

# Nuclear Magnetic Resonance Studies of Chirality in Triarylmethyl Cations. Mechanism of Enantiomer and Diastereomer Interconversion

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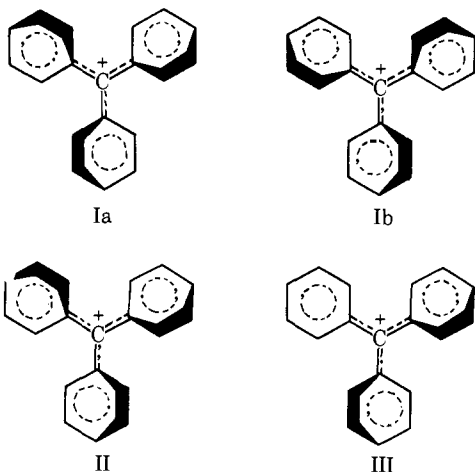
**Abstract:** Chirality in triarylmethyl cations has been detected and the mechanism for enantiomer and diastereomer interconversion studied using *m*- and *p*-CF<sub>3</sub>H groups as diastereotopic nmr probes. The <sup>19</sup>F nmr spectra of these cations exhibit ABX patterns at low temperature which collapse to A<sub>2</sub>X at temperatures above 0° where enantiomer interconversion becomes rapid, and analysis of the variable temperature spectra yields activation parameters for the interconversion process. Distinct resonances for syn and anti diastereomers are also observed for the para'-substituted, *m*-CF<sub>3</sub>H cations. A transition state for propeller interconversion in which two aryl rings rotate perpendicular to the trigonal plane while the third ring rotates into this plane is required by the findings that Δ*F*<sup>‡</sup> for enantiomer interconversion is markedly lowered by para donor substituents and that enantiomers and diastereomers interconvert at about the same rate. A novel source of dissymmetry which is independent of propeller chirality and related to biphenyl-type atropisomerism has been observed for certain disubstituted cations. Equilibration of atropisomers requires a different transition state from that for propeller interconversion and with suitable substitution both processes can be observed. A unique example is given of a compound in which the rotational barrier about an aryl-sp<sup>2</sup> bond leads to the presence of the three discreet types of stereoisomers.

Elucidation of the detailed conformation of the triphenylmethyl (trityl) cation has remained an intellectual challenge for at least 30 years.<sup>1</sup> Since severe steric interactions between the neighboring ortho protons of phenyl rings presumably prohibit the coplanar geometry required for maximum resonance stabilization of the positive charge, the molecule must assume a compromise conformation. Electronic<sup>2</sup> and infrared<sup>3</sup> spectra and p*K*<sub>R</sub><sup>-4</sup> data have been interpreted to favor propeller (I),<sup>5</sup> skew-helix (II),<sup>5a,6</sup> and plane-propeller (III)<sup>4a</sup> conformations. The propeller (I) is now generally accepted as the most likely conformation, since X-ray studies demonstrate that trityl perchlorate

exists in a propeller conformation in the crystalline state<sup>7</sup> and nmr studies<sup>8,9</sup> give no evidence for dissymmetric structures II or III.

The chiral propeller conformation requires the presence of two enantiomeric forms (Ia and Ib). These enantiomers differ by the opposite pitch of their phenyl rings and can be interconverted by rotating each phenyl ring either *through* or *perpendicular* to the trigonal plane. Since the former motion leads to increased steric interactions between neighboring ortho protons and the latter leads to decreased charge stabilization by phenyl, studies of the mechanism and energetics for this interconversion provide information on the relative importance of steric and electronic effects in the system. Once available, this information will be useful as a calibration point for the many theoretical calculations<sup>10</sup> which use the trityl system as a model and as a guideline for studies of optically active triarylmethyl cations.<sup>11</sup>

Hindered rotation of aryl rings in multisubstituted trityl cations containing at least one non-para substituent can also result in the existence of geometric isomers (diastereomers), and the elegant fluorine nmr study of the interconversion of geometric isomers for multi-fluorine-substituted trityl cations by Schuster, Colter, and Kurland<sup>9</sup> provided the first quantitative measure of the conformational stability of trityl cations. The low temperature, proton-decoupled, fluorine nmr spectra of 3,3'-difluorotrityl cation and 3,3',3''-trifluoro-



- (1) G. N. Lewis and M. Calvin, *Chem. Rev.*, **25**, 273 (1939).
- (2) S. F. Mason and R. Grinter in "Steric Effects in Conjugated Systems," G. W. Gray, Ed. Academic Press, New York, N. Y., 1958.
- (3) D. W. A. Sharp and N. Sheppard, *J. Chem. Soc.*, 674 (1957).
- (4) (a) N. C. Deno and A. Schriesheim, *J. Amer. Chem. Soc.*, **77**, 3051 (1955); (b) N. N. Lichtin and M. J. Vignale, *ibid.*, **79**, 579 (1957).
- (5) (a) G. N. Lewis, T. T. Magel, and D. Lipkin, *ibid.*, **64**, 1774 (1942); (b) F. Seel, *Naturwissenschaften*, **31**, 504 (1943); (c) N. C. Deno, P. T. Groves, and G. Saines, *J. Amer. Chem. Soc.*, **81**, 5790 (1959).
- (6) M. S. Newman and N. C. Deno, *ibid.*, **73**, 3644 (1951); G. Branch and H. Walba, *ibid.*, **76**, 1564 (1954).

(7) A. H. Gomes de Mesquita, C. H. MacGillavry, and K. Eriks, *Acta Crystallogr.*, **18**, 437 (1965).

