Gauche/trans equilibria of 2,2′-bi-1,3-dioxolanyl, 2,2′-dimethyl-2,2′-bi-1,3-dioxolanyl, 2,2′-bi-1,3-dithiolanyl and 2,2′-dimethyl-2,2′-bi-1,3-dithiolanyl in different media—theory and experiment†

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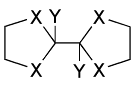
The dipole moments of 2,2′-bi-1,3-dioxolanyl (**1**), 2,2′-dimethyl-2,2′-bi-1,3-dioxolanyl (**2**), 2,2′-bi-1,3-dithiolanyl (**3**) and 2,2′-dimethyl-2,2′-bi-1,3-dithiolanyl (**4**) in carbon tetrachloride and benzene have been measured over a range of temperatures. Analysis of the relative permittivity data in carbon tetrachloride show that at 25 °C, **1**, **2** and **3** favour the *trans* form. However, replacement of the hydrogens on C-2 of the dithiolane ring with methyl groups completely reverses the *trans gauche* equilibrium such that **4** exists in 70% *gauche* conformation. In benzene, all four compounds were found to exist predominantly in the *trans* form. The experimentally derived values of the energy difference between the *gauche* and *trans* conformers and the *gauche/trans* population quotients were compared with values predicted by molecular orbital calculations. Theory predicts that **1**, **2** and **4** prefer a *gauche* conformer in the gas phase due to favourable CH···X (X = O and S) interactions. Surprisingly, we found that a solvent reaction field has a larger stabilization effect on the less polar *trans* form. For compounds **1** and **2**, the solvent effect is sufficiently large that the *gauche/trans* equilibrium is reversed on going from the gas phase to a polar dielectric medium. The crystal and molecular structures of **2** and **4** were determined by single-crystal X-ray diffraction methods. In the solid state, compound **2** exists in the *trans* conformation whilst **4** favours the *gauche* form.

The structures of monocyclic, 1,3-diheteroanes containing O or S atoms have been actively studied for many years as these compounds exhibit interesting and unusual conformational behaviour, which is not explained by steric and dipolar interactions alone, and compounds analogous to the parent system but bearing substituents have been shown to behave differently from their cycloalkane analogues.[1–5] In contrast, there has been a paucity of data concerned with the conformational preferences in bi-1,3-diheteroanes and relatively little is known about the conformational consequences of introducing a second 1,3-diheteroane moiety into the system.[6–10] To address this deficiency, we have initiated a systematic study of the conformational preference in various bi-1,3-diheteroanes. We now report our findings on 2,2′-bi-1,3-dioxolanyl (**1**), 2,2′-dimethyl-2,2′-bi-1,3-dioxolanyl (**2**), 2,2′-bi-1,3-dithiolanyl (**3**) and 2,2′-dimethyl-2,2′-bi-1,3-dithiolanyl (**4**), based on dipole moment determinations, X-ray diffraction measurements and molecular orbital calculations. High-level molecular orbital calculations were employed to study the *gauche/trans* equlibria of **1–4** in the gas phase and to examine the influence of solvent reaction field on their conformational equilibria.



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

Experiment and theory

Reagents for the syntheses were purchased from Aldrich and used without further purification. ^{1}H NMR spectra were recorded on a Bruker ACF300 spectrometer and the mass spectra were obtained on a Finnigan MAT 95XLT spectrometer. Elemental analyses were determined on a Perkin–Elmer PE 2400 CHNS elemental analyzer whilst melting points were measured using a Thomas Hoover capillary melting point apparatus and are uncorrected.

Preparation of compounds

Compounds 1–4 were synthesized by the acid-catalysed condensation of α-diketone (R–CO–CO–R where R = H or CH_3) with ethylene glycol[11] or 1,2-ethanedithiol.[12] Compound **1** had mp 112 °C. Found: C, 49.05; H, 6.92% M$^+$, 146. $C_6H_{10}O_4$ (MW 146) requires C, 49.32; H, 6.85%. δ_H (300 MHz; $CDCl_3$; Me_4Si) 4.8 (2H, s, O–C*H*–O) and 4.0 (8H, m, C*H*$_2$ C*H*$_2$). Compound **2** had mp 31 °C. Found: C, 55.50; H, 7.98%; M$^+$, 174. $C_8H_{14}O_4$ (MW 174) requires C, 55.17; H, 8.04%. δ_H (300 MHz; $CDCl_3$; Me_4Si) 3.97 (8H, m, C*H*$_2$ C*H*$_2$) and 1.36 (6H, s, C–C*H*$_3$). Compound **3** had mp 135 °C. Found: C, 34.15; H, 4.97; S, 60.88%; M$^+$, 210. $C_6H_{10}S_4$ (MW 210) requires C, 34.28; H, 4.76; S, 60.71%. δ_H (300 MHz; $CDCl_3$; Me_4Si) 4.74 (2H, s, S–C*H*–S) and 3.27 (8H, m, C*H*$_2$ C*H*$_2$). Compound **4** had mp 85 °C. Found: C, 40.47; H, 5.73; S, 53.61%; M$^+$, 238. $C_8H_{14}S_4$ (MW 238) requires C, 40.34; H, 5.89; S, 53.77%. δ_H (300 MHz; $CDCl_3$; Me_4Si) 3.42 (8H, m, C*H*$_2$ C*H*$_2$) and 2.05 (6H, s, C–C*H*$_3$).

