational change in the molecule on passing into different solutions.

*B. 2,2′-Dimethyl-2,2′-bi-1,3-dioxanyl (**2**).* Table 1 shows that the dipole moments obtained in both carbon tetrachloride and benzene solutions increase with increasing temperatures, indicating that, like in **1**, the trans conformer is more stable than the gauche and is higher in population in these solvents. Application of the Lennard-Jones−Pike analysis[19] to our dipole moment data yields ΔG values of 4.53 and 5.00 kJ mol^{-1} in carbon tetrachloride and benzene, respectively. The μ_g and percentage of gauche population at 25 °C were found to be 2.89 D and 24% in carbon tetrachloride and 4.08 D and 21% in benzene.

*C. 2,2′-Bi-1,3-dithianyl (**3**).* The large dipole moments in carbon tetrachloride indicate that the polar gauche conformer must be present in high proportion in this solvent. From Table 1, it can also be seen that the dipole moment of the compound decreases with increasing temperature in carbon tetrachloride solution, indicating that the gauche conformer is more stable than the trans and is higher in population.

Application of the Lennard-Jones−Pike analysis to our dipole moment data yields ΔG value of −5.26 kJ mol^{-1} and μ_g of 2.74 D. From eq 2, the percentage gauche population at 25 °C was found to be 81%. These results contrast with those for 2,2′-diphenyl-2,2′-bi-1,3-dithianyl,[8] **1**, **2**, and **4**, which favor the trans conformer when the compounds are in carbon tetrachloride. Because **3** exists in the trans conformation in the solid state (as shown by our X-ray data), the preference for the gauche conformer in carbon tetrachloride may plausibly be attributed to the greater solvent stabilization of the polar conformer in **3** so as to reverse the gauche/trans equilibrium.

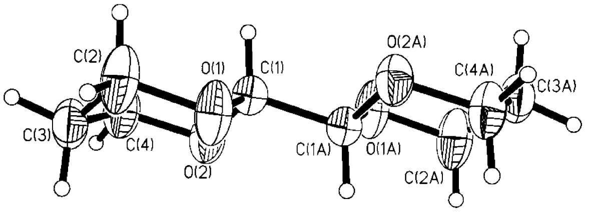


Figure 2. Thermal ellipsoid diagram of **1**.

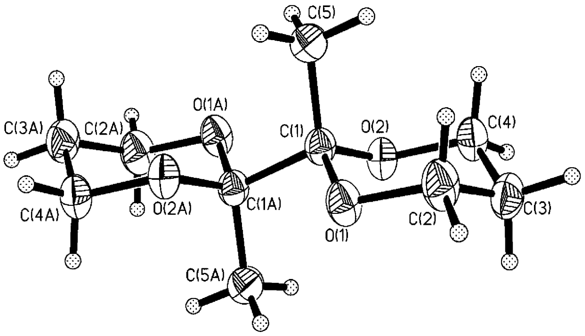


Figure 3. Thermal ellipsoid diagram of **2**.

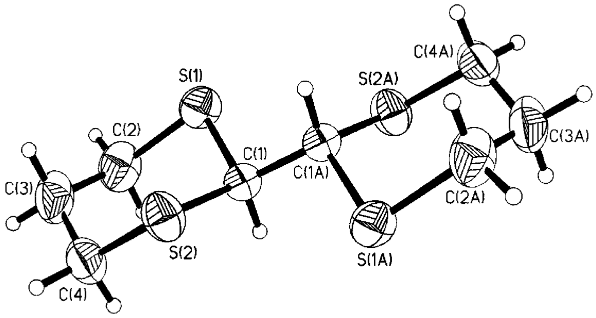


Figure 4. Thermal ellipsoid diagram of **3**.