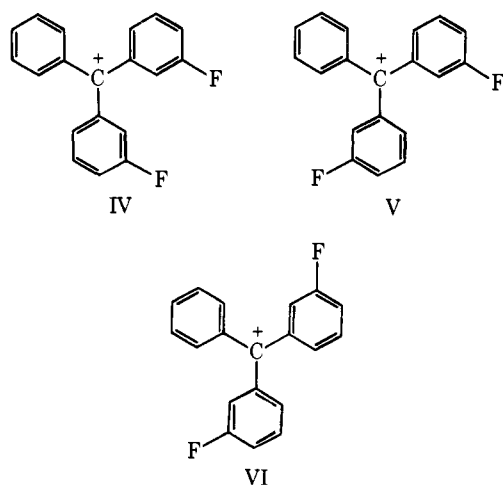
(8) R. B. Moodie, T. M. Connor, and R. Stewart, *Can. J. Chem.*, **37**, 1402 (1959); R. Dehl, W. R. Vaughn, and R. S. Berry, *J. Org. Chem.*, **24**, 1616 (1959).

(9) A. K. Colter, I. I. Schuster, and R. J. Kurland, *J. Amer. Chem. Soc.*, **87**, 2278 (1965); R. J. Kurland, I. I. Schuster, and A. K. Colter, *ibid.*, **87**, 2279 (1965); I. I. Schuster, A. K. Colter, and R. J. Kurland, *ibid.*, **90**, 4679 (1968).

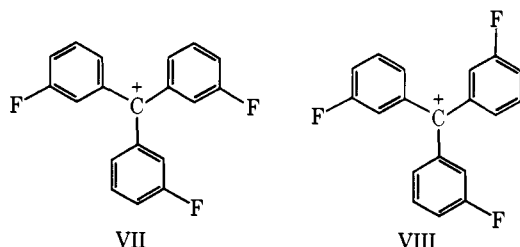
(10) R. Hoffmann, R. Bissell, and D. G. Farnum, *J. Phys. Chem.*, **73**, 1789 (1969), and references therein.

(11) (a) B. L. Murr and C. Santiago, *J. Amer. Chem. Soc.*, **90**, 2964 (1968), and references therein; (b) unpublished work of H. H. Freedman and coworkers.

trityl cation show distinct resonances for the diastereomeric fluorines in IV–VI and VII–VIII, respectively,



and analysis of variable temperature spectra allowed the calculation of activation energies for the interconversion of these isomers. Isomerization occurs when one or more fluorophenyl rings flip (*i.e.*, rotate about the



bond to the central carbon through a plane perpendicular to the trigonal plane), and to maintain the assumed propeller conformation, the rings which do not flip reverse pitch by simultaneously passing through the trigonal plane. From an analysis of their results Schuster, Colter, and Kurland came to the important conclusion that isomerization *via* a three-ring flip transition state is most favored, despite recognizing the unattractive feature of complete loss of charge delocalization to all three phenyl rings. It would be desirable to ascertain the validity of this controversial transition state since others<sup>10</sup> have apparently accepted it as being equally valid for the interconversion of unsubstituted trityl cation enantiomers.

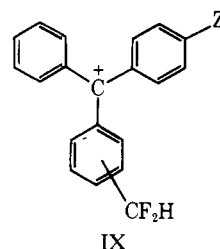
Schuster, Colter, and Kurland also conclude that their nmr data establish the propeller conformation for these trityl cations in solution. In fact, their detection of diastereomers effectively establishes the presence (and magnitude) of a rotational barrier in the trityl cation but is noncommittal regarding the presence of the enantiomers required by a chiral propeller conformation. In actuality, were it not for its intuitive unacceptability on steric grounds, a trityl cation with coplanar ground state conformation could not be excluded by their data. Remarkably, and as detailed below, the nmr demonstration of chirality in a trityl cation by Breslow, *et al.*,<sup>12</sup> also cannot be attributed to a propeller conformation, their interpretation notwithstanding.

(12) R. Breslow, L. Kaplan, and D. LaFollette, *J. Amer. Chem. Soc.*, **90**, 4056 (1968).

Studies of conformational chirality by nmr are best accomplished by observations using a diastereotopic probe,<sup>13</sup> and in a preliminary communication<sup>14</sup> we reported the first direct observation and study of the interconversion of enantiomeric propeller conformations of a trityl cation in solution using a *m*- or *p*-CF<sub>2</sub>H group as such a probe. Also reported was a study of the nature of the transition state for the interconversion process by means of substituent effects, which allowed the conclusion that a two-ring rather than three-ring flip is involved. This paper presents details of our earlier findings and discloses evidence for a second element of dissymmetry in trityl cations which is independent of propeller chirality but of predominant importance in determining the nmr spectral<sup>12</sup> and optical<sup>15</sup> behavior of some substituted trityl cations.

## Results and Discussion

**Basic Nmr Results and Substituent Effects.** For a group CX<sub>2</sub>Y in a chiral molecule, magnetic nuclei at X are diastereotopic,<sup>13</sup> and when the theoretically predicted chemical shift nonequivalence for the X nuclei is experimentally observable the group is useful for studying the chiral center. Such groups have special utility in systems for which the rate of enantiomer interconversion changes from fast to slow on the nmr time scale within an accessible temperature range, since analysis of such variable temperature spectra can yield activation parameters for the interconversion process. Variable temperature <sup>19</sup>F 94.1-MHz nmr spectra obtained for the *m*-difluoromethyltrityl cation (IXa) are shown in Figure 1. The fluorine spectra change from an A<sub>2</sub>X doublet ( $J_{\text{HF}} = 56$  Hz) at 25° to an ABX octet



- |  |  |
|--|--|
| a, <i>m</i> -CF <sub>2</sub> H, Z = H                | d, <i>p</i> -CF <sub>2</sub> H, Z = H                |
| b, <i>m</i> -CF <sub>2</sub> H, Z = CH <sub>3</sub>  | e, <i>p</i> -CF <sub>2</sub> H, Z = CH <sub>3</sub>  |
| c, <i>m</i> -CF <sub>2</sub> H, Z = OCH <sub>3</sub> | f, <i>p</i> -CF <sub>2</sub> H, Z = OCH <sub>3</sub> |

( $\Delta\nu_{\text{FF}} = 140$  Hz,  $J_{\text{FF}} = 301.5$  Hz) below  $-30^\circ$ , and the nonequivalence of the fluorines<sup>16</sup> can be attributed unambiguously to diastereotopism in the chiral trityl group.<sup>17</sup> Comparison of the experimental spectra with computer-generated spectra yields the activation parameters<sup>18</sup> for interconversion between the enantiomeric propellers listed in Table I. These spectra are such ( $\Delta\nu_{\text{FF}}/J_{\text{FF}} < 0.5$ ) that changes in line shape for the intense central four lines of the spectra and the

(13) For nomenclature and background of nmr spectroscopy of chiral compounds see: (a) M. van Gorkom and G. E. Hall, *Quart. Rev., Chem. Soc.*, **32**, 14 (1968); (b) K. Mislow and M. Raban, *Top. Stereochem.*, **1**, 1 (1967).