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† Electronic supplementary information (ESI) available: tables of optimized MP2/6-31G* structural parameters for 1–4 and calculated atomic charges for **1** and **2**. See http://www.rsc.org/suppdata/nj/b2/b205139g/

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Dipole moment determination

Relative permittivities were determined with a heterodyne-beat meter[13] and densities and refractive indices by standard procedures.[14] All solvents were carefully distilled and dried before use. The physical constants required for the relative permittivity have been given previously.[15,16]

Crystal structure determination and refinement

Single crystals of **2** and **4** were obtained from hexane solutions. The crystals were attached to glass fibers using epoxy glue, mounted on a Siemens SMART CCD system with Mo-Kα radiation, and cooled to 223 K in a stream of cold N_2 gas. Data was collected using three ω-scans on each crystal over a 180° range at a fixed φ value of 54.74° with 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,[17] and for the absorption effects with SADABS.[18] Structural solution and refinement were carried out with the SHELXTL programs.[19] The structures were solved by direct methods followed by full-matrix least-squares refinements. All non-hydrogen atoms were refined anisotropically whereas hydrogen atoms were placed at calculated positions.

CCDC reference numbers 186624 and 186625. See http://www.rsc.org/suppdata/nj/b2/b205139g/ for crystallographic files in CIF or other electronic format.

Crystal data of 2. $C_8H_{14}O_4$, $M = 174.19$. Monoclinic, colourless rectangular prism, $a = 5.6870(9)$ Å, $b = 11.0509(17)$ Å, $c = 6.852(11)$ Å, $\beta = 102.624(3)°$, $V = 420.22(11)$ Å^3, space group $P2_1/n$, $Z = 2$ μ(Mo-Kα) = 0.110 mm^{-1}, 3404 reflections measured, 1219 unique ($R_{\text{int}} = 0.0647$), which were used in all calculations. The final R and R_w were 6.68% and 16.34% [for $I > 2\sigma(I)$].

Crystal data of 4. $C_8H_{14}S_4$, $M = 238.43$. Triclinic, colourless rectangular prism, $a = 6.486(6)$ Å, $b = 7.358(7)$ Å, $c = 12.386(12)$ Å, $\alpha = 101.20(2)°$, $\beta = 95.68(2)°$, $\gamma = 106.40(2)°$, $V = 548.8(9)$ Å^3, space group P-1, $Z = 2$, μ(Mo-Kα) = 0.812 mm^{-1}, 6540 reflections measured, 3032 unique ($R_{\text{int}} = 0.0551$), which were used in all calculations. The final R and R_w were 5.84% and 12.45% [for $I > 2\sigma(I)$].

Molecular orbital calculations

Standard *ab initio* and density functional calculations were carried out using the GAUSSIAN 98 series of programs.[20] The *gauche*/*trans* rotational equilibria of compounds **1–4** in the gas phase ($\varepsilon = 1$) were investigated at the G3(MP2) level of theory.[21] In brief, the G3(MP2) method is a composite procedure that aims at providing an accurate approximation to the high level of theory of QCISD(T)/GTMP2LARGE//MP2/6-31G*, with incorporation of the zero-point energy (calculated from HF/6-31G* vibrational frequencies, scaled by 0.8929) and higher-level corrections. This level of theory is usually within ±7 kJ mol^{-1} of accurate experimental values.[21] The *gauche*/*trans* 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 $\Delta H_T = \Delta H_0 + (H_T - H_0)$.

The effect of solute-solvent interactions was examined by two self-consistent reaction field (SCRF) methods: (1) Onsager's theory at the dipole level[22] and (2) self-consistent isodensity polarizable continuum model (SCIPCM).[23] In these continuum models, the solvent is represented by a continuous dielectric, characterized by a given dielectric constant (ε). The solute is assumed to occupy a spherical cavity of radius a_0 in the medium in Onsager's method, while the solute is taken to occupy a cavity that is determined self-consistently from an isodensity surface (0.0004 a.u.) in the SCIPCM method. For the solvent-effect calculations of **1–4**, geometry optimizations were performed at the B3LYP[24] level together with the split-valence polarized 6–31G* basis set using the dipole model. Higher-level relative energies were computed at the B3LYP/6-311+G(2d,p) level using the SCIPCM method, based on the SCRF(dipole)-B3LYP/6-31G* optimized geometries. Charge density analysis was performed using the natural bond orbital (NBO)[25] approach based on the MP2/6-31G* wavefunction.

