

pendence versus $n^{-1/3}$ (Figure 8). Describing the molecular cluster by a dielectric sphere of radius $\bar{R} = r_s n^{-1/3}$, where r_s is the (mean) radius of the molecular constituent, yields²² $EABE(\bar{R}) = EVBE(\infty) + An^{-1/3}$ and $EVBE(\bar{R}) = EABE(\infty) + Bn^{-1/3}$, where $A = (e^2/2r_s)(1 - D_s^{-1})$ and $B = (e^2/2r_s)(1 + D_{op}^{-1} - 2D_s^{-1})$ where D_s and D_{op} are the static and optical dielectric constants of the material, respectively. The values of the predicted slopes A and B from the dielectric model agree with those obtained from the simulations results (Figure 8). Furthermore, an extrapolation of the EABE to $n \rightarrow \infty$

yields values in agreement with current experimental estimates, i.e., -1.7 eV for water (Figure 7) and -1.1 eV for ammonia for the bulk heats of solution of an electron in these materials.³⁷ Size dependence of EABE and EVBE for internal states established a continuous transition between microscopic solvation effects in finite systems and in the macroscopic polar fluids.

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Conformational Analysis of Six-Membered, Sulfur-Containing Saturated Heterocycles

EUSEBIO JUARISTI

Departamento de Química, Centro de Investigación y de Estudios Avanzados del IPN, Apdo. Postal 14-740, 07000 México, D.F., México

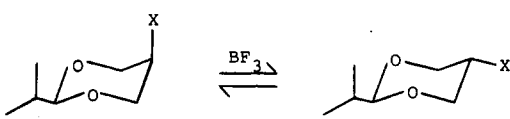
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The area of organosulfur chemistry has grown rapidly during the last 20 years,^{1,2} partly because the structural characteristics of sulfur have led to numerous studies of sulfur bonding, and partly because the unusual reactivity of organic sulfur compounds has resulted in the development of many useful synthetic reagents such as sulfur-stabilized carbanions and sulfur ylides. It is the purpose of this Account to show that the conformational behavior of the title systems is not only interesting but also, in some of its aspects, unusual since it reveals several conformational effects not readily explained in the light of the classical steric and dipolar interactions.

Eclipsed Conformation in *cis*-2-*tert*-Butyl-5-(*tert*-butylsulfonyl)-1,3-dioxane³

In a series of publications,^{4,5} it was reported that repulsive interactions beyond those accounted for by steric and polar factors are responsible for the large predominance of equatorial 5-methoxy- and 5-(methylthio)-1,3-dithianes. The existence of the "repulsive gauche effect" is most likely due to the destabilizing overlap between electron lone pairs on the gauche-oriented heteroatoms, which leads to the formation of filled bonding and antibonding orbitals. In connection with this work, chemical equilibration of 5-(*tert*-butylthio)-2-isopropyl-1,3-dioxane (*cis*-1 \rightleftharpoons *trans*-1), 5-(*tert*-butylsulfinyl)-2-isopropyl-1,3-dioxane (*cis*-2 \rightleftharpoons *trans*-2), and 5-(*tert*-butylsulfonyl)-2-isopropyl-1,3-di-

Table I
Conformational Equilibria in 5-Substituted 1,3-Dioxanes 1-12



compd	X	ΔG° , ^a kcal/mol	solvent	temp, °C
1	S- <i>t</i> -Bu ^b	-1.90	CHCl ₃	23.0
2	S(O)- <i>t</i> -Bu ^b	+0.10	CHCl ₃	23.0
3	SO ₂ - <i>t</i> -Bu ^b	-1.14	CHCl ₃	23.0
4	SMe ^c	-1.73	ether	26.5
5	S(O)Me ^c	+0.82	CHCl ₃	54.0
6	SO ₂ Me ^c	+1.19	CHCl ₃	50.0
7	SC ₆ H ₅ ^d	-1.93	CHCl ₃	25.0
8	S(O)C ₆ H ₅ ^d	+1.59	CHCl ₃	25.0
9	SO ₂ C ₆ H ₅ ^d	-0.44	CHCl ₃	25.0
10	S- <i>c</i> -C ₆ H ₁₁ ^d	^e	-	-
11	S(O)- <i>c</i> -C ₆ H ₁₁ ^d	+0.81	CHCl ₃	25.0
12	SO ₂ - <i>c</i> -C ₆ H ₁₁ ^d	0.0	CHCl ₃	25.0

^a Positive ΔG° values indicate axial preference. ^b Reference 3. ^c Reference 6. ^d Reference 7. ^e Unreliable measurement due to extensive decomposition.

oxane (*cis*-3 \rightleftharpoons *trans*-3) was carried out,³ and the results were examined in light of those obtained earlier for the

(1) See, for example: Oae, S. *Organic Chemistry of Sulfur*; Plenum Press: New York, 1977. Block, E. *Reactions of Organosulfur Compounds*; Academic Press: New York, 1978. *Organic Sulfur Chemistry*; Bernardi, F., Csizmadia, I. G., Mangini, A., Ed.; Elsevier: Amsterdam, 1985.

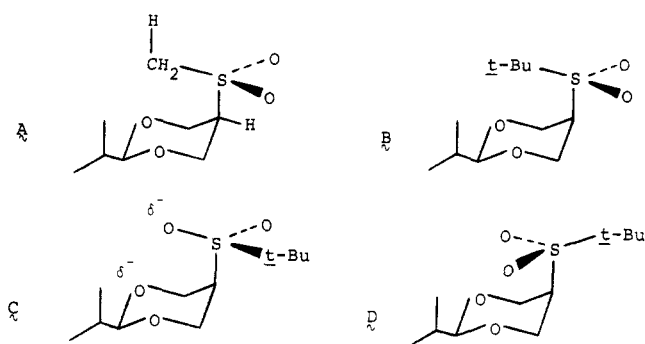
(2) For an earlier Account, see: Eliel, E. L. *Acc. Chem. Res.* 1970, 3, 1-8.

(3) Juaristi, E.; Martínez, R.; Méndez, R.; Toscano, R. A.; Soriano-García, M.; Eliel, E. L.; Petsom, A.; Glass, R. S. *J. Org. Chem.* 1987, 52, 3806-3811.

(4) Zefirov, N. S.; Blagoveshchensky, V. S.; Kazimirchik, I. V.; Surova, N. S. *Tetrahedron* 1971, 27, 3111-3118. Zefirov, N. S.; Gurvich, L. G.; Shashkov, A. S.; Krimer, M. Z.; Vorob'eva, E. A. *Tetrahedron* 1976, 32, 1211-1219.

Eusebio Juaristi was born in Querétaro, México, in 1950. He received the B.Sc. degree in 1972 from the Instituto Tecnológico de Monterrey (with Prof. X. A. Domínguez) and the Ph.D. degree from the University of North Carolina at Chapel Hill (with Prof. E. L. Eliel). He spent 1977-1978 as a postdoctoral fellow (with Prof. A. Streitwieser, Jr.) at the University of California, Berkeley, and was appointed Associate Professor at Instituto Politécnico Nacional in 1979, and was promoted to Professor of Chemistry in 1984. In 1988, he received the Award of the Academy of Sciences of Mexico for young scientists.

Scheme I



methyl analogues (4–6),⁶ which demonstrated the importance of attractive interactions between sulfoxide or sulfone and ether functional groups (Table I).