(14) J. W. Rakshys, Jr., S. V. McKinley, and H. H. Freedman, *J. Amer. Chem. Soc.*, **92**, 3518 (1970).

(15) B. L. Murr and L. W. Feller, *ibid.*, **90**, 2966 (1968).

(16) That nonequivalent methyls were not observed for the analogous *m*-isopropyl compound attests to the greater sensitivity of fluorine chemical shifts.

(17) The spectra demonstrate rigorously only a chiral conformation for the trityl cation and not necessarily a propeller conformation; however, we accept the propeller conformation as the most reasonable source of chirality.

(18) G. Binsch, *Top. Stereochem.*, **3**, 123 (1968).

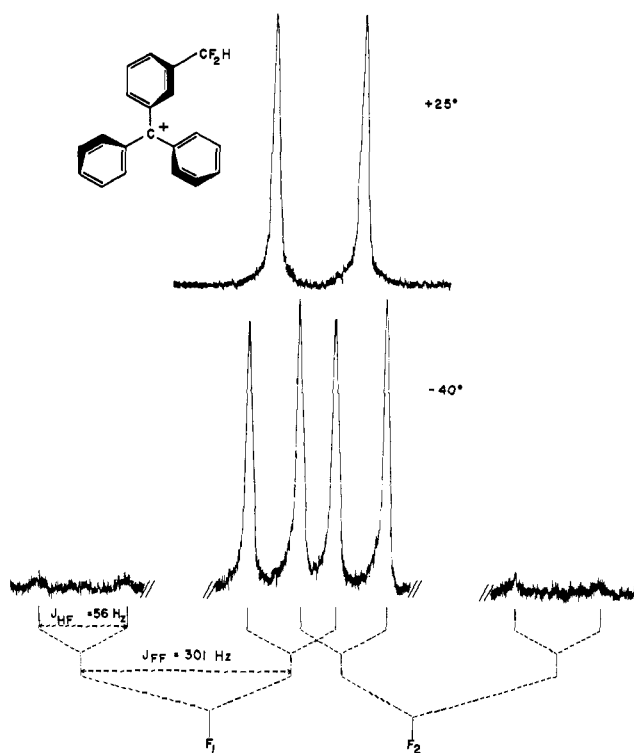


Figure 1. Fluorine nmr spectra of *m*-CF<sub>2</sub>H-trityl<sup>+</sup> SbCl<sub>5</sub>OH<sup>-</sup> in acetonitrile at 94.1 MHz showing limits of slow (−40°) and fast (25°) exchange.

weaker outer four lines occur over different temperature ranges, and the accuracy of the results thus benefits from the ability to make rate measurements over the large combined temperature range (40°). Spectra were also measured for the *p*-CF<sub>2</sub>H isomer (IXd) and exhibit similar trends but with a reduced chemical shift nonequivalence ( $\Delta\nu_{FF} = 62$  Hz), consistent with the greater distance of the para position from the source of dissymmetry. Activation parameters derived from these spectra are also listed in Table I.

Table I. Activation Parameters for Substituted Trityl Cation Propeller Interconversion<sup>a</sup>

Compd	Substituents	$\Delta F_{25^\circ}^\ddagger$	$\Delta S_{25^\circ}^\ddagger$	$T_c^\circ$	$\nu_{F1} - \nu_{F2}$ (−40°) <sup>b</sup>
IXa <sup>f</sup>	<i>m</i> -CF <sub>2</sub> H	12.7	−6.2	0	140
IXd <sup>f</sup>	<i>p</i> -CF <sub>2</sub> H	12.3	13.3	−2	62
IXb <sup>g</sup>	<i>p</i> '-CH <sub>3</sub> , <i>m</i> -CF <sub>2</sub> H	11.6	−0.7	−14, −48 <sup>c</sup>	127, 14 <sup>d</sup>
IXe <sup>g</sup>	<i>p</i> '-CH <sub>3</sub> , <i>p</i> -CF <sub>2</sub> H	10.4 <sup>e</sup>		−30	47
IXf <sup>h</sup>	<i>p</i> '-OCH <sub>3</sub> , <i>p</i> -CF <sub>2</sub> H	~8.7 <sup>e</sup>		−85	

<sup>a</sup>  $\Delta F^\ddagger$  is in kilocalories per mole and  $\Delta S^\ddagger$  is in entropy units. Probable uncertainty in  $\Delta F^\ddagger$  is 0.4 kcal/mol. <sup>b</sup> Chemical shift between diastereotopic fluorines in hertz at 94.1 MHz at −40°. <sup>c</sup> Coalescence temperature for diastereomer interconversion process. <sup>d</sup> Chemical shift between diastereomers (see Figure 3). <sup>e</sup> Approximate value calculated from rate observed at  $T_c$  with  $\Delta S^\ddagger = 13.3$  eu. <sup>f</sup> In acetonitrile. <sup>g</sup> In propionitrile. <sup>h</sup> In propionitrile–vinyl chloride mixture.