Results and discussion

Dipole moment measurements

The results of the dipole moment measurements of **1–4** are presented in Table 1 with standard notation. Three concentration dependencies, namely those of the relative permittivities, densities and refractive indices ($\alpha\varepsilon_1$, βd_1 and $\gamma {n_1}^2$) were determined for each solvent at the three temperatures. Using the least squares method, the experimental values of the slopes $\alpha\varepsilon_1$, βd_1 and $\gamma {n_1}^2$ [given by eqn. (1)] at infinite dilutions of the compounds (w_2 denoting the solute weight fraction) and the respective molar polarization, refractions and dipole moments were calculated.

$$\alpha\varepsilon_1 = \left(\frac{\delta\Delta\varepsilon}{\delta w_2}\right)_{w_2\to 0} \qquad \beta d_1 = \left(\frac{\delta\Delta d}{\delta w_2}\right)_{w_2\to 0} \qquad \gamma n_1^2 = \left(\frac{\delta\Delta n^2}{\delta w_2}\right)_{w_2\to 0} \tag{1}$$

By measuring the dielectric effects in extremely dilute solutions of the compounds in non-polar solvents like carbon tetrachloride and benzene, we may interpret our present system as consisting of isolated molecules immersed in a well-defined environment. The dipole moments were determined using the method of LeFevre and Vine.[14,26]

2,2′-Bi-1,3-dioxolanyl (1). 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. Application of the Lennard-Jones–Pike method of analysis[27] to our dipole moment data in carbon tetrachloride yields a $\Delta E(= E_g - E_t)$ value of 5.154 kJ mol^{-1} and a *gauche* conformer dipole moment (μ_g) of 4.59 D.

Crystal structure analysis of **1** shows that the molecules exists in the *trans* configuration with an H–C–C–H torsion angle of 180°.[8] Hence, assuming that the *trans* conformer dipole moment $\mu_t = 0$ D (theory, however, predicts that the most stable *trans* form has a non-zero dipole moment) and μ_g is independent of temperature, an estimate of the *gauche* conformer population (x%) in solution can be made from eqn. (2), which on substituting the observed moment and μ_g values yields a population of 19% *gauche* and 81% *trans* at 25 °C.

$$x = \frac{100\mu_{\text{obs}}^2}{\mu_g^2} \tag{2}$$

The Lennard-Jones–Pike analysis of the dipole moment data in benzene gives a ΔE value of 7.85 kJ mol^{-1}. The dipole moment of the *gauche* conformer is, however, 6.65 D, which is 2.06 D higher than that found in carbon tetrachloride. It appears, therefore, that the intermolecular interactions between **1** and the benzene solvent molecules cause an appreciable extent of conformational change in the molecule. This could be ascribed to the greater conformational mobility of 1,3-dioxolane. Conformational analyses of this latter compound[28,29] have shown that the five-membered ring has a large number of

Table 1 Molar polarization, refractions and dipole moments at infinite dilution of 2,2′-bi-1,3-dioxolanyl (**1**) 2,2′-dimethyl-2,2′-bi-1,3-dioxolanyl (**2**) 2,2′-bi-1,3-dithiolanyl (**3**) and 2,2′-dimethyl-2,2′-bi-1,3-dithiolanyl (**4**)

T/°C	Solvent	Solute weight fraction[a] (10^5 w_2)	$\alpha\varepsilon_1$	β	γ	P_2/cm^3	R_D/cm^3	μ^b/D
(a) 2,2′-bi-1,3-dioxolanyl (**1**, $R_D = 32.33$ cm^3)								
7	CCl_4	230–440	5.59	−0.250		117.1		1.95 ± 0.01
25	CCl_4	155–490	5.42	−0.211	−0.082	116.4	27.95	2.01 ± 0.01
45	CCl_4	170–440	5.52	−0.230		122.3		2.15 ± 0.01
7	Benzene	230–785	2.34	0.292		97.0		1.70 ± 0.01
25	Benzene	245–850	2.90	0.306	−0.089	114.2	28.72	1.98 ± 0.01
45	Benzene	280–810	3.68	0.342		138.6		2.34 ± 0.02
(b) 2,2′-dimethyl-2,2′-bi-1,3-dioxolanyl (**2**, $R_D = 41.61$ cm^3)								
7	CCl_4	270–420	3.76	−0.301		108.4		1.72 ± 0.01
25	CCl_4	160–450	3.67	−0.285	0.067	108.7	41.71	1.78 ± 0.01
45	CCl_4	140–470	3.44	−0.286		107.4		1.82 ± 0.02
7	Benzene	342–855	2.06	−0.242		109.7		1.74 ± 0.01
25	Benzene	255–735	2.10	0.248	−0.051	113.5	40.60	1.85 ± 0.01
45	Benzene	250–735	2.12	0.260		116.6		1.95 ± 0.02
(c) 2,2′-bi-1,3-dithiolanyl (**3**, $R_D = 57.5$ cm^3)								
7	CCl_4	178–433	2.22	−0.096		89.7		1.16 ± 0.01
25	CCl_4	149–395	2.32	−0.068	0.183	92.9	55.71	1.26 ± 0.01
45	CCl_4	190–440	2.44	−0.018		96.3		1.37 ± 0.01
7	Benzene	270–626	1.19	0.438		85.5		1.08 ± 0.01
25	Benzene	297–656	1.13	0.374	0.107	89.8	54.15	1.20 ± 0.01
45	Benzene	192–664	1.17	0.364		94.2		1.33 ± 0.02
(d) 2,2′-dimethyl-2,2′-bi-1,3-dithiolanyl (**4**, $R_D = 66.8$ cm^3)								
7	CCl_4	300–650	2.26	−0.171		105.9		1.28 ± 0.01
25	CCl_4	70–329	1.95	−0.116	0.150	98.0	63.91	1.16 ± 0.01
45	CCl_4	217–409	1.59	−0.156		92.5		1.08 ± 0.01
7	Benzene	342–853	1.26	0.296		111.3		1.37 ± 0.01
25	Benzene	255–733	1.43	0.394	0.006	113.6	65.28	1.46 ± 0.01
45	Benzene	255–740	1.45	0.418		115.4		1.54 ± 0.01