In the case of sulfides 1 and 4, the ΔG° values are very similar. It is reasonable here that both the methyl and *tert*-butyl groups point outside the dioxane ring, and therefore the effective steric interactions are comparable. The effect of changing from methyl to *tert*-butyl in the sulfones, in contrast, is quite dramatic; the large preference in the methyl analogue (6) for the axial isomer (1.19 kcal/mol) is reversed in *cis*-3 \rightleftharpoons *trans*-3, in which the equatorial isomer is more stable by 1.14 kcal/mol. Thus, the *tert*-butyl ligand on sulfur shifts the equilibrium toward the equatorial conformation by 2.33 kcal/mol.³

The axial preference of the methylsulfonyl group in 6 has been rationalized in terms of an attractive, electrostatic interaction between the positive end of the S^+-O^- dipole and the negative ring oxygen atoms.⁶ It is clear that some of this stabilizing interaction is still present in *cis*-3 (axial sulfone), since the equatorial predominance of 1 ($\Delta G^\circ = -1.90$ kcal/mol) decreases in 3 ($\Delta G^\circ = -1.14$ kcal/mol) despite the increase in steric bulk.

A large long-range (*W*) coupling constant of 1.14 Hz between the sulfonyl methyl and the hydrogen at C(5) of the dioxane was taken as an indication that *cis*-6 exists with the methyl group pointing into the ring (structure A, Scheme I). This in turn was explained by postulating electrostatic repulsion between the electronegative ring oxygens and the negative end of the $S-O$ dipole.⁶ Two explanations suggested themselves to account for the contrasting behavior of 3 and 6:³ (1) An axial sulfonyl group with the alkyl ligand still inside the ring (structure B, Scheme I) would lead to significant steric congestion, causing the axial isomer to be destabilized. (2) A conformation with the *tert*-butyl group turned outward (structure C, Scheme I) places the (negative) ring oxygens close to the (negative) sulfonyl oxygen, leading to an unfavorable electrostatic interaction.

For sulfone *cis*-3, ¹H and ¹³C NMR spectra corresponding to a plane of symmetry through C(2) and C(5) were recorded. This is to be expected for structure B (Scheme I) or two equally populated, rapidly equi-

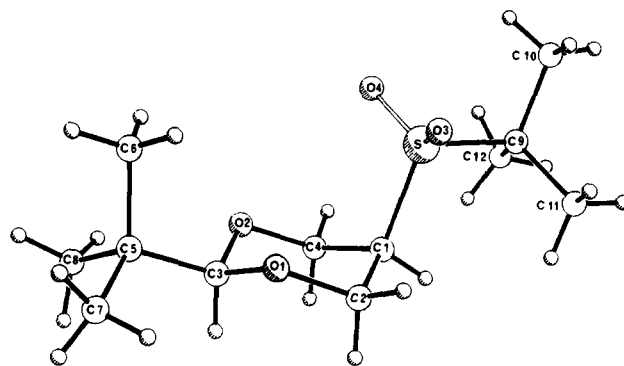


Figure 1. Structure and solid-state conformation of 2-*tert*-butyl-5-(*tert*-butylsulfonyl)-1,3-dioxane.

ibrating (by rotation around the C(5)–S bond) mirror-image conformations corresponding to C and its enantiomer (Scheme I). The symmetrical conformer D was initially disregarded in view of the normally expected much higher energy of eclipsed conformations. However, definitive evidence that the structure of 3 in the solid state corresponds to D was obtained by single-crystal X-ray diffraction of its 2-*tert*-butyl analogue [the crystals of the *cis*-2-isopropyl-5-(*tert*-butylsulfonyl)-1,3-dioxane (*cis*-3) were not of sufficient quality for crystallographic work]. A perspective view of the molecular structure of the 2-*tert*-butyl compound is shown in Figure 1.

The heterocyclic six-membered ring exists in a chair conformation, with the substituent at C(5) being axial. The sulfonyl *tert*-butyl group is outside the ring, suggesting that the steric congestion that would be present if the alkyl group was inside the ring is more severe than the electrostatic repulsion between the (negative) oxygens. The repulsion is nonetheless manifested as some bending of the C(5)–S bond away from the ring [C(4)–C(5)–S = 112°, C(6)–C(5)–S = 112.7°]⁸ and by an unusually large torsional angle in the O–C–C–S segments of ca. 78°. Also, the C(5)–S bond length (1.829 Å) is longer than normal (1.80 Å).

The most interesting feature of the crystallographic data is, however, that they correspond to structure D (Scheme I). The average torsional angles O–S–C–C are $8.25 \pm 2.35^\circ$, indicating the nearly eclipsed nature of the crystal structure, homologous to D (Scheme I). In solution, while it is difficult to distinguish between structure D and the rapidly interconverting enantiomeric conformers C, the lack of an upfield compression effect at *t*-BuSO₂ in the ¹³C NMR spectrum of *cis*-3³ and the manifestation of a δ -compression downfield effect on the same group in the ¹⁷O NMR spectrum,³ argue against structure B (Scheme I). Nevertheless, molecular orbital calculations at the CNDO level⁹ indicate that rotamer D is significantly more stable than staggered B and C in the gas phase.

The theoretical study of *cis*-3 shows also that the eclipsing of bonds in D is a necessary evil to mitigate *t*-Bu/CH₂ steric interactions present in C. In addition, conformer D leads to stabilizing attraction between the negatively charged sulfone oxygens and the positively

(5) Eliel, E. L.; Juaristi, E. *J. Am. Chem. Soc.* **1978**, *100*, 6114–6119. Eliel, E. L.; Juaristi, E. In *Anomeric Effect Origin and Consequences*; Szarek, W. A., Horton, D., Eds.; ACS Symposium Series 87; American Chemical Society: Washington, DC, 1979. Juaristi, E. *J. Chem. Educ.* **1979**, *56*, 438–441.

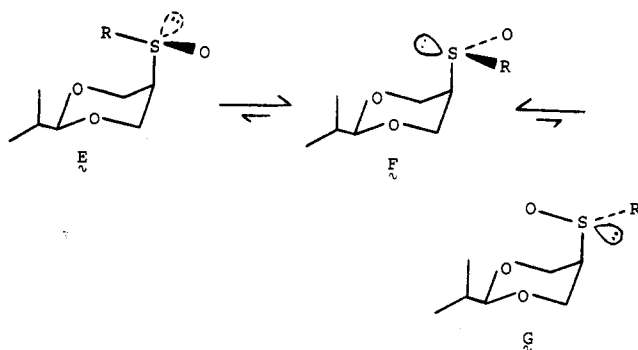
(6) Eliel, E. L.; Evans, S. A. *J. Am. Chem. Soc.* **1972**, *94*, 8587–8589. Kaloustian, M. K.; Dennis, N.; Mager, S.; Evans, S. A.; Alcudia, F.; Eliel, E. L. *J. Am. Chem. Soc.* **1976**, *98*, 956–965.

(7) Juaristi, E.; Gordillo, B.; Sabahi, M.; Glass, R. S. *J. Org. Chem.* Submitted.