$\Delta F_{25^\circ}^\ddagger$ <sup>19</sup> from Table I for the meta and para isomers (IXa and IXd), which are identical within the experimental uncertainty, are in fair agreement with the Schus-

(19) We choose to use  $\Delta F^\ddagger$  rather than  $\Delta H^\ddagger$  or  $E_a$  in this and subsequent discussions as the most accurately known and probably most significant parameter.

ter, Colter, and Kurland value of 14 kcal/mol. However we believe these results are inconsistent with the three-ring flip transition state suggested by Schuster, Colter, and Kurland. For example, simple HMO calculations, such as those performed by Schuster, Colter, and Kurland,<sup>9</sup> suggest that an activation energy of 30 kcal/mol should be associated with this transition state. A three-ring flip mechanism is also intuitively unsatisfactory; a two-ring flip transition state should logically be of lower energy since the full charge delocalization energy of one phenyl ring is maintained and space-filling molecular models suggest that unfavorable steric interactions would still be small. Finally, recent potential energy calculations<sup>10</sup> probing the mechanism for interconversion of enantiomers of the diphenylmethyl cation favor a transition state in which one ring, rather than two, is perpendicular.

For these reasons a substituent effect experiment to test the importance of the three-ring flip transition state was designed, based on the following considerations. Substitution of a resonance stabilizing group in the trityl cation must lower the ground state energy, but would be expected to have little effect on the energy of the three-ring flip transition state since the aryl  $\pi$  orbitals are perpendicular to and not conjugated with the p orbital of the central carbon. On the other hand, transition states for two-, one-, or zero-ring flips have at least one coplanar aryl ring oriented for maximum overlap with the central p orbital, with those conformations in which the donor-substituted phenyl is coplanar being favored. The donor substituent thus stabilizes these transition states more than the nonplanar ground state, where such maximum overlap is not possible. Additionally, in two- or one-ring flip transition states this increased stabilization by the remaining coplanar aryl groups will likely be enhanced as the result of increased electron demand by the central carbon.<sup>20, 21</sup>

Consequently, one can predict that the activation energy will be raised by substitution of a resonance donor group if a three-ring flip is most important and lowered if a two-, one-, or zero-ring flip occurs.<sup>22</sup> The markedly lowered activation free energies observed for the *p*'-methyl and -methoxy substituted cations (IXb, e, and f) in the table therefore clearly militate against a three-ring flip mechanism for our system.

**Spectral Analysis for Disubstituted Cations.** Conformational analysis for *p*'-substituted-*m*-difluoromethyltrityl cations is more complex. Figure 2 illustrates that four different conformations now exist for these compounds: a and b are enantiomeric and each is diastereomeric to the other enantiomeric pair c and d. Spectral analysis is thus complicated since CF<sub>2</sub>H groups in the syn (a and b) and anti (c and d) diastereomers are in nonequivalent environments and can give rise to a doubling of the lines in Figure 1. The low temperature spectrum of *p*'-methyl-*m*-difluoromethyltrityl cation (IXb) in Figure 3 demonstrates the consequence of these two diastereomeric sets of enantiomeric pairs. The spectrum appears as two ABX octets separated by ca. 14 Hz, corresponding to CF<sub>2</sub>H in the equally

(20) L. D. McKeever and R. W. Taft, *J. Amer. Chem. Soc.*, **88**, 4544 (1966).

(21) J. W. Rakshys, Jr., S. V. McKinley, and H. H. Freedman, *Chem. Commun.*, 1180 (1969).

(22) This argument relies on the reasonable assumption that exchange in the substituted and unsubstituted cations occurs by the same mechanism.

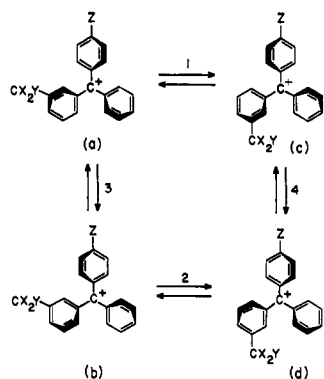
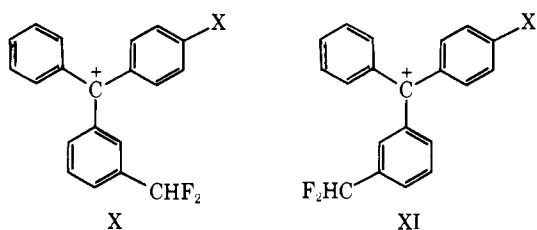


Figure 2. Enantiomers and diastereomers of meta,para'-disubstituted trityl cations, and processes for their interconversion. Conformers a and b are enantiomers and each is diastereomeric to the enantiomeric pair, c and d.

populated syn and anti diastereomeric environments, X and XI, with fluorines diastereotopic in each. Only the central eight lines of the 16-line spectrum are reproduced in Figure 3. It is to be noted that *p*'-substituted-



*p*-CF<sub>2</sub>H trityl cations (IXe,f) do not suffer this complication because diastereomers are now not possible; it was because of this simpler spectral interpretation that the *p*-CF<sub>2</sub>H isomers were studied.

Although the spectra of Figure 3 are more complicated than those in Figure 1 they also yield more information. In particular, line-shape analysis for these spectra provides further insight concerning the transition state for propeller interconversion. The processes which exchange diastereomers and diastereotopic nuclei are assigned separate rate constants,  $k_d$  and  $k_n$ , respectively, and their ratio  $a$  ( $k_n/k_d$ ) is included as a variable in the equations used to calculate the spectra (see Experimental Section). The  $a$  value is important since its value is determined by the transition state structure. The interconversion of diastereotopic nuclei would occur through transition states with any combination of coplanar and perpendicular rings<sup>23</sup> whereas interconversion of diastereomers (X  $\rightleftharpoons$  XI) requires a transition state in which the *m*-difluoromethylphenyl ring is perpendicular to the trigonal plane. In terms of Figure 2, processes 1, 2, 3, and 4 can interconvert diastereotopic nuclei whereas only processes 1 and 2 interconvert diastereomers.