[a] Solute weight fraction, 10^5 w_2 = weight of solute/weight of solvent. [b] $P_D = 1.05$ R_D; 1D = 3.337×10^{-30} cm.

minimum-energy conformations and the free energy differences between these diastereoisomers are small (0.2–1.2 kJ mol^{-1}). The torsion angles of the molecule may therefore change to a significant extent on passing into different solutions. In solution, a complicated mixture of forms under rapid equilibrium would also occur (*a*) with respect to the conformation of the 1,3-dioxolane moiety, and (*b*) with respect to the rotation about the *exo* C–C bond, being *trans* or *gauche*, thus resulting in changes in the dipole moment of the *gauche* conformer. From eqn. (2), the amount of *gauche* form in benzene solution was found to be 9% at 25 °C.

2,2′-Dimethyl-2,2′-bi-1,3-dioxolanyl (2). Analysis of the data in 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 method of analysis[27] to our dipole moment data yields ΔE values of 3.44 and 5.53 kJ mol^{-1} in carbon tetrachloride and benzene, respectively; the dipole moment of the *gauche* conformer and percentage of *gauche* population at 25 °C were found to be 3.04 D and 34% in carbon tetrachloride and 4.37 D and 18% in benzene. The difference in the dipole moments of the *gauche* form of **2** in carbon tetrachloride and benzene is significantly smaller than that of **1**. This may be attributed to the presence of the bulky methyl groups, which introduces small energy barriers in the pseudorotation circuit such that the conformational change becomes less facile.

2,2′-Bi-1,3-dithiolanyl (3). Table 1 shows that the dipole moment of this compound increases with increasing temperature in both carbon tetrachloride and benzene solutions, indicating that, like in **1**, the *trans* conformer is more stable than the *gauche*, and is higher in population in these solvents. Analysis of our dipole moment data in carbon tetrachloride solution according to the Lennard-Jones–Pike method gives values of ΔE, dipole moment of the *gauche* conformer and percentage *gauche* conformer at 25 °C as 6.24 kJ mol^{-1}, 3.35 D and 14%, respectively.

The experimental data for benzene solutions show that the dipole moment results are very similar to those for carbon tetrachloride solutions. From the Lennard-Jones–Pike analysis,[27] the dipole moment the *gauche* conformer was found to be 3.65 D, which is close to that found in carbon tetrachloride. It appears, therefore, that the benzene solvent effect on **3** is much weaker than that in the corresponding oxygen analogue **1**. This could be partially attributed to the increased size of the sulfur atom and the longer carbon–sulfur bond (C–S = 1.8 Å in **3**;[5] C–O = 1.41 Å in **1**[3]), which causes a smaller 1,3-transannular non-bonded interaction in **3** than in the corresponding **1**, thus resulting in a decrease in the flexibility of the 1,3-dithiolane ring. From Lennard-Jones–Pike analysis,[27] the internal energy difference between the two conformers, ΔE, is found to be 6.96 kJ mol^{-1}. This corresponds to a composition of 89% *trans* and 11% *gauche* at 25 °C.