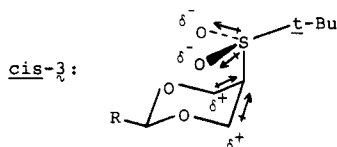
(8) By comparison, the C–C–S angle in the analogous sulfoxide, *cis*-2, is only $108.1 \pm 0.6^\circ$. Juaristi, E.; Gordillo, B.; Martinez, R.; Toscano, R. *J. Org. Chem.* In press.

(9) Gordillo, B.; Juaristi, E.; Rubio, M. F. To be submitted.

Scheme II



charged methylenes.⁹ Finally, dipole-induced dipole interactions seem also important in lowering the energy of the eclipsed sulfone.^{9,10}



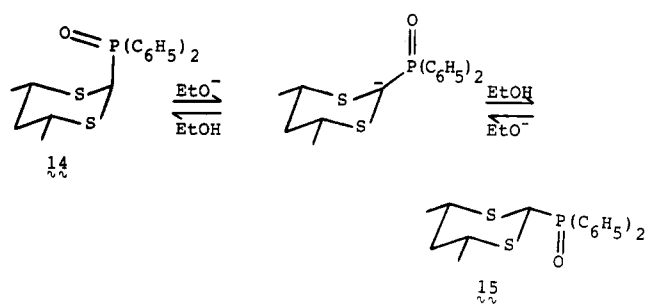
As for the axial sulfoxides, the large chemical shift difference between H(4eq) and H(6eq) in *cis*-2, 0.60 ppm,³ supports rotamers E and F (Scheme II) in view of the known downfield proton shift induced by a syn S=O group.¹¹ By contrast, $\Delta\delta(4ax/6eq) = 0.24$ ppm in *cis*-2, and $\Delta\delta(4eq/6eq) = 0.18$ ppm and $\Delta\delta(4ax/6ax) = 0.03$ ppm in *trans*-2. Conformer G for *cis*-2 is ruled out in view of the small shifting effect expected from the *tert*-butyl group as evidenced in related, sterically congested compounds. On the other hand, the lack of any compression effect on the ¹³C NMR chemical shifts for the *tert*-butylsulfinyl methyls³ argues for a negligible contribution of rotamer E. The high predominance of conformation F (Scheme II) is also supported by the lanthanide-induced shifts on the ¹H NMR spectra of *cis*-2.³

Concerning the conformational behavior of sulfoxides 2 and 5, both equilibria favor the axial isomers; however, *cis*-2 is favored only marginally ($\Delta G^\circ = +0.10$ kcal/mol, Table I), while in the methyl analogue (5) the axial preference is 0.82 kcal/mol. This difference arises from the repulsive steric hindrance between the gauche *t*-BuS and endocyclic methylene groups in structure F (Scheme II).

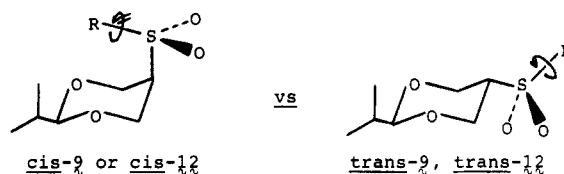
Table I includes also the results of the conformational behavior exhibited by analogous systems in which groups intermediate in size to methyl and *tert*-butyl have been incorporated at sulfur.⁷ The stabilizing effect operative in *cis*-8 can again be rationalized in terms of an electrostatic attraction between the endocyclic oxygens (partial negative charge) and the partially positive sulfinyl sulfur,⁶ the more electronegative phenyl group leading to a stronger attractive interaction in axial 8 ($\Delta G^\circ = +1.59$ kcal/mol), relative to axial 5 ($\Delta G^\circ = +0.82$ kcal/mol), owing to the increased positive charge at sulfur in the former.

The spectroscopic observations from the ¹H NMR spectra of *cis*-9 and *cis*-12 demonstrate that the aryl and alkyl substituents on the axial sulfonyl groups are or-

Scheme III



oriented above the 1,3-dioxane ring.⁷ The contrasting behavior of 6, 9 and 12 (+1.19, -0.44, and 0.0 kcal/mol, respectively) can be explained, at least in part, in terms of an entropic effect: whereas the *S*-alkyl or *S*-aryl groups in equatorial 9 and 12 are capable of rotation, inspection of Dreiding models indicates that rotation in the axial isomers is restricted, owing to the steric bulk of the two rings in the molecule.



S-C-P Anomeric Interactions^{12,13}

2-[1,3]Dithianyldiphenylphosphine oxide (13) was prepared in our laboratory and studied as a precursor of ketene dithioketals.¹⁴ It soon became obvious that the conformational behavior of 13 could provide useful information concerning the nature of the anomeric effect,^{15a} a phenomenon whose general chemical implications have recently been reviewed.^{15b} While much work has been dedicated to studies of the effect involving first-row elements, much less effort has been devoted to systems containing second-row elements.

Assignment of the proton NMR spectrum of 13 indicated a very large (ca. 1.2 ppm) chemical shift difference between axial and equatorial protons at C(4,6).¹² This observation was taken as evidence for a deshielding effect of a *predominantly axial* phosphoryl group on the syn-axial H(4,6). Definitive proof for the conformation of 13 in the solid state was obtained by single-crystal X-ray diffraction. The heterocyclic six-membered ring exists in a chair conformation with the substituent being axial.¹²

In order to quantitate the conformational effect present in 13, chemical equilibration of ananomeric 14 and 15 was successfully effected with basic catalysis using ethanolic sodium ethoxide (Scheme III). Integration of the signals for H(2) in the proton NMR spectra served for the analysis of the diastereomer ratios and afforded an average value of 1.0 kcal/mol for the conformational free energy difference favoring the axial isomer 14.¹³

(12) Juaristi, E.; Valle, L.; Mora-Uzeta, C.; Valenzuela, B. A.; Joseph-Nathan, P.; Fredrich, M. F. *J. Org. Chem.* 1982, 47, 5038-5039.

(13) Juaristi, E.; Valle, L.; Valenzuela, B. A.; Aguilar, M. A. *J. Am. Chem. Soc.* 1986, 108, 2000-2005.

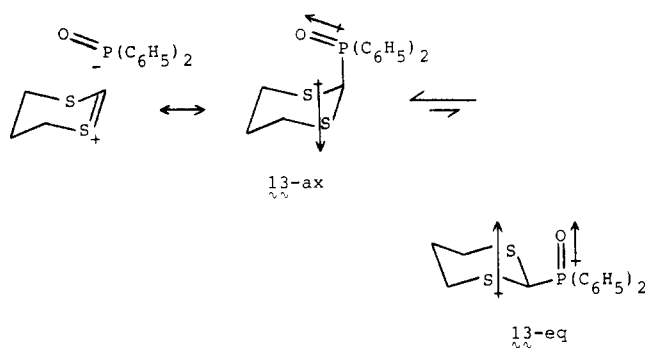
(14) Juaristi, E.; Gordillo, B.; Valle, L. *Tetrahedron* 1986, 42, 1963-1970.

(15) (a) Kirby, A. J. *The Anomeric Effect and Related Stereoelectronic Effects at Oxygen*; Springer-Verlag: Berlin, 1983. (b) Deslongchamps, P. *Stereoelectronic Effects in Organic Chemistry*; Pergamon Press: Oxford, 1983.

(10) Cf.: Wiberg, K. B.; Martin, E. *J. Am. Chem. Soc.* 1985, 107, 5035-5041. Wiberg, K. B. *Ibid.* 1986, 108, 5817-5822.