Consider a one-ring flip transition state, for example, with one aryl ring perpendicular and two coplanar. If in the first approximation the probability of each ring being in the perpendicular orientation is equal (see subsequent discussion), then the probability of the *m*-

(23) This statement assumes the chemical shift difference between diastereotopic fluorines in this compound results mainly from the propeller dissymmetry and not atropisomerism (*vide infra*). Since the chemical shift difference observed is similar to that for the unsubstituted compound where only propeller dissymmetry exists, the assumption seems reasonable.

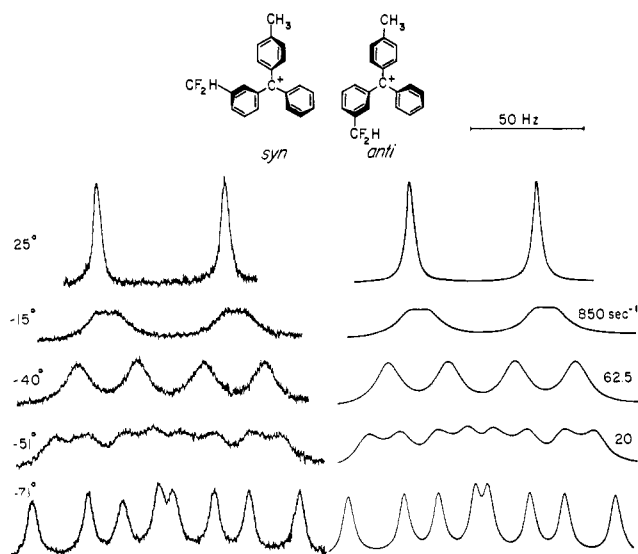


Figure 3. Temperature dependence of fluorine nmr spectra of *m*-CF<sub>2</sub>H-*p*'-trityl<sup>+</sup> BF<sub>4</sub><sup>-</sup> in propionitrile along with calculated spectra and corresponding rate constants. The low intensity outer eight lines of both calculated and experimental spectra are not reproduced, but are included in the line-shape calculations.

difluoromethylphenyl ring being perpendicular is one-third and consequently  $a$  equals 3.0 for a one-ring flip transition state. Similar reasoning predicts  $a$  values of 1.0, 1.5, and infinity for three-, two-, and zero-ring flips, respectively. Comparison of calculated and experimental spectra over the entire temperature range thus yields a best  $a$  value, as well as activation parameters for the exchange process. For the *p*'-methyl compound IXb, calculated spectra matching the experimental spectra over the entire temperature range could not be obtained for  $a$  greater than 2.0. Matching was possible with  $a$  less than 2.0, however, and best Arrhenius plots were obtained for  $1.5 \geq a \geq 1.0$ . These findings thus discriminate against zero- and one-ring flip models and favor a two-ring flip transition state.

However, inasmuch as our assumption of the equally probable perpendicular orientation of each phenyl, regardless of substituent, is only an approximation, the case against a one-ring flip is weakened. In particular, the one-ring flip transition state conformation in which the *m*-difluoromethylphenyl is always perpendicular is also consistent with the finding  $1.5 \geq a \geq 1.0$ , and it is conceivable that the combined electronic effects of *m*-CF<sub>2</sub>H and *p*'-CH<sub>3</sub> would stabilize this conformation, relative to the other two isomeric one-ring flip conformations, to the extent that it dominates the one-ring flip exchange process. For similar reasons we believe the results of Schuster, Colter, and Kurland can also be consistent with a two-ring flip transition state, despite the fact that their observed exchange kinetics were apparently in better agreement with their rate equation calculated for a three-ring flip process than with their equation predicted for a two-ring flip process. In deriving their equation for a two-ring flip the *a priori* assumption was made that the two possible transition states for the 3,3'-difluorotrityl cation, XII and XIII, are equally populated. However, the stereochemical consequence of a three-ring flip and of a two-ring flip where both *m*-fluorophenyls are always perpendicular (XII) is identical and the mechanisms cannot

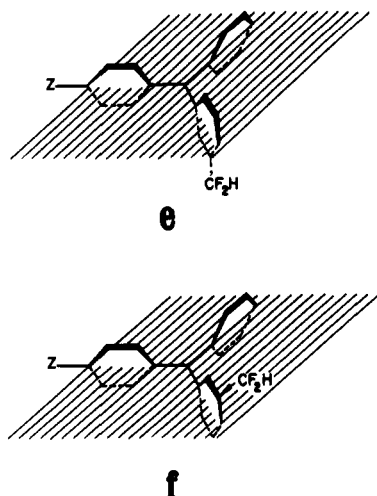
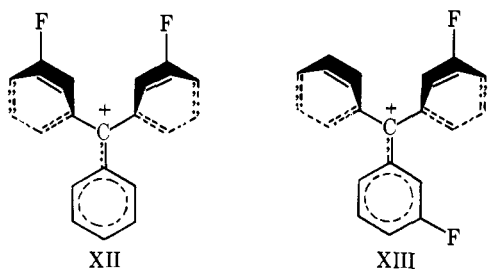


Figure 4. Hypothetical conformations of *m*-CF<sub>2</sub>H, para'-substituted trityl cations demonstrating atropisomerism, where e and f are nonsuperimposable mirror images.

be distinguished by the kinetics. The difference between their predicted rate equations for two- and three-ring flip processes thus resulted from an assumption that XII and XIII are equally probable (*i.e.*, equal in energy) transition states for a two-ring flip process,



and the validity of their conclusion rests on this assumption. It is therefore necessary to consider whether XII could be sufficiently lower in energy than the isomeric two-ring flip transition state structure XIII so as to dominate the two-ring flip exchange process. XII must be of somewhat lower energy than XIII since the destabilizing meta fluorines<sup>24</sup> will have a smaller effect on XII where they are on nonconjugated phenyls than on XIII where one fluorine is on a maximally conjugated phenyl. Consequently, and since only a small energy difference would make XII predominate (*e.g.*, a 1.4 kcal/mol difference in energy would cause a 10:1 population ratio), it is likely that the two-ring flip process would occur predominantly through transition state XII, thereby invalidating the original basis for a three-ring flip transition state. It is fortunate, however, that the results of Schuster, Colter, and Kurland can and do conclusively eliminate a one-ring flip mechanism, since our results cannot do this rigorously.