2,2′-Dimethyl-2,2′-bi-1,3-dithiolanyl (4). From Table 1, it can be seen that the dipole moment of the compound in carbon tetrachloride decreases with increasing temperature, indicating that the *gauche* conformer is more stable than the *trans*, and is higher in population. Application of the Lennard-Jones–Pike analysis[27] to our dipole moment data yields a ΔE value of 2.94 kJ mol^{-1} and a *gauche* conformer dipole moment

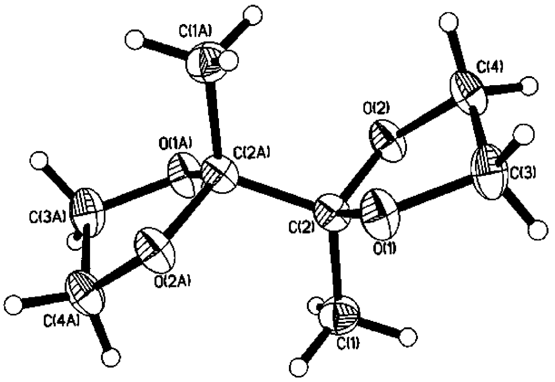


Fig. 1 Thermal ellipsoid diagram of **2**.

(μ_g) of 1.39 D. From eqn. (2), the percentage *gauche* population at 25 °C was found to be 70%. These results contrast with those of **1–3**, which favour the *trans* isomer when the compounds are in carbon tetrachloride. Since **4** also exists in the *gauche* conformation in the solid state (as shown by our X-ray data), the preference for the *gauche* conformer in carbon tetrachloride solution may be attributed to the intrinsic properties of the compound.

Analysis of the dipole moment data in benzene, however, shows that the values increase with increasing temperature, indicating that the *trans* conformer is more stable than the *gauche*, and is higher in population in this solvent. Application of the Lennard-Jones–Pike analysis to the dipole moment data of **4** in benzene yield a ΔE value of 5.42 kJ mol^{-1} and a *gauche* conformer dipole moment (μ_g) of 3.39 D. From eqn. (2), the percentage *gauche* population at 25 °C was found to be 18%. Since the dielectric constants of carbon tetrachloride and benzene are similar in value, the larger *trans* population in benzene is indicative of possible interactions between **4** and the benzene solvent molecules (and supported by our molecular orbital calculations). This solute-benzene interaction phenomenon is consistent with the results for compounds **1–3**, which show higher percentage of the *trans* conformer in benzene than in carbon tetrachloride solutions.

Crystal structure determination

The crystal structures of **1** and **3** have been determined earlier.[8,10] Fig. 1 and 2 depict the structures and define the atomic numbering of **2** and **4**, respectively.

Molecule **2** exists in the *trans* conformation in the solid state, like **1**[8] and 2,2′-diphenyl-2,2′-bi-1,3-dioxolanyl.[6] The dioxolane rings in **2** adopt the envelope form with C(3) being located at 0.4361 Å from the C(4)O(2)C(2)O(1) plane.

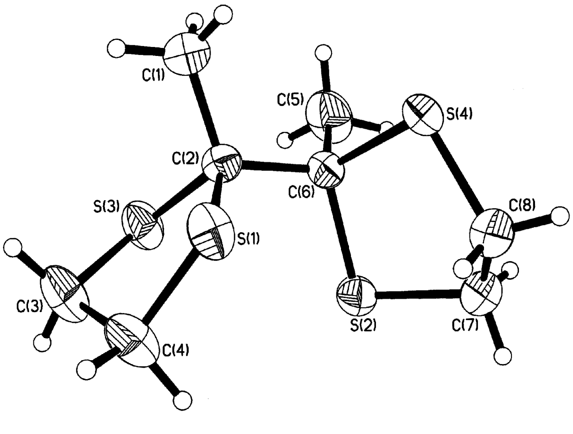


Fig. 2 Thermal ellipsoid diagram of **4**.

Molecule **4** adopts the *gauche* conformation with a C(1)–C(2)–C(6)–C(5) torsion angle of −55.53(38)°. This result contrasts with the parent compound **3**[10] and the oxygen analogues, **1**[8] and **2**, which favour the *trans* configuration in the solid state. Our X-ray data also show that the 1,3-dithiolanyl rings in **4** are in a twist form with the methylene carbons lying on either side at ~0.31 Å from the S–C–S plane.

Table 2 Calculated relative energies (ΔE, ΔH_{298} and ΔG_{298}, in kJ mol^{-1}) in the gas phase[a]

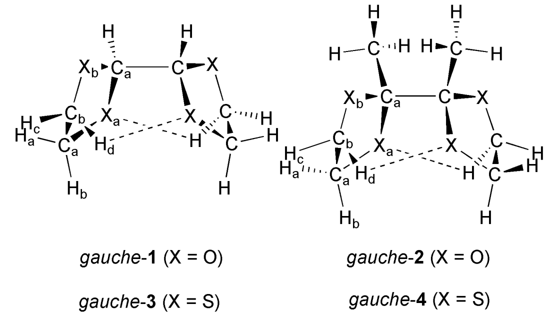
	ΔE(*gauche*/*trans*)			
Species	ΔE_0	ΔH_{298}	ΔG_{298}	$\Delta E_0(C_2/C_i)^b$
1	−8.2 (−5.6)[c]	−6.5	−3.6	−0.2
2	−9.4 (−9.2)[c]	−9.1	−5.3	−0.6
3	1.3 (5.8)[c]	1.0	3.7	1.4
4	−4.5 (−1.2)[c]	−4.3	−3.1	0.3

[a] G3(MP2) level. [b] Energy difference between the C_2 and C_i structures of the *trans* conformer. [c] B3LYP/6-311+G(2d,p)//B3LYP/6-31G*+ZPE.