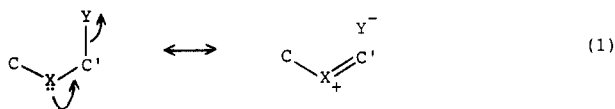
(11) Cf.: Juaristi, E.; Cruz-Sánchez, J. S.; Petsom, A.; Glass, R. S. *Tetrahedron* 1988, 44, 5653-5660 and references cited therein.

Scheme IV



The magnitude of anomeric effects is usually expressed as the difference of ΔG° 's in cyclohexane and the system studied.^{15a} The conformational preference of the diphenylphosphinoyl group in cyclohexane has recently been determined:¹⁶ ΔG° [$\text{P}(\text{O})(\text{C}_6\text{H}_5)_2$] = -2.74 kcal/mol. Accordingly, the anomeric effect present in 2-(diphenylphosphinoyl)-1,3-dithiane (13) is thus estimated as 3.74 kcal/mol. Of course, there is a well-recognized difficulty with evaluation in this fashion:¹⁷ in the system at hand, the steric requirement of a group at the 2-position is generally smaller (because of the long C-S bonds) than the steric requirement in a cyclohexane. Indeed, it has been shown² that the ΔG° (2-*tert*-butyl) in 1,3-dithianes is about 60% of ΔG° (*tert*-butyl) in cyclohexane. Thus, the expected size of the diphenylphosphinoyl group in 13 is 60% of 2.74 kcal/mol, which affords an anomeric effect equal to $1.0 + (0.60 \times 2.74) = 2.64$ kcal/mol, still one of the largest yet recorded.

Most commonly, the anomeric effect has been rationalized in terms of stabilization by (1) dipole-dipole interaction¹⁸ and (2) delocalization of the lone pair on the endocyclic heteroatom into the antiperiplanar (axial) adjacent polar bond.¹⁹ According to the second interpretation, in *gauche* (axial) C-X-C'-Y systems, the C'-X distances are significantly shorter than normal while the C'-Y bond lengths are longer than normal (eq 1).



Comparison of the structural data of 13 (axial)¹² and 15 (equatorial)²⁰ was made in order to examine the possible importance of $n_S \rightarrow \sigma^*_{\text{C-P}}$ interactions, which, if significant, would be manifested in shortened C-S and elongated C-P bond distances in the axial vs the equatorial isomer. The observation²⁰ that the C-P distance in 15 (equatorial) appears to be significantly longer than that in 13 (axial), as well as the lack of any significant difference in the mean S(1)-C(2) lengths, is *contrary* to expectations if an $n_S \rightarrow \sigma_{\text{C-P}}$ interaction makes an important contribution to the preferred axial

(16) Juaristi, E.; López-Núñez, N. A.; Glass, R. S.; Petsom, A.; Hutchins, R. O.; Stercho, Y. *J. Org. Chem.* **1986**, *51*, 1357-1360.

(17) Cf.: Franck, R. W. *Tetrahedron* **1983**, *39*, 3251-3252.

(18) Edward, J. T. *Chem. Ind. (London)* **1955**, 1102-1104.

(19) Romers, C.; Altona, C.; Buys, H. R.; Havinga, E. *Top. Stereochem.* **1969**, *4*, 39-97.

(20) Juaristi, E.; Valenzuela, B. A.; Valle, L.; McPhail, A. T. *J. Org. Chem.* **1984**, *49*, 3026-3027.

Table II
Solvent Effect on the Conformational Energies (ΔG°) in *trans*-2-(Diphenylphosphinoyl)-5-methyl-1,3-dithiane (17)²²

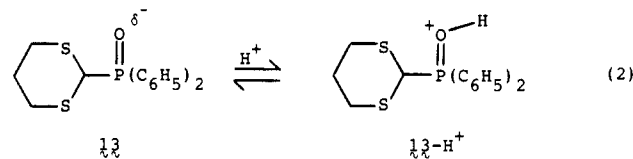
solvent	ϵ	$\Delta G^\circ_{39^\circ\text{C}}$, ^a kcal/mol
CDCl_3	4.7	1.07
$\text{CF}_3\text{CO}_2\text{D}$	8.2	0.30
CD_2Cl_2	8.9	1.12
CD_3COCD_3	20.7	1.74
CD_3CN	37.5	1.06
$\text{Me}_2\text{SO}-d_6$	48.9	1.78

^aThese values were estimated by taking into account the conformational preference of the 5-methyl group: 1.07 kcal/mol.²

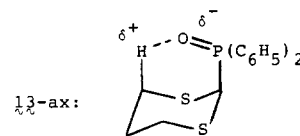
conformation in 13 (or in $14 \rightleftharpoons 15$).

According to the interpretation of the anomeric effect given by Edward,¹⁸ electrostatic dipole-dipole repulsion disfavors the equatorial conformer while dipole-dipole attraction should favor the axial conformer in an equilibrium such as that depicted in Scheme IV. Thus, if dipole-dipole interactions were dominant in the conformational equilibria of 13 ($14 \rightleftharpoons 15$), it would be expected that the contribution of the equatorial form should increase with increasing dielectric constant of the medium.²¹ In fact, the results *did not* show the expected solvent effect (Table II);¹³ rather, they gave an erratic trend, which hints at the simultaneous participation of several effects.

It is remarkable, however, that the axial preference of the 2-diphenylphosphinoyl group decreases substantially in trifluoroacetic acid (Table II). This very acidic solvent is likely to transfer a proton to the phosphoryl oxygen (eq 2), and in this event the stability present in 13-ax is evidently lost.



This result can be accommodated within the framework of the so-called reverse anomeric effect,²³ which in our system could be best explained as neutralization of an electrostatic, attractive interaction between the phosphoryl oxygen and the axial hydrogens at C(4,6) in 13-ax.



Support for this hypothesis comes from the conformational behavior of 2-(diphenylphosphinoyl)-1,3,5-trithiane (18), which shows an even higher predomi-

(21) See, for example: Eliel, E. L.; Giza, C. A. *J. Org. Chem.* **1968**, *33*, 3754-3758.

(22) The methyl group in 17 serves as a counterpoise, so that the equilibrium constant is close to unity, permitting a more precise calculation of ΔG° than would be possible in 13.

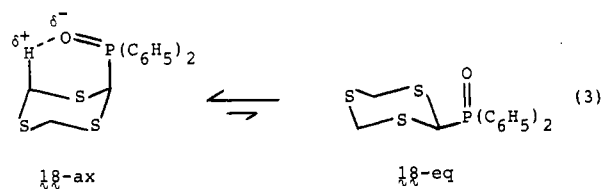
(23) Lemieux, R. U. *Pure Appl. Chem.* **1971**, *25*, 527-548.