The experimental data for benzene solutions, however, show that the dipole moment results are in the reverse trend from those for carbon tetrachloride solutions. The μ_g obtained is 5.17 D, which is 2.43 D higher that that found in carbon tetrachloride. From the Lennard-Jones−Pike analysis, ΔG is found to be 4.76 kJ mol^{-1}. This corresponds to a composition of 23% gauche and 77% trans at 25 °C. It appears that, unlike **1**, interactions between **3** and the benzene solvent molecules cause an appreciable extent of configurational change in the molecule. This may be partly attributed to the large dithiane rings (C−S ~1.8 Å) as compared to the dioxane rings (C−O ~1.4 Å) and the greater conformational mobility of **3**. Earlier studies of 2-substituted 1,3-dioxanes and 1,3-dithianes have shown that the dioxa and dithia rings may exist in either the chair or twist form,[20] with the chair-twist interconversion of 1,3-dioxane and 1,3-dithiane being 33−36 and 16.7 kJ mol^{-1}, respectively (the chair-twist interconversion in cyclohexane is 25.2 kJ mol^{-1}). Changes in torsion angles may therefore occur (a) with respect to the conformation of the ring or the position of the ring being pseudoaxial or pseudoequatorial and (b) with respect to the rotation about the exo C−C bond, being trans or gauche, thus resulting in the changes in the dipole moment and population of the gauche conformer. On the other hand, because the dielectric constants of carbon tetrachloride and benzene are similar in value, the large trans population in benzene is also indicative of possible interactions between **3** and the benzene solvent molecules. This solute−benzene interaction phenomenon is consistent with compounds **1**, **2**, and **4**, which show higher percentages of the trans conformer in benzene than in carbon tetrachloride solutions.

*D. 2,2′-Dimethyl-2,2′-bi-1,3-dithianyl (**4**).* Table 1 shows the dipole moment of the compound increases with increasing temperatures in both carbon tetrachloride and benzene solutions, indicating that, unlike **3**, the trans conformer is more stable than the gauche and is higher in population in these solvents. Analysis of our dipole moment data according to the Lennard-Jones−Pike analysis gives values of ΔG, μ_g, and percentage gauche conformer at 25 °C as 4.81 and 5.26 kJ mol^{-1}, 5.33 and 5.96 D, and 22% and 20% for carbon tetrachloride and benzene, respectively.

Solid-State Structure. Figures 2−5 depict the structures and define the atomic numbering of **1**−**4**, respectively. In **4**, each asymmetric unit of the cell contains two independent molecules in general position. The independent molecules are essentially

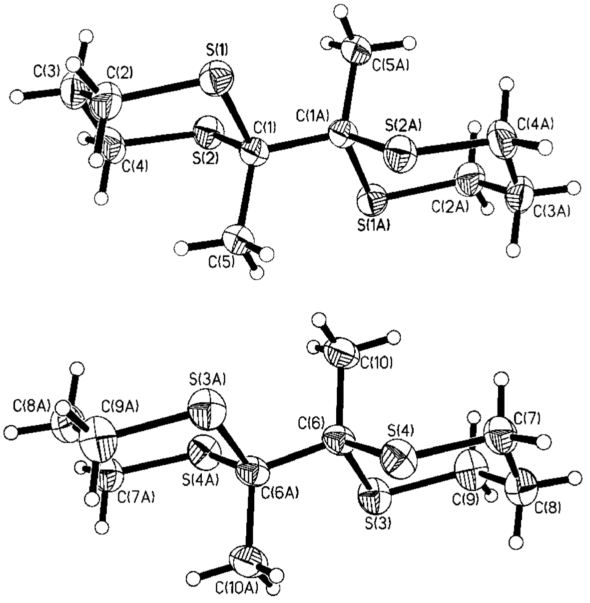
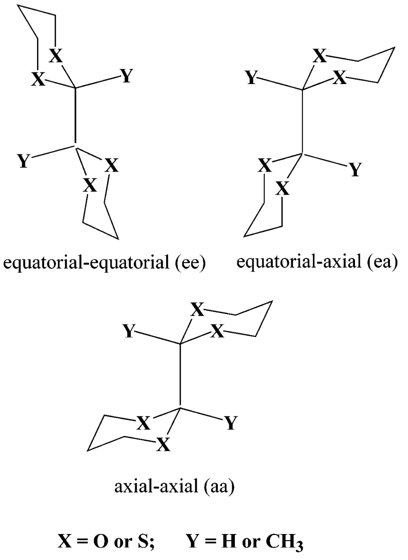