Theoretical results

We begin our discussion on the calculated *gauche*/*trans* rotational equilibria of the bi-1,3-dioxolanyl systems (**1** and **2**) in the gas phase. The *gauche* form is the preferred conformation in both **1** and **2** (Table 2). Our previous study has shown that the *gauche* rotamer is more stable than the *trans* form for the parent compound (**1**) at various levels of *ab initio* and density functional theories.[6] In fact, the *gauche* preference is also predicted by semi-empirical and simple force field methods. At the G3(MP2) level, the predicted *gauche*/*trans* free energy differences at 298 K (ΔG_{298}) are 3.6 and 5.3 kJ mol^{-1} for **1** and **2**, respectively. What is the origin of the *gauche* preference? Inspection of the calculated geometries of the *gauche* conformers of **1** and **2** indicates that there are two favourable CH···O interactions in the *gauche* forms (Fig. 3 and Table S1 in the Electronic supplementary information). The internuclear distance between the oxygen atom of one dioxolane ring and the methylene hydrogen of the adjacent dioxolane ring is 2.46 Å in **1** (2.40 Å in **2**), significantly shorter than the sum of their van der Waal's radii (2.60 Å). Accordingly, a larger degree of charge is developed in the O and H atoms, compared to those in the *trans* conformer (Table S2 in ESI). It is also worth noting that the central CH (in **1**) or methyl (in **2**) hydrogens are in close proximity (2.60–2.67 Å) to the oxygen atoms in the dioxolane rings.

For the bi-dithiolanyl species, the parent compound (**3**) favours the *trans* rotamer while the methyl substituted system



gauche-**1** (X = O) *gauche*-**2** (X = O)

gauche-**3** (X = S) *gauche*-**4** (X = S)

Fig. 3 Calculated structures for the *gauche* forms of **1–4** showing the CH···X (X = O or S) interactions.

(**4**) prefers the *gauche* form. As with the oxygen analogues, there are favourable CH···S interactions in the *gauche* forms of **3** and **4** (Fig. 3) The S···H distances (~2.86 Å, Table S1) are less than the sum of their atomic radii (3.05 Å). Since sulfur has a lower electronegativity than oxygen, the CH···S interaction is expected to be less strong than the CH···O interaction. As a consequence, the favourable CH···S interaction in the *gauche* form is not sufficient to reverse the rotational equilibrium in **3**. Similar to the oxygen analogues, methyl substitution (R = CH_3) has a stabilization effect on the *gauche* form, leading to a slight preference of the *gauche* rotamer in **4** (Table 2). We have also examined the *gauche*/*trans* energy differences using density functional theory at the B3LYP/6-311+G(2d,p)//B3LYP/6-31G*+ZPE level. The calculated DFT energy differences (Table 2) agree well with the G3(MP2) values in all cases. There are three possible geometrical structures for the *trans* conformer: C_{2h}, C_i and C_2. The C_{2h} structure is calculated not to be a local energy minimum. Both the C_i and C_2 structures are stable equilibrium structures with very similar structural parameters. The C_2 structure has a non-zero dipole moment while the C_i form has a zero dipole moment. The calculated torsional angles (τRCCR) of the C_2 structures of **1**–**4** are significantly less than 180°, 172–175° (Table S1). The C_i and C_2 structures are predicted to lie very close in energy (±2 kJ mol^{-1}, Table 2). For **3** and **4**, the C_i form with zero dipole moment is favoured. In contrast, the C_2 structure is marginally more stable (< 1 kJ mol^{-1}) than the C_i form for **1** and **2**. Interestingly, the observed crystal structure of **2** has C_i symmetry. This discrepancy between theory and experiment may be attributed to the crystal packing effect. It is important to note also that if the *trans* conformers of **1** and **2** exist as the C_2 structure in solution, their *gauche*/*trans* energy differences derived from the dipole moment method are likely to be overestimated.

The torsional angle (τRCCR) of the *gauche* form of **1** and **2** is predicted to be ≈62° (Table S1). A significantly smaller torsional angle is predicted for the bi-1,3-dithiolanyl systems, by 10–12° (Table S1). As with 1,3-dioxolane and 1,3-dithiolane, the 5-membered rings in **1**–**4** are significantly distorted from planarity. The sulfur-containing compounds are more puckered than the oxygen analogues (Table S1). Based on QVBMM calculations, the non-planarity of this system was attributed primarily to torsional and dipolar effects.[5] We note that the calculated MP2/6-31G* geometries (Table S1) are in good accord with the X-ray structures of **2** and **4**. For instance, the calculated X–C–C–X (where X = O or S) dihedral angles in *trans*-**2** and *gauche*-**4** are 36.8° and 51.6°, which compare well with the experimental values of 33.8° and 50.3°. Interestingly, the *gauche* conformer has a less puckered dioxolane ring than the corresponding *trans* form in **1** and **2**.