It is appropriate to summarize our conclusions at this time. Propeller interconversion for the compounds of our study occurs most readily *via* a two-ring flip transition state, and although it would not be reasonable to claim this as a universal mechanism for propeller interconversion in all types of trityl cation derivatives, it is likely that a two-ring flip will also prevail for those

(24) Based on  $pK_R^+$  data<sup>9</sup> *m*-fluorine destabilizes the trityl cation by 1.4 kcal/mol.

trityl cations bearing only weakly interacting substituents. Assuming such a transition state, and accepting the premise that electron-donor substituents stabilize this transition state relative to the ground state, and that electron-withdrawing or ortho substituents lead to ground state destabilization, the following predictions of the effect of structural variation on the activation energy for trityl propeller interconversion can be made. (1) All *mono* substituents, whether ortho, electron withdrawing, or donating will lower the activation energy. (2) The effects of two ortho substituents, two electron-withdrawing substituents, or one electron-donating substituent and one electron-withdrawing substituent on different rings will be complementary. (3) The effects of two electron-donating substituents on different rings will tend to cancel.

**Detection and Role of Atropisomerism in Disubstituted Trityl Cations.** Thus far we have been concerned mainly with processes in which the *m*-CF<sub>2</sub>H ring becomes perpendicular in the transition state. Though these processes (1 and 2 of Figure 2) simultaneously interchange diastereomers as well as propeller enantiomers, an additional source of chirality is still present and is maintained so long as processes 3-4 of Figure 2, in which the *m*-CF<sub>2</sub>H ring rotates through the trigonal plane, is slow. This latter source of dissymmetry, requiring a transition state with the *m*-CF<sub>2</sub>H ring coplanar, is directly analogous to that found in the hindered biphenyls and can be regarded as a novel example of atropisomerism.<sup>25, 26</sup>

The origin of this atropisomerism is made clear by considering the exaggerated conformers e and f in Figure 4 in which all three rings are perpendicular to the trigonal plane. (We do not imply these conformations have physical significance and use them only as an aid to understanding the molecular dissymmetry.) Although dissymmetry arising from the pitch of the phenyl rings has been removed, e and f are still nonsuperimposable mirror images since CF<sub>2</sub>H is below the trigonal plane in e but above the plane in f. This atropisomerism illustrated in Figure 4 also exists in addition to, and independent of, the propeller dissymmetry for all other conformations in which *m*-CF<sub>2</sub>H does not lie in the trigonal plane. The presence of these two independent sources of nonequivalence in our diastereotopic probe now offers the opportunity to detect both sources of chirality in the same molecule,<sup>27</sup> and such an example has been found.

Variable temperature spectra for the *m*-difluoromethyl-*p*'-methoxytrityl cation (IXc) shown in Figure 5 are similar to those observed for the analogous *p*-methyl compound but have one new feature, the small splitting ( $\sim 4$  Hz) observed between  $-20$  and  $-50^\circ$ . Since this splitting is field dependent and therefore does not result from spin coupling, we see no reason-

(25) Use of this word is not rigorously consistent with the original definition but there is precedent in its use to describe the similar dissymmetry in hindered biphenyls (*e.g.*, M. Hanack, "Conformational Theory," Academic Press, New York, N. Y., 1965, p 98).

(26) A still more closely related example involving 9-arylxanthyl cations has been recently explored by S. V. McKinley, P. A. Grieco, A. E. Young, and H. H. Freedman, *J. Amer. Chem. Soc.*, **92**, 5900 (1970).

(27) The presence of such a  $sp^2$ - $sp^2$  "dual barrier" is theoretically observable in any molecule in which an appropriate combination of both steric and electronic effects operates so as to cause the height of the barrier to both coplanarity and to orthogonality, relative to that of a common skewed ground state, to be within the nmr range.

able interpretation other than to attribute this feature to the inner lines of the octet arising from the nonequivalent fluorines in the atropisomeric enantiomers.<sup>28</sup> Further lowering of the temperature gives rise to the usual diastereomers, each of which now contains fluorines which are diastereotopic due to contributions from both propeller and biphenyl-type chirality. It follows that the results of raising the temperature to  $-70^\circ$  can be considered an epimerization.

Figure 2 is useful in summarizing how the spectra of Figure 5 arise. According to our earlier discussion, interconversion of propellers and diastereomers in this system occurs most easily through a two-ring flip transition state with  $p\text{-CH}_3\text{OC}_6\text{H}_4$  in the trigonal plane and  $\text{C}_6\text{H}_5$  and  $m\text{-CF}_2\text{HC}_6\text{H}_4$  perpendicular to the plane (processes 1 and 2) and has a smaller activation energy than unsubstituted trityl (*i.e.*,  $<12.5$  kcal/mol) because of the transition state stabilization provided by the coplanar  $p\text{-CH}_3\text{OC}_6\text{H}_4$  group. On the other hand, atropisomerism is averaged only by processes 3 or 4 where the  $m\text{-CF}_2\text{HC}_6\text{H}_4$  ring passes through the trigonal plane and an extension of previously discussed concepts suggests that the activation energy for these processes is *larger* than for unsubstituted trityl. Processes 3 and 4 most likely occur *via* either a two-ring flip transition state with  $m\text{-CF}_2\text{HC}_6\text{H}_4$  in the trigonal plane, or less likely by a one-ring flip transition state with both  $m\text{-CF}_2\text{HC}_6\text{H}_4$  and  $p'\text{-CH}_3\text{OC}_6\text{H}_4$  simultaneously in the trigonal plane. Thus the higher activation energy for these processes is due to either loss of the  $p'\text{-OCH}_3$  stabilization energy in the former transition state or to unfavorable steric interactions between the coplanar aryl rings in the latter. We prefer the first explanation on the intuitive grounds that the stabilization energy of  $p'\text{-OCH}_3$  will not be large enough to change the earlier finding that the unfavorable steric interaction energy between two coplanar aryl rings in a trityl cation is not overcome by the additional resonance stabilization energy provided by the donor-substituted ring.