Figure 5. Thermal ellipsoid diagram of **4**.



equatorial-equatorial (ee) equatorial-axial (ea)

axial-axial (aa)

Figure 6. Possible trans conformers.

identical structures with equivalent bond lengths and bond angles differing by approximately 0.02 Å and 1°, respectively.

X-ray crystal structure analyses of **1**−**4** show that all four molecules exist in the trans conformation with the dioxane and dithiane rings adopting the chair form. Assuming that the chair form is the favored ring geometry, the exo (C(1)−C(1A)) bond may be placed at the equatorial (e) or axial (a) position of the dioxane/dithiane ring. Ring inversion leads to three possible combinations of the rings: ee, ea, and aa (Figure 6). The resulting solid-state structures of **1**−**4** show that only the trans-ee conformation is realized.

Theoretical Calculations. Standard ab initio and density functional calculations were carried out using the GAUSSIAN 98 series of programs.[21] Geometry optimizations were performed at the B3LYP[22] level using the split-valence polarized 6-31G* basis set. Higher level relative energies were computed at the B3LYP/6-311+G(2d,p) level based on the B3LYP/6-31G* optimized geometries and include the zero-point energy (ZPE) correction (B3LYP/6-31G* value, scaled by a factor of 0.9804).[23] For the smaller systems (**1** and **3**), their gas-phase gauche/trans equilibria were also examined at the G3(MP2) theory.[24] In the present study, we have employed the Onsager's self-consistent reaction field (SCRF) theory[25] and the self-consistent isodensity surface polarized continuum model (SCIPCM)[26] to examine the solute−solvent interaction. For the solvent calculations, geometry optimizations were performed using the SCRF method and the single-point energy calculations were carried out with the SCIPCM model. The free energy differences (ΔG) were computed from the equation $\Delta G_T = \Delta H_T - T\Delta S$, where ΔS is the entropy change and $\Delta H_T = \Delta H_0 + (H_T - H_0)$.

We shall first examine the gauche/trans equilibria of **1**−**4** in the gas phase. There are three possible arrangements of the two rings for both the trans and gauche rotamers, resulting in six possible conformations, namely trans-ee, trans-ea, trans-aa, gauche-ee, gauche-ea, and gauche-aa. The calculated relative

TABLE 3: Calculated Dipole Moments[a] (μ, D) and Relative Energies[b] (ΔE_0, ΔH_{298}, and ΔG_{298}, in kJ mol^{-1})

				ΔG_{298}[c]	
species	μ	ΔE_0	ΔH_{298}	$\epsilon = 1.0$	$\epsilon = 40.0$[d]
1					
trans-ee	0.00	0.0	0.0	0.0	0.0
trans-ea	3.36	17.3	17.4	14.2	11.0
trans-aa	0.00	34.1	31.7	37.5	38.4
gauche-ee	0.80	4.5	4.5	4.4	2.5
gauche-ea	3.14	16.0	15.9	15.0	19.0
gauche-aa	1.26	33.2	32.9	34.1	38.1
2[e]					
trans-ee	0.00	0.0	0.0	0.0	0.0
trans-ea	0.45	33.7	31.0	34.0	32.2
gauche-ee	0.06	10.0	10.0	9.6	9.0
gauche-ea	2.86	5.4	5.3	3.8	6.7
gauche-aa	2.21	17.2	17.0	18.1	23.6
3					
trans-ee	0.00	0.0	0.0	0.0	0.0
trans-ea	4.08	6.4	6.5	1.6	0.7
trans-aa	0.00	15.3	13.0	19.4	18.0
gauche-ee	2.01	0.9	0.8	0.7	−1.1
gauche-ea	3.13	7.6	7.1	7.4	9.9
gauche-aa	3.46	11.0	10.4	13.3	18.5
4					
trans-ee	0.00	0.0	0.0	0.0	0.0
trans-ea	3.22	8.3	8.2	6.0	5.2
trans-aa	0.00	15.3	14.9	15.5	15.2
gauche-ee	1.36	5.5	5.1	5.9	3.5
gauche-ea	2.85	8.2	7.8	6.7	9.0
gauche-aa	2.91	8.4	7.9	7.7	12.8