In all cases, the *gauche* form has a significantly larger dipole moment than the corresponding *trans* form (by ~2 Debyes, Table 3). Based on the difference in dipole moment, one would expect the *gauche* form to be stabilized preferentially in a polarizable dielectric medium. However, both the *trans* and *gauche* conformers are calculated to have large quadrupole moments (Table 3), arising from their quadrupolar charge distribution. These higher multipole moments may also play a significant role in stabilizing the solute in a dielectric medium, *via* dipole-quadrupole and quadrupole-quadrupole interactions. Thus, we have examined the effect of a solvent reaction field on the *gauche*/*trans* equilibria of **1**–**4** using the continuum solvation models.

Table 4 Calculated *gauche*/*trans* free energy difference (ΔG) and solvation energies (δΔE)[a] in kJ mol^{-1} in different media

Species	$\varepsilon = 1^b$	$\varepsilon = 2^c$		$\varepsilon = 40^c$	
	ΔG	ΔG	$\delta\Delta E$	ΔG	$\delta\Delta E$
1	−3.6	2.2	4.8	6.1	9.7
2	−5.3	−1.7	3.6	2.5	7.8
3	3.7	4.5	0.8	5.2	1.5
4	−3.1	−2.4	0.7	−1.0	2.1

[a] $\delta\Delta E = \Delta E_{\text{solution}} - \Delta E_{\text{vapour}}$, were calculated at the B3LYP/6-311+G(2d,p) level based on the SCIPCM solvation model. [b] G3(MP2) level. [c] $\Delta G_{\text{solution}} = \Delta G_{\text{vapour}} + \delta\Delta E$.

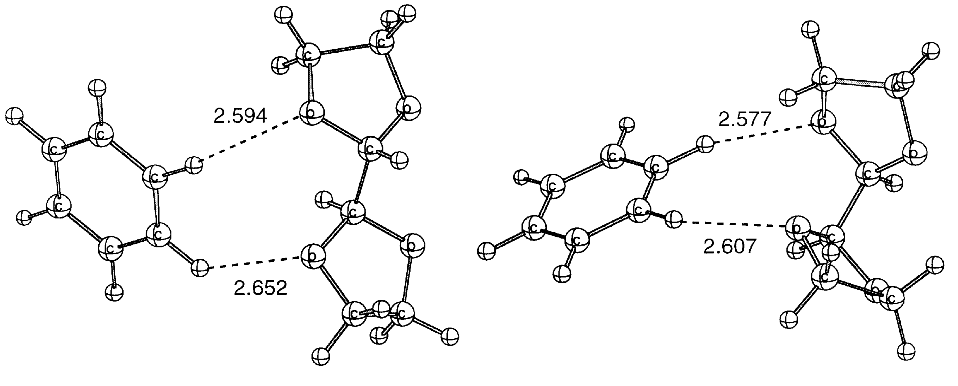
It is instructive to first examine the solvation energies, $\delta\Delta E = \Delta E_{\text{solution}} - \Delta E_{\text{vapour}}$, of **1** calculated using Onsager's dipole and SCIPCM methods in a polar medium of ε = 40. As expected, the dipole model, which takes into account only the solvent stabilization due to the solute dipole, predicts a larger solvent stabilization of the *gauche* form ($\delta\Delta E = -2.0$ kJ mol^{-1}). In sharp contrast, the SCIPCM method predicts a substantial solvent stabilization of the *trans* structure ($\delta\Delta E = 9.7$ kJ mol^{-1}). In fact, the solvation stabilization is sufficiently large that the conformational preference of **1** is reversed even in a non-polar medium of ε = 2 (Table 4). The large differential stabilization effect of the *trans* form is readily attributed to the solvent stabilization due to its higher multipole moments. This, perhaps, represents the first example of differential solvent stabilization of a less polar species in a conformational equilibrium. Similarly, a strong solvent influence is calculated for the rotational equilibrium of **2**, leading to a preference of the *trans* form in a polar medium (Table 4). In summary, theory predicts that there is a shift of the *gauche*/*trans* equilibrium in **1** and **2** on going from the gas phase to a solvent of high dielectric constant. Our theoretical finding is in accord with the observation of the *trans* conformer in solution and in solid state.