Table III
Room-Temperature ^{13}C NMR Signals for the Aromatic Carbons in Compounds 13–15, 19, and 20

compd	C_{ipso}	C_{ortho}	C_{meta}	C_{para}
13	132.17	131.07	128.30	131.69
14	<i>a</i>	130.94	128.28	131.49
15	<i>a</i>	131.83	128.16	132.25
19	132.64	131.41	128.15	131.22
20	<i>a</i>	132.18	128.25	131.73

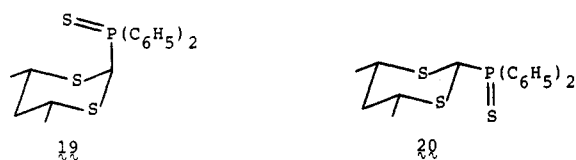
^a Obscured by base-line noise.

nance of the axial conformer (eq 3). The conformational analysis of 18 and its anancomeric (conformationally fixed) models yielded $\Delta G^{\circ}_{39^{\circ}\text{C}} = 1.43$ kcal/mol for the free energy difference favoring 18-ax over 18-eq. This result could be rationalized in terms of a stronger electrostatic interaction in 18-ax, with its more acidic H(4,6).¹³



This hypothesis cannot explain, however, the rather large effects of DMSO and acetone favoring the axial isomer. In fact, these solvents could be expected to compete for the H(4,6) hydrogens, causing a weakened electrostatic attraction in axial $\text{P}(\text{O})\text{Ph}_2$, contrary to observation (Table II).

A most interesting observation suggests, however, some form of electron transfer to the axial phosphinoyl group. Indeed, the aromatic ring ^{13}C chemical shifts for the ortho and para carbons in the axial isomers 13, 14, and 19^{24,25} appear at significantly higher fields than those in equatorial 15 and 20 (Table III). By contrast, the signal for the *meta* carbons in 13–15 and in 19–20 are essentially constant. These results are indicative of increased electron density at phosphorus in the axial isomers. Because the crystallographic data are contrary to a $n_{\text{S}} \rightarrow \sigma^*_{\text{C-P}}$ mechanism (vide supra), an alternative explanation is called for.



In view of the importance of through-space 2p–3d overlap effects between methoxy or dimethylamino groups and phosphorus in various organophosphorus compounds,²⁶ through-space 3p–3d electron donation from sulfur to phosphorus might help to account for the preferred axial orientation of the phosphorus moiety in 13, 14, and 19. Indeed, the P–S distance of ca. 3.0 Å in 13-ax is much less than the sum of the van der Waals radii (3.75 Å) of P and S, and therefore a bonding interaction may be operative.

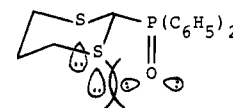
(24) A slight predominance of axial over equatorial 2-(diphenylthio-phosphinoyl)-1,3-dithiane reflects nonetheless a S–C–P anomeric interaction comparable with that observed in 13.²⁵

(25) Juaristi, E.; López-Núñez, N. A.; Valenzuela, B. A.; Valle, L.; Toscano, R. A.; Soriano-García, M. *J. Org. Chem.* 1987, 52, 5185–5189.

(26) Cf.: McEwen, W. E.; Cooney, J. V. *J. Org. Chem.* 1983, 48, 983–987 and references cited therein.

Of course, the predominance of 13-ax over 13-eq may be due not to a stabilizing effect in the axial isomer but rather to a destabilizing interaction in the equatorial isomer. In fact, Mikolajczyk et al.²⁷ have proposed a repulsive interaction between the lone pairs on sulfur and on phosphoryl oxygen in the equatorial conformation. While experimental support for this hypothesis is lacking, it should be pointed out that such an effect would be a particular example of the repulsive gauche effect.^{4,5}

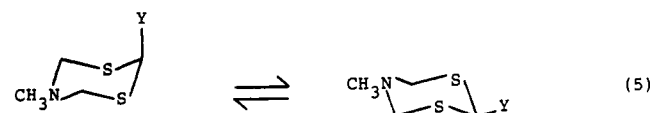
Repulsive gauche effect in equatorial 13:



In summary, the very strong S–C–P anomeric effect displayed by 2-(diphenylphosphinoyl)-1,3-dithiane and some of its derivatives is not easily explained in terms of dipole–dipole or $n_{\text{S}} \rightarrow \sigma^*_{\text{C-P}}$ stereoelectronic interactions. Some support for the participation of electrostatic $\text{P}=\text{O}^{\delta-} \cdots \delta^+\text{H}(4,6)$ attraction and 3p \rightarrow 3d stabilization in axial 13 has been recorded. In addition, a repulsive gauche interaction in equatorial 13 could also account for the axial preference. However, no single effect seems to dominate the 13-ax \rightleftharpoons 13-eq equilibrium, which probably deserves the attention of the community of theoretical chemists.

Study of the Anomeric Effect in Other 2-Substituted 1,3-Dithianes²⁸

In contrast to the unusual conformational behavior of 13 (vide supra), the conformational analysis of 2-substituted 1,3-dithianes²⁸ [eq 4; Y = SCH_3 , SC_6H_5 , CO_2H , CO_2CH_3 , COC_6H_5 , $\text{N}(\text{CH}_3)_2$] as well as several 2-substituted 5-methyl-5-aza-1,3-dithiacyclohexanes²⁹ [eq 5; Y = SCH_3 , SC_6H_5 , COC_6H_5 , $\text{CO}_2\text{CH}_2\text{CH}_3$, $\text{CO}_2\text{C}_6\text{H}_5$] reveals the expected interplay of steric, electrostatic, and stereoelectronic interactions.



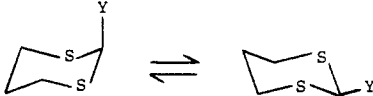
The low-temperature (–90 to –100 °C) ^{13}C NMR spectra of mobile dithianes 21–24 give rise to two sets of signals, which correspond to the axial and equatorial conformers. Integration of the peak areas for each of the conformers in the spectra afforded the equilibrium constants and the conformational free energy differences summarized in Table IV. Sizable anomeric effects (axial preferences) were apparent for 21–25. By contrast, the room-temperature ^{13}C NMR data for aminodithiane 26 (Y = NMe_2) shows that this compound exists in a highly predominant ($\geq 95\%$) equatorial conformation.²⁸ When the corresponding *A* values for

(27) Mikolajczyk, M.; Graczyk, P.; Kabachnik, M. I.; Baranov, A. P. *J. Org. Chem.* 1989, 54, 2859–2861.

(28) Juaristi, E.; Tapia, J.; Méndez, R. *Tetrahedron* 1986, 42, 1253–1264.

(29) Juaristi, E.; González, E. A.; Pinto, B. M.; Johnston, B. D.; Nagelkerke, R. *J. Am. Chem. Soc.* In press.

Table IV
Low-Temperature (-90 or -100 °C) Conformational
Equilibria of 2-Substituted 1,3-Dithianes (Eq 4)



compd	Y	solvent	K	ΔG° , ^a kcal/mol
21	SCH ₃	toluene-d ₈	9.3	0.77
		CD ₂ Cl ₂	6.5	0.64
		CD ₃ OD/(CD ₃) ₂ CO (1:1)	5.7	0.63
22	SC ₆ H ₅	CD ₂ Cl ₂	14.7	0.92
		CD ₃ OD/(CD ₃) ₂ CO (1:1)	10.4	0.85
23	CO ₂ CH ₃	CD ₂ Cl ₂	11.1	0.83
24	COC ₆ H ₅	toluene-d ₈	24.0	1.16
25	CO ₂ H	CD ₂ Cl ₂	≥32.3	≥1.26

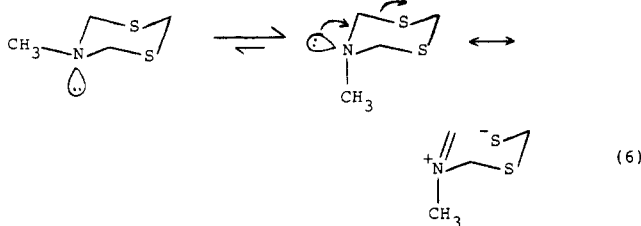
^a Positive ΔG° values indicate axial preference.

the substituents are taken into consideration, the relative magnitude of the anomeric effects observed is CO₂H > COC₆H₅ > CO₂CH₃ > SC₆H₅ > SCH₃ >>> N(CH₃)₂ (≤0).