[a] B3LYP/6-31G* values. [b] Based on the B3LYP/6-311+G(2d,p)//B3-LYP/6-31G*+ZPE level. [c] $\Delta G_{298} = \Delta H_{298} - 298\Delta S$. [d] Based on SCIPCM//SCRF calculations. [e] The trans-aa conformation of **2** does not exist.

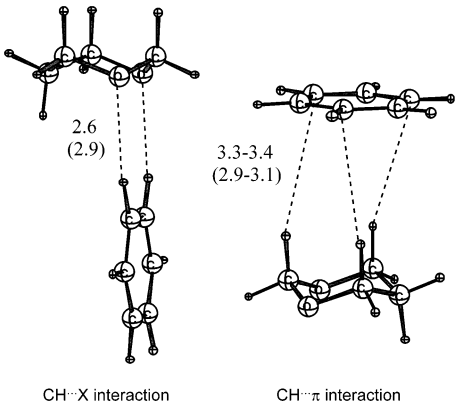
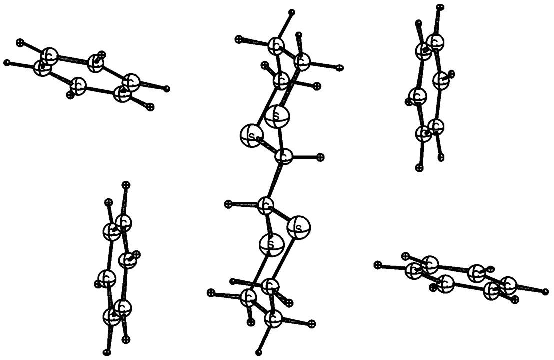
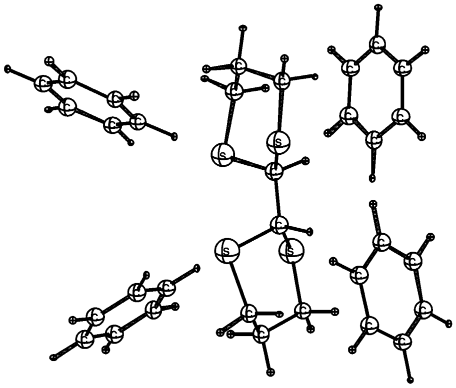


Figure 7. CH···X (X = O or S) and CH···π interactions in 1,3-dioxane− and 1,3-dithiane−benzene complexes. B3LYP/6-31G* bond distances are in ångstroms, with the dithiane (X = S) values in parentheses.



1:4 *trans*-ee-**3** benzene complex



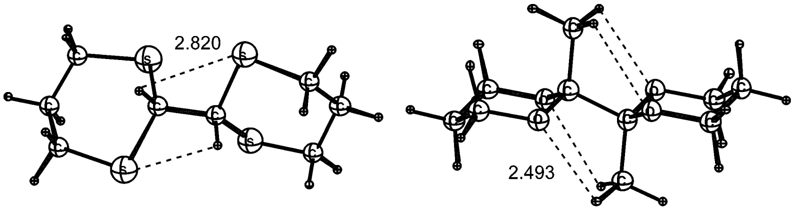
1:4 *gauche*-ee-**3** benzene complex

Figure 8. Optimized B3LYP/6-31G* geometries of the trans and gauche 1:4 **3**···benzene complexes.