Upon generalizing these concepts it is apparent that the donor strength of the para substituent (Z in Figure 2) and possibly the size of the other substituent (*e.g.*, if it were ortho instead of meta as in Figure 2) determine the relative activation energies for processes 1,2 and 3,4. Increasing the donor strength of Z lowers the activation energy for transitions 1 and 2 and raises it for transitions 3 and 4. At the limit of a poor electron donor substituent the transition states for transitions 1 through 4 become energetically degenerate with the consequence that loss of both types of dissymmetry has the same activation energy. The  $p'$ -methyl compound apparently approaches this limit, while the moderate electron donor ability of methoxy allows both types of processes to be observed. Increasing the size of an ortho substituent should lower the activation energy for processes 1 and 2 and increase it for processes 3 and 4 (*i.e.*, for exchange of atropisomers). In this regard the optical activity of Murr and Feller's<sup>15</sup> novel phenylbiphenyl-1-(8-methylnaphthyl)carbonium ion (XIV) is probably a consequence of slow exchange between atropisomers gen-

(28) The possibility that this splitting is due to the magnetically nonequivalent  $\text{CF}_2\text{H}$  groups of diastereomers resulting from hindered rotation about the  $\text{Ar-OCH}_3$  bond can be ruled out by the observation that (a) this splitting is not present in the  $-108^\circ$  spectra and (b) based on rotational barriers observed in related systems,<sup>21</sup> such a methoxy barrier can be estimated to be no larger than 6 kcal/mol, a value considerably less than that suggested by the coalescence temperature.

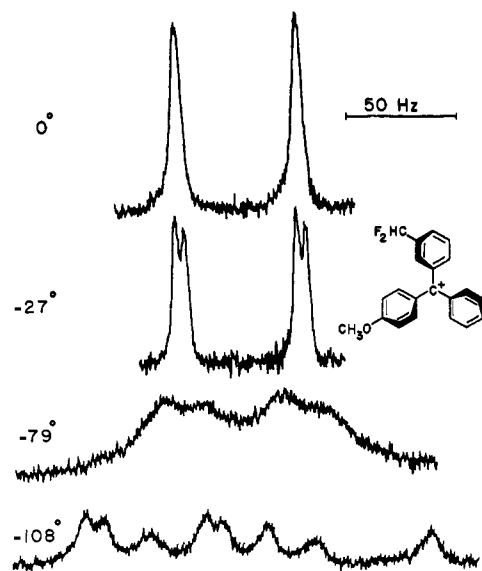
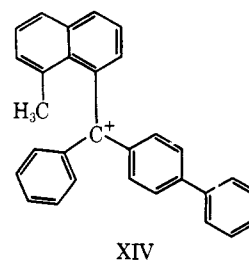
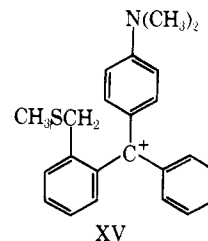


Figure 5. Variable temperature nmr spectra for  $m$ -difluoromethyl- $p'$ -methoxytrityl tetrafluoroborate in propionitrile-vinyl chloride solution.

erated by the presence of the very bulky 8-methylnaphthyl group.



In general, experimental results to verify our several predictions are not available, but the single pertinent study known to us is apparently contrary to our previous prediction. Breslow, *et al.*,<sup>12</sup> found that the methylene protons of XV are diastereotopic ( $\Delta\nu = 0.36$  ppm) at room temperature and attributed their observa-



tion to the presence of trityl propellers which interconvert slowly on the nmr time scale. Since XV contains the bulky  $o\text{-CH}_2\text{SCH}_3$  group and the strongly donor  $p'\text{-N}(\text{CH}_3)_2$  group, our earlier predictions require a small activation energy for propeller interconversion ( $\lesssim 9$  kcal/mol) by processes 1 and 2, but a large activation energy for the atropisomerization of processes 3 and 4. Inasmuch as the data of Breslow, *et al.*,<sup>12</sup> suggest the relatively high activation energy of  $\sim 25$  kcal/mol for the exchange of the diastereotopic methylene protons of XV and only enantiomers but not diastereomers are observed, it is most likely that interconversion of trityl propellers for XV is indeed very

rapid at room temperature, and that the spectra observed in fact reflect the residual atropisomerism which is averaged only at higher temperatures. This interpretation involves a mechanism for exchange of the diastereotopic methylene protons in which the ortho-substituted ring passes through the trigonal plane, and differs from Breslow's, *et al.*,<sup>12</sup> conclusion that the exchange process is one in which the phenyls become perpendicular to the trigonal plane. Our interpretation is however consistent with the finding on which they originally based their conclusion, that substitution of a second *o*-CH<sub>2</sub>SCH<sub>3</sub> group lowers the coalescence temperature for CH<sub>2</sub> equilibration, since substitution of this bulky group will lower the activation energy for processes 3 and 4 (Figure 2) for the reasons discussed previously.

Breslow, *et al.*,<sup>12</sup> have also studied several trisubstituted trityl cations containing *o*-CH<sub>2</sub>SCH<sub>3</sub> or *o*-CH<sub>2</sub>OCH<sub>3</sub> groups. Their results for these systems can be qualitatively rationalized by an extension of these concepts but complete analysis would be difficult since four diastereomeric sets of enantiomeric conformer pairs must be considered and apparently the diastereomeric conformations are unequally populated.

The conformational dynamics of the trityl cations described above are particularly significant in that, to our knowledge, it is the first example of a molecule with a noncoplanar ground state in which two independent rotational processes about the same bond are directly observable.<sup>27</sup> In principle, additional examples of such dual barriers about sp<sup>2</sup>-sp<sup>2</sup> bonds, free of the complications resulting from extraneous trityl propeller chirality, should be accessible and are being sought.