The relative order of the effects as a function of substituent is similar in the corresponding 1,3,5-dithiazines 27–31 (eq 5); however, the effects are smaller in magnitude.²⁹ There is a general tendency for a diminished axial preference in the more polar solvents, and this result confirms the importance of dipole–dipole interactions in these systems:²⁸ electrostatic repulsion disfavors the equatorial conformer, while dipole–dipole attraction favors the axial conformer.^{18,21}

The smaller anomeric effect in the dithiazines vis-à-vis the dithianes is not due to increased steric repulsion between the axial substituent at C(2) and the methylene groups at C(4,6) since the conformational energy of a 2-methyl group is of similar magnitude in both systems: $\Delta G^\circ = -2.0$ kcal/mol in the dithiazine,²⁹ and $\Delta G^\circ = -1.8$ kcal/mol in the dithiane.³⁰ Furthermore, a photoelectron spectrum of 5-methyl-5-aza-1,3-dithiacyclohexane gave the lowest ionization potential at 8.55 eV,²⁹ which is very similar to the one measured in 1,3-dithiane: 8.54 eV.³¹ This result indicates that the smaller anomeric effect found in the 5-aza analogues is not due to a lower lying HOMO, leading to decreased $n_S \rightarrow \sigma^*_{C-Y}$ interactions.

In this context, it is known that the methyl group at nitrogen in this system adopts an axial orientation in order to avoid the repulsion between lone pairs of electrons³² and, possibly, to allow for favorable $n_N \rightarrow \sigma^*_{C-S}$ interactions^{29,33} (eq 6).



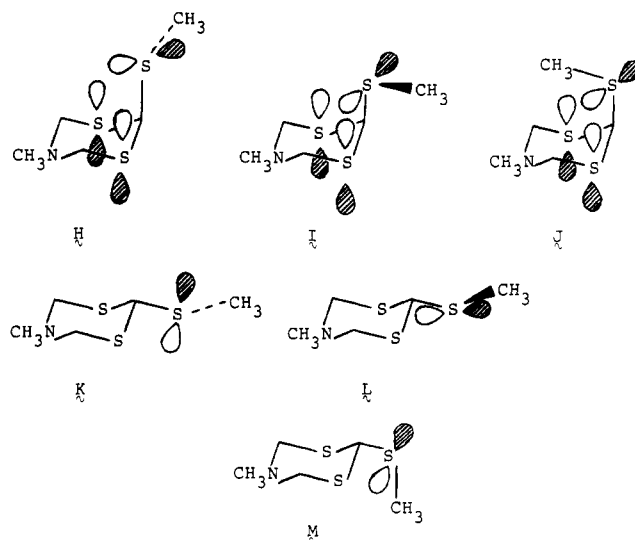
(30) Eliel, E. L.; Hutchins, R. O. *J. Am. Chem. Soc.* **1969**, *91*, 2703–2715.

(31) Sweigart, D. A.; Turner, D. W. *J. Am. Chem. Soc.* **1972**, *94*, 5599–5603.

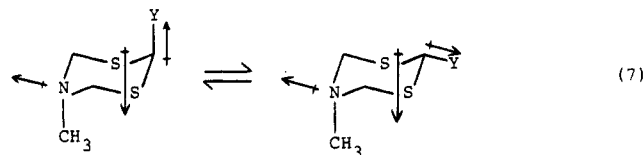
(32) Angiolini, L.; Duke, R. P.; Jones, R. A. Y.; Katritzky, A. R. *J. Chem. Soc., Perkin Trans. 2* **1972**, 674–680.

(33) Pinto, B. M.; Johnston, B. D.; Nagelkerke, R.; Juaristi, E.; González, E. A. *Can. J. Chem.* In press.

Scheme V



Because the axial disposition of the *N*-alkyl group in the dithiazine causes some cancellation of the ring dipole encountered in the 1,3-dithiane ring,³⁴ it is very likely that the smaller anomeric effects observed in this system are the consequence of a less important dipole–dipole component stabilizing the axial conformers (eq 7).



The relative order in the magnitude of the anomeric effects observed in dithiazines 27–31, CO₂C₆H₅ > CO₂CH₂CH₃ > COC₆H₅, and SC₆H₅ > SCH₃,²⁹ which is the trend also observed in the 1,3-dithiane analogues,²⁸ is adequately explained in terms of endo and exo hyperconjugative interactions.³⁶ Indeed, the antiperiplanar orientation of the p-type lone-pair orbital on the endocyclic sulfurs and the axial C(2)–SCH₃ bond allows for a significant endo anomeric interaction in conformations H and I (Scheme V; conformer J is disfavored on steric grounds). Axial 27 is also stabilized by exo anomeric interactions in H and I. However, exo anomeric interactions also stabilize the equatorial conformers K–M (Scheme V), and a relatively weak axial preference is therefore observed.

Substitution of the methyl group for a phenyl group in 28 (SCH₃ → SC₆H₅) leads to an increased axial preference because the endo anomeric effect is stronger in axial 28 (lower energy of the σ^*_{C-S} orbital; greater stabilization through the $n_S \rightarrow \sigma^*_{C-S}$ interaction), but the exo anomeric interactions are less important (lower energy of the donor n_S orbital).

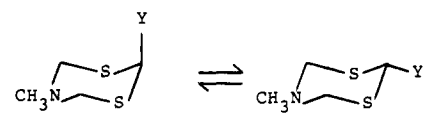
In 29–31, the endo anomeric effect results from $n_S \rightarrow \sigma^*_{C-CO}$ interactions whereas torsion about the exocyclic C–CO bond can now turn on $\pi_{CO} \rightarrow \sigma^*_{C-S}$ interactions associated with an exo anomeric effect. However, $\pi_{CO} \rightarrow \sigma^*_{CX}$ interactions have been shown not to be domi-

(34) The dipole moment determined by Havinga et al. for 1,3-dithiane, $\mu = 2.09$ D,³⁵ drops to 1.47 D in 5-methyl-5-aza-1,3-dithiacyclohexane.³²

(35) Kalf, H. T.; Havinga, E. *Recl. Trav. Chim. Pays-Bas* **1966**, *85*, 467–484.

(36) Praly, J.-P.; Lemieux, R. U. *Can. J. Chem.* **1987**, *65*, 213–223.