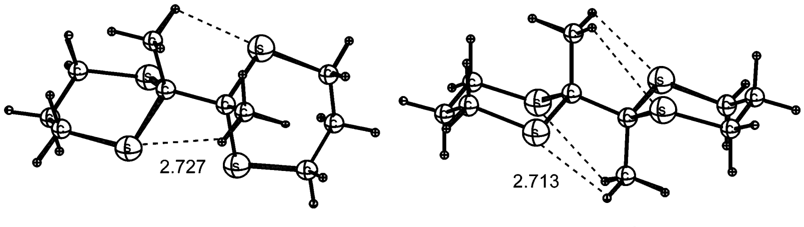
energies of the various conformers are summarized in Table 3. In agreement with the observed X-ray structures, the trans-ee conformation is the preferred conformation in all cases. Except for **2**, the gauche-ee form is the next most stable conformation. The gauche-ea conformation is 5.8 kJ mol^{-1} more stable than the gauche-ee form in **2**. For both the trans and gauche rotational forms, the aa arrangement is very unfavorable due to strong steric repulsion between the R (R = H or CH_3) group and the adjacent ring. In fact, the trans-aa form of **2** does not exist as a stable energy minimum on the B3LYP/6-31G* potential energy surface. It collapses to the gauche-aa form upon geometry optimization without symmetry constraint. In most cases, the ea arrangement lies close in energy to the corresponding ee configuration. Our computed gas-phase gauche/trans free energy differences for **1**−**4** are 4.4, 3.8, 0.7, and 5.9 kJ mol^{-1}, respectively. These calculated values are in good accord with the experimental measurements except for **3**. The gauche-ee rotamer of **3** lies very close in energy to the global minimum, trans-ee form. To assess the reliability of our DFT relative energies, higher-level calculations at the G3(MP2) level were also performed for the two smaller systems **1** and **3**. The calculated G3(MP2) gauche/trans free energy difference at 298 K (ΔG_{298}) are 4.8 and 0.3 kJ mol^{-1}, respectively, in excellent agreement with the B3LYP/6-311+G(2d,p)+ZPE results. This lends strong confidence to our reported DFT energies.

All trans-ee and trans-aa forms of **1**−**4** have a zero dipole moment, but a significant dipole moment is predicted for the other conformations (Table 3). Thus, we expect a solvent medium may influence their gauche/trans equilibria. To this end, we have examined the solvent effects of the rotational equilibria of **1**−**4** using the reaction field methods (SCRF and SCIPCM). In our recent study,[8] we showed that the quadrupole moments of bi-1,3-diheteroanes play a significant role in stabilizing the solute in a dielectric medium. In other words, it is not straightforward to predict the solvent effect based simply on the dipole moment alone. All the conformers examined in this study are calculated to have a large quadrupole moment. As a result, not all the polar conformers are calculated to have a stronger solvent stabilization than the corresponding trans-ee conformer, with a zero dipole moment. For instance, the trans-ee form having a larger solvent stabilization than the more polar gauche-aa form results in a larger energy difference in the presence of a dielectric medium of $\epsilon = 40$ (Table 3). For the gauche/trans energy difference, our SCIPCM calculations predict a small change of relative energy (~2 kJ mol^{-1}) on going from the gas phase to a polar dielectric medium of $\epsilon = 40$. Therefore, the trans-ee form is predicted to be the predominant form in the isolated state as well as in solution for **1**, **2**, and **4**. On the other hand, the differential solvation effect is sufficient to reverse the gauche/trans rotational equilibrium in **3**. Hence, the gauche-ee conformation is the preferred conformation of **3** in a polar medium, in excellent accord with the observed preference of gauche form in CCl_4.