As in the cases of bi-1,3-dioxolanyl compounds, **3** and **4** are calculated to have a differential solvent stabilization of the *trans* form in a dielectric medium. However, the magnitude of the solvent effect is smaller in the sulfur-containing compounds (Table 4). As a result, the *gauche*/*trans* equilibrium is maintained in the presence of a solvent reaction field for both **3** and **4**. In other words, theory predicts that **3** favours

Table 3 Calculated dipole (μ/D) and quadrupole (Θ/DA^{-2}) moments[a]

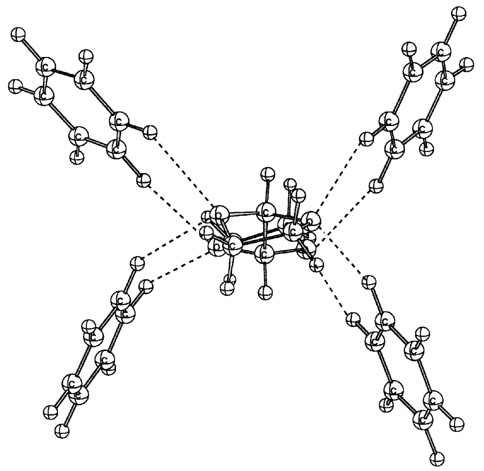
	1		**2**		**3**		**4**	
	trans (C_2)[b]	*gauche*	*trans* (C_2)[b]	*gauche*	*trans* (C_i)[b]	*gauche*	*trans* (C_i)[b]	*gauche*
μ	0.22	2.40	0.25	1.96	0.00	2.18	0.00	1.60
Θ_{xx}	−53.89	−58.36	−63.20	−66.42	−100.28	−89.42	−113.79	−110.88
Θ_{yy}	−43.88	−56.93	−61.25	−67.37	−90.61	−91.01	−103.34	−95.67
Θ_{zz}	−67.74	−56.71	−80.53	−75.54	−72.97	−86.23	−84.48	−97.34
Θ_{xy}	−6.77	−4.99	7.84	0.00	−1.26	−7.52	1.68	−0.08
Θ_{xz}	0.00	0.00	0.00	0.19	1.46	0.00	−0.94	0.00
Θ_{yz}	0.00	0.00	0.00	0.00	7.51	0.00	−5.71	0.00

[a] MP2/6-31G* values. [b] The symmetry point groups of the *trans* conformers are given in parenthesis.

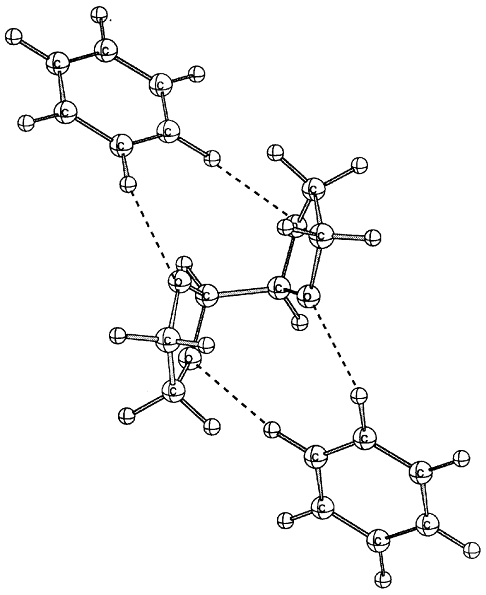


1:1 *trans*-**1**···benzene complex 1:1 *gauche*-**1**···benzene complex

Fig. 4 Optimized B3LYP/6-31G* geometries of 1:1 2,2′-bi-1,3-dioxolanyl···benzene complexes (bond lengths in Å).



1:4 *trans*-**1**···benzene complex



1:2 *gauche*-**1**···benzene complex

Fig. 5 Structures of 4:1 *trans*-**1**···benzene and 2:1 *gauche*-**1**···benzene complexes.

the *trans* structure while **4** favours the *gauche* form in both the gas and condensed phases, in good accord with experimental findings in solution phases and solid state.

To gain further insight into the specific solute-solvent interaction in benzene solution, we have examined the structures and binding energies of the **1**–benzene complexes at the B3LYP/6-311+G(2d,p)//B3LYP/6-31G*+ZPE level. As evident in Fig. 4, the 1 : 1 solute–benzene molecular complexes have two favourable noncovalent CH···O interactions between the benzene hydrogen and the oxygen lone pair of the solute. The *trans* complex is predicted to have a slightly larger binding energy than the *gauche* one (2.5 *vs.* 2.1 kJ mol^{-1}). Furthermore, we found that the *trans* rotamer can easily form a 4 : 1 solute–benzene complex (Fig. 5). On the other hand, the *gauche* form can only accommodate comfortably two benzene molecules because of its geometrical arrangement of the oxygen lone pairs (Fig. 5). Thus, the *trans* conformer is better solvated by benzene solvent than the *gauche* form. Preliminary calculations also indicate that attractive noncovalent CH···S interactions exist for the sulfur-containing systems (**3** and **4**) in the solute–benzene complexes. In summary, our calculations confirm the experimental finding that benzene solvent has a strong influence on the conformational equilibria of the bi-1,3-dioxolanyl and bi-1,3-dithiolanyl systems.

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