Table V
Thermodynamic Parameters for 28–31 (Eq 5)^a



compd	Y	solvent	ΔH° , ^b kcal/mol	ΔS° , ^c cal/(mol K)
28	SC ₆ H ₅	CD ₂ Cl ₂ /CFCl ₃ (15:85)	+0.70	+0.56
28	SC ₆ H ₅	CD ₃ COCD ₃	+0.50	+1.40
28	SC ₆ H ₅	CD ₃ OD	+0.54	+1.29
29	COC ₆ H ₅	C ₆ D ₅ CD ₃	+0.10	-2.46
29	COC ₆ H ₅	CD ₂ Cl ₂	-0.01	-0.80
29	COC ₆ H ₅	CD ₃ COCD ₃	-0.58	-2.04
30	CO ₂ CH ₂ CH ₃	C ₆ D ₅ CD ₃	-0.35	-5.46
30	CO ₂ CH ₂ CH ₃	CD ₂ Cl ₂	-0.03	-1.70
30	CO ₂ CH ₂ CH ₃	CD ₃ OD	+0.27	-0.95
31	CO ₂ C ₆ H ₅	CD ₂ Cl ₂	-0.17	-3.90
31	CO ₂ C ₆ H ₅	CD ₃ COCD ₃	-0.05	-2.24
31	CO ₂ C ₆ H ₅	CD ₃ OD	+0.29	-1.87

^a Additional data are provided in ref 36. ^b Positive values indicate that the axial conformer is favored enthalpically. ^c Positive values indicate that the equatorial conformer is favored entropically.

nant,³⁷ probably because of the low energy of the π_{CO} orbital.³⁸ One can focus, therefore, on the unique endo anomeric interaction in the axial conformations.

With respect to the "abnormal" equatorial preference of the dimethylamino group in 26, this result must mean that, in the equatorial conformer, the antiperiplanar $n_N \rightarrow \sigma^*_{C-S}$ interaction is more important (best combination of orbital overlap and energetic difference) than the antiperiplanar $n_S \rightarrow \sigma^*_{C-N}$ interaction in the axial isomer; i.e., there is a stereoelectronic preference for the conformation in which the best donor lone pair is antiperiplanar to the best acceptor bond.^{15a}

The Enthalpic Anomeric Effect

Recently, Booth et al.³⁹ have stressed that in studies of the anomeric effect it is the ΔH° values that correlate with the steric, polar, and stereoelectronic interactions of interest. Therefore, the enthalpic and entropic contributions to the anomeric interactions involved in the conformational equilibria of 28–31 were evaluated.²⁹ This rigorous study was particularly important in view of the fact that the existence of significant anomeric effects in X–C–Y segments containing second-row and lower row elements has been questioned on theoretical grounds.⁴⁰

The equilibrium data for (28–31)-ax \rightleftharpoons (28–31)-eq were derived by direct integration of the signal pairs in the temperature range 176–202 K [solvents CD₂Cl₂, CD₃COCD₃, C₆D₅CD₃, and CD₃OD; compound 28 was also analyzed in the temperature range 144–207 K in solvent CD₂Cl₂/CFCl₃ (15:85)]. Plots of $\ln K$ vs $1/T$ were linear, and the thermodynamic parameters derived from these plots are listed in Table V.

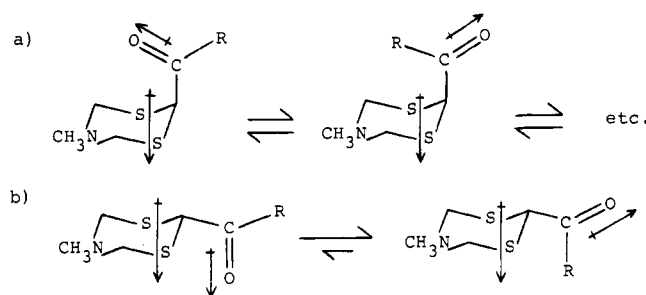
The thermodynamic data obtained for the 28-ax \rightleftharpoons 28-eq equilibrium shows definitively that the axial preference of the thiophenyl group is of enthalpic origin; the enthalpy term dominates over the entropy contri-

(37) Cantacuzene, D.; Tordeux, M. *Can. J. Chem.* 1976, 54, 2759–2766.
Pinto, B. M.; Johnston, B. D.; McLeod, R. Personal Communication.
(38) Ouedraogo, A.; Viet, M. T. P.; Saunders, J. K.; Lessard, J. *Can. J. Chem.* 1987, 65, 1761–1768.

(39) Booth, H.; Khedhair, K. A. *J. Chem. Soc., Chem. Commun.* 1985, 467–468. Booth, H.; Khedhair, K. A.; Readshaw, S. A. *Tetrahedron* 1987, 43, 4699–4723.

(40) Schleyer, P. v. R.; Jemmis, E. D.; Spitznagel, G. W. *J. Am. Chem. Soc.* 1985, 107, 6393–6394.

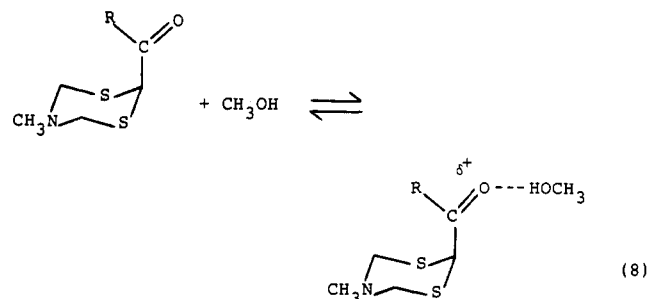
Scheme VI



bution, which actually favors 28-eq. the sizable ΔH° terms (0.4–0.7 kcal/mol; Table V) must of course overcome the steric hindrance present in 28-ax, so that the magnitude of the anomeric effect in this system may well exceed 1.0 kcal/mol.

In contrast to 28 the thermodynamic data for the carbonyl derivatives 29–31 show that the ΔH° term in most solvents is close to 0. Of course, $\Delta H^\circ \sim 0$ in these systems may still be indicative of a significant anomeric effect owing to the countervailing steric effect. Inspection of Table V shows that the axial predominance of 29–31 is controlled by the entropy difference, the axial conformers being of higher entropy. A likely explanation for this phenomenon can be advanced in terms of the local dipole–dipole interactions present in the axial and equatorial conformers. (A significant solvent effect is found in the equilibria of 29–31; the anomeric effect decreases as the polarity of the solvent increases.) For axial 29–31, the C=O dipole should always be aligned antiparallel to the ring dipole, independently of rotation around the C(2)–CO bond (Scheme VI, part a), and all rotamers would then be favorable on electrostatic grounds. In equatorial 29–31, however, a lower energy rotamer would only be obtained when the C=O bond dipole is pointing away from the ring dipole; this would restrict the conformational freedom of the equatorial conformer (Scheme VI, part b). Supporting evidence for this explanation comes from the observation that this entropy effect is more important in the less polar solvents, where the electrostatic interaction is more demanding (Table V).

Interestingly, ΔH° is positive for 30 and 31 in *methanol*, but negative in all other solvents. A plausible interpretation of this effect is as follows: hydrogen bonding by the hydroxylic solvent methanol to the carbonyl group makes the endo anomeric effect more effective, by lowering the energy of the σ^*_{C-CO} orbital (eq 8).



Conclusions

The first section of this Account describes the use of chemical equilibrations, multinuclear NMR spectro-

copy, precise structural information, and theoretical calculations for the understanding of the conformational behavior of several 5-sulfur-substituted 1,3-dioxanes. An unprecedented finding, with far-reaching implications, was the discovery of an eclipsed rotamer in the axial 5-*tert*-butylsulfonyl derivative.