In general, we do not expect a significant change in the gauche/trans equilibrium in both benzene and CCl_4 solutions. How do we account for the observed strong preference of the trans form of **3** in benzene solvent? Recent studies have shown



gauche-ee-**3** *trans*-ee-**2**



gauche-ee-**4** *trans*-ee-**4**

Figure 9. Optimized B3LYP/6-31G* geometries of the gauche-ee conformers of **3** and **4** and the trans-ee conformers of **2** and **4**. Bond distances are given in ångstroms.

that 1,3-dioxane and 1,3-dithiane can interact favorably with benzene in two possible modes: CH···X (X = O or S) and "cooperative" CH···π (i.e., multiple CH hydrogens interact with an aromatic system in a cooperative manner)[27] (Figure 7). Here, we have considered the benzene solvation of **3**. Both the trans-ee and gauche-ee forms can accommodate four benzene solvent molecules comfortably via these noncovalent interactions. As shown in the optimized geometries of the trans and gauche 1:4 **3**···benzene complexes (Figure 8), there are two CH···S interactions and two "cooperative" CH···π interactions in each case. Interestingly, the benzene molecules are oriented perpendicular to each other in the trans complex. It is well established that benzene dimer favors a perpendicular arrangement.[28] As a consequence, the trans conformer is calculated to have a larger binding energy than the corresponding gauche-ee form, by 5 kJ mol^{-1} (B3LYP/6-31G*). In other words, the trans conformer is better solvated by benzene solvent via specific solute−solvent interaction. This readily explains the preference of the trans-ee form of **3** in benzene solution. The importance of specific solvation effect in benzene is also reflected in the significant difference in the measured dipole moments of **3**, 2.74 D versus 5.17 D, in CCl_4 and benzene, respectively. Similar specific solvation effect of benzene is also calculated for the oxygen analogue **1**. However, the differential stabilization is calculated to be smaller (3 kJ mol^{-1}) and is insufficient to reverse the gauche/trans equilibrium. In summary, our calculations strongly support the experimental finding that the gauche/trans equilibrium in **3** depends on the nature of the medium and the polarity of the solvent.

In our previous study on bi-1,3-dioxolanyl and bi-1,3-dithiolanyl systems, we have shown that the noncovalent CH···X (X = O or S) interaction plays an important role in governing their rotational equilibria.[8] In these systems, the gauche form is stabilized by two favorable CH···X interactions between the X atom of one five-membered ring and the methylene hydrogen of the adjacent five-membered ring. For the 1,3-diheterones (**1**−**4**) examined in this paper, similar CH···X interactions between two six-membered rings can be found for all the ea and aa configurations of the gauche rotamer. However, the two rings are too far apart to allow the favorable CH···X interaction in the gauche-ee conformation. There are several other interesting structural features of the bi-1,3-dioxanyl and bi-1,3-dithianyl systems that warrant further discussion. For the gauche-aa conformers of **1**−**4**, the calculated torsional angle between the two central R groups (R = H or CH_3) are 69.6, 65.5, 64.3, and 54.9°, respectively. The substantially smaller torsional angle in **4** allows the methyl hydrogen to interact favorably with the sulfur atom of adjacent ring via the CH···S interaction (Figure 9). The CH···S distance in *gauche-ee-***4** is 2.727 Å, less than the sum of their van der Waal radii (3.05 Å). The smaller gauche/trans relative energy in **3** may also be rationalized in terms of the noncovalent CH···S interaction. Two favorable CH···S interactions between the central CH and the sulfur of adjacent ring can be located in the gauche-ee conformer (Figure 9), but not in the trans-ee form. It is important to note also that the CH···X (X = O or S) interaction can be found in the trans conformations. For instance, both the trans-ee conformations of **2** and **4** are stabilized by four CH···O and CH···S interactions, respectively, between the methyl hydrogen and the X atom of adjacent ring (Figure 9).

Finally, we note that there are low-lying conformations, particularly the ea configurations, for both the trans and gauche rotamers of **1**−**4** (Table 3). This suggests that other polar conformations may contribute to the observed dipole moments in addition to the most stable gauche form. In other words, the assumption that the observed dipole moment is due to one gauche conformation may not be always correct.

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Supporting Information Available: Crystallographic information files (CIF) for compounds **1**−**4**. This material is available free of charge via the Internet at http://pub.acs.org.

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