The second section relates the determination of a very strong S-C-P anomeric effect in 2-(diphenylphosphinoyl)-1,3-dithiane. While a combination of electrostatic and orbital interactions could account for this effect, no single factor seems to dominate, and it is likely that this phenomenon deserves more attention by theoretical chemists.

The third section shows the participation of dipole-dipole and hyperconjugative effects in the axial preference of 2-substituted 1,3-dithianes and 1,3,5-dithiazines. Analysis of the enthalpic and entropic terms in these equilibria leaves little doubt that second-row anomeric interactions exist.

I am indebted to all my co-workers in the references in this review. Several stimulating discussions with Professors E. L. Eliel, W. E. McEwen, and B. M. Pinto and the constructive remarks of the referees are here acknowledged. Our work in this area has been supported by the Consejo Nacional de Ciencia y Tecnología, Consejo del Sistema Nacional de Educación Tecnológica, and by Laboratorios Prosalud.

The Life and Times of $[\text{Ru}(\text{bpy})_3]^{2+}$: Localized Orbitals and Other Strange Occurrences

M. KEITH DE ARMOND* and MICHAEL L. MYRICK

Department of Chemistry, New Mexico State University, Las Cruces, New Mexico 88003

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The utility of and interest in $[\text{Ru}(\text{bpy})_3]^{2+}$ and its analogue compounds is attested to by a recent long review¹ focusing primarily on the photochemistry of $[\text{RuL}_3]^{2+}$ type compounds. The ability of the colored $[\text{Ru}(\text{bpy})_3]^{2+}$ to absorb light and photocatalyze a variety of bimolecular electron transfer reactions at room temperature has served to generate literally hundreds of papers dealing with topics as diverse as the water splitting reaction²⁻⁵ and the photocatalytic snipping of DNA.⁶⁻⁸ Electrochemists have utilized the photooxidative ability of the $[\text{Ru}(\text{bpy})_3]^{2+}$ unit to modify⁹⁻¹² the redox capability of metal electrodes. Incorporation of $[\text{Ru}(\text{bpy})_3]^{2+}$ into various clays¹³⁻¹⁵ results in a photocatalytic system capable of reacting with various redox partners. In the great majority of examples, the key to the utility of the $[\text{RuL}_3]^{2+}$ species is the existence of lowest emitting excited states that are reasonably stable to decomposition.

This stability results from the fact that this emitting state is a $d\pi^*$ excited state rather than a dd^* state. In spite of the great quantity of useful bimolecular photochemistry done with these $[\text{RuL}_3]^{2+}$ materials, a description of this unique emission was developed only recently. The so-called "localized orbital" description (Figure 1)¹⁶⁻¹⁸ used by us to explain the multiple

emission from the mixed-ligand $[\text{Rh}(\text{bpy})_2(\text{phen})]^{3+}$ and $[\text{Rh}(\text{bpy})(\text{phen})_2]^{3+}$ complexes was suggested^{16,18} as a reasonable description of the emission of the parent $[\text{Rh}(\text{bpy})_3]^{3+}$ and $[\text{Rh}(\text{phen})_3]^{3+}$ complexes and, further, as a feasible description of the $d-\pi^*$ emission from $[\text{Ru}(\text{bpy})_3]^{2+}$. Certainly, the concept of an orbital localized on one bpy chelate ring but not interacting with adjacent orthogonal π electron systems was reasonable for the Rh(III) complexes but was difficult to comprehend for a system in which the orbital character of the emitting state is described as $d\pi^*$. In such a system, the emitting state involves an unpaired electron in an orbital on one atom, Ru(III), which is common to each of the three π chelate rings in the metal complex. Consequently, a series of results from our lab and the labs of others, for solution and crystal media, have been presented to elaborate the localized orbital character

M. Keith De Armond, born in Fort Wayne, IN, received his B.A. degree in Chemistry from De Pauw University in 1958 and a Ph.D. in Physical Chemistry (1963) from the University of Arizona. He has utilized luminescence and ESR spectroscopy, as well as electrochemical methods, to probe the photo-physic and charge localization properties of transition-metal complexes. Current efforts are directed to the environmental effects produced by molecular assemblies (Langmuir-Blodgett films, pendant polymer complexes, and liquid-liquid interfaces) on these molecular charge separation and localization effects. He currently is Professor and Head of the Chemistry Department at New Mexico State University after spending over 20 years in the Chemistry Department at North Carolina State University.

Dr. Michael L. Myrick was born in Greensboro, NC and received his B.S. in Chemistry from North Carolina State University in 1985. He moved with Professor De Armond to New Mexico State, where he received his Ph.D. in 1988. He currently is a postdoctoral fellow at the Lawrence Livermore Laboratory in Livermore, CA.

- (1) Juris, A.; Barigelletti, F.; Campagna, S.; Balzani, V.; Belser, P.; von Zelewsky, A. *Coord. Chem. Rev.* 1988, 84, 85.
- (2) Kalyanasundaram, K. *Coord. Chem. Rev.* 1982, 46, 159.
- (3) *Photochemical Conversion and Storage of Solar Energy*; Connolly, J. S., Ed.; Academic Press: New York, 1981.
- (4) *Energy Resources through Photochemistry and Catalysis*; Graetzel, M., Ed.; Academic Press: New York, 1983.
- (5) Scandola, F.; Balzani, V. *J. Chem. Educ.* 1983, 60, 814.
- (6) Barton, J. K.; Danishefsky, A.; Goldberg, J. *J. Am. Chem. Soc.* 1984, 106, 2172.
- (7) Kelly, J. M.; Tossi, A. B.; McConnell, D. J.; Oh Vigin, C. *Nucleic Acids Res.* 1985, 13, 6017.
- (8) Kelly, J. M.; McConnell, D. J.; Oh Vigin, C.; Tossi, A. B.; Kirsch-De Mesmaeker, A.; Masschelein, A.; Nasielski, J. *J. Chem. Soc., Chem. Commun.* 1987, 1821.
- (9) Calvert, J. M.; Meyer, T. J. *Inorg. Chem.* 1981, 20, 27.
- (10) Calvert, J. M.; Caspar, J. V.; Binstead, R. A.; Westmoreland, T. D.; Meyer, T. J. *J. Am. Chem. Soc.* 1982, 104, 6620.
- (11) Ellis, C. D.; Margerum, L. D.; Murray, R. W.; Meyer, T. J. *Inorg. Chem.* 1983, 22, 1283.
- (12) Leidner, C. R.; Denisevich, P.; Willman, K. W.; Murray, R. W. *J. Electroanal. Chem.* 1984, 164, 63.
- (13) Della Guardia, R. A.; Thomas, J. K. *J. Phys. Chem.* 1983, 87, 990.
- (14) Schoonheydt, R. A.; De Pauw, P.; Vliers, D.; De Schrijver, F. C. *J. Phys. Chem.* 1984, 88, 5113.
- (15) Ghosh, P. K.; Bard, A. J. *J. Phys. Chem.* 1984, 88, 5519.
- (16) Halper, W.; De Armond, M. K. *J. Lumin.* 1972, 5, 225.
- (17) Halper, W.; De Armond, M. K. *Chem. Phys. Lett.* 1974, 24, 114.
- (18) De Armond, M. K.; Carlin, C. M. *Coord. Chem. Rev.* 1981, 36, 325.