**Anion and Solvent Effects.** Nmr studies of rotational barriers in delocalized ions are plagued by the possibility that the temperature-dependent spectra observed may actually result from a covalent-ionic equilibrium.<sup>29</sup> This is not likely for the present system since exchanges between trityl cations and their carbinol precursors are known to be slow on the nmr time scale even at room temperature.<sup>30</sup> It is likely, however, that the cations exist in solution as ion pairs<sup>31</sup> and this may influence our results somewhat, although use of either SbCl<sub>5</sub>OH<sup>-</sup> or BF<sub>4</sub><sup>-</sup> counterions gave identical spectra and no solvent effect on the activation parameters was observed. Large solvent effects on the chemical shift nonequivalence between diastereotopic fluorines were observed, however. The effects are so large that spectra for *m*-difluoromethyltrityl cation which coalesce at 0° in acetonitrile or propionitrile show no fluorine nonequivalence in methylene chloride even at -80°, and show intermediate behavior in mixtures of methylene chloride with the nitriles, trifluoroacetic acid, or propionic acid. Noting that solvents which cause the largest chemical shifts contain anisotropic groups (*i.e.*, C≡N and C=O), one can speculate that these solvents provide a strongly anisotropic solvent sheath around the cation which greatly magnifies the small intrinsic nonequivalence of the diastereotopic fluorines. The importance of solvent and conformational effects

(29) V. R. Sandel, S. V. McKinley, and H. H. Freedman, *J. Amer. Chem. Soc.*, **90**, 495 (1968).

(30) A. E. Young, V. R. Sandel, and H. H. Freedman, *ibid.*, **88**, 4532 (1966).

(31) N. Kalfoglou and M. Szwarc, *J. Phys. Chem.*, **72**, 2233 (1968), and references therein.

on the chemical shifts of diastereotopic nuclei has been recognized by others.<sup>18b</sup> Our observation of a marked temperature dependence on the fluorine chemical shifts is consistent with this solvation explanation. At temperatures below coalescence, shifts between the diastereotopic fluorines increase at rates as large as 1.1 Hz/deg.

The large chemical shift nonequivalences observed for the CF<sub>2</sub>H group in this study recommend its further exploitation as a relatively innocuous but sensitive nmr diastereotopic probe, although the apparently severe requirements of solvent (and probably structure) may limit its utility.

## Experimental Section

**Materials.** SbCl<sub>5</sub>OH<sup>-</sup> and BF<sub>4</sub><sup>-</sup> carbonium ion salts were prepared from the corresponding carbinols by known methods.<sup>32</sup> The carbinols were obtained from the reaction in THF under argon atmosphere of an appropriately substituted benzophenone with the aryllithium reagent prepared at -70° from butyllithium and *m*- or *p*-difluoromethylbromobenzene. After 1 hr the reaction was brought to room temperature and allowed to stir for 8 hr. Following hydrolysis of the reaction mixture with saturated aqueous NH<sub>4</sub>Cl and separation of the organic phase, column chromatography on silica gel (petroleum ether-methylene chloride solvent mixtures) yielded the pure carbinol as an oil in approximately 50% yield. *m*-Difluoromethylbromobenzene (bp 60° (5.0 mm)) and *p*-difluoromethylbromobenzene (bp 62° (4.8 mm)) were obtained by fluorinating the bromobenzaldehydes with SF<sub>4</sub>.<sup>33</sup>

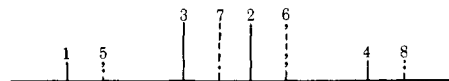
The structures of all compounds prepared were confirmed by their <sup>1</sup>H and <sup>19</sup>F nmr and infrared spectra.

**Measurement and Analysis of Nmr Spectra.** Samples 0.3-0.5 *M* in carbonium ion salt and containing 1,1,2,2-tetrachloro-3,3,4,4-tetrafluorocyclobutane (TCTFCB) as internal reference were prepared in sealed tubes for nmr measurements. Measurement at temperatures below -90° required addition of vinyl chloride to the sample to keep the solution fluid.

Spectra were obtained on a Varian HA-100 operated at 94.1 MHz using TCTFCB for an internal lock. Probe temperatures were measured by inserting a thermometer into the probe.<sup>34</sup> The thermometer was in a conventional nmr tube along with 0.5 ml of toluene as a heat conductor, the thermometer bulb being positioned in the sensitive coil region of the probe. The uncertainty in the probe temperature thus obtained is less than 0.5°.

Kinetic analyses were performed by calculating and plotting theoretical spectra using a modified version of a computer program written by Whitesides. In the simpler case where no geometric isomers are possible the CF<sub>2</sub>H group gives rise to an ABX spectrum in the slow exchange limit, and exchange of A and B fluorines can be treated as two separate overlapping quartets.<sup>35</sup> The equation for calculating the line shape of the individual quartets is given by Whitesides and coworkers.<sup>36</sup>

For the more complex 16-line CF<sub>2</sub>H spectrum of *m*-CF<sub>2</sub>H-*p*'-X-trityl cation, the two syn and anti diastereomers each give rise to an ABX pattern of equal intensity, and exchange of A and B fluorines within each isomer as well as exchange between isomers occurs. For simplicity of explanation, coupling to X can be temporarily neglected and the spectra considered as the sum of individual AB patterns for each isomer shown figuratively below. The solid lines 1, 3, 2, and 4 belong to one isomer, (AB)<sub>1</sub>, while



(32) H. J. Dauben, Jr., L. R. Honnen, and K. M. Harmon, *J. Org. Chem.*, **25**, 1442 (1960); W. M. Pasika, *Tetrahedron*, **22**, 557 (1966).

(33) W. R. Hasek, W. C. Smith, and V. A. Engelhardt, *J. Amer. Chem. Soc.*, **82**, 543 (1960).

(34) We thank Dr. S. W. Tobey for suggesting and demonstrating this technique. Thermometers were obtained from Brooklyn Thermometer Co. Probe temperatures measured by thermometer compared closely to those obtained at 100 MHz using a methanol sample and the revised van Geet calibration (*Anal. Chem.*, **40**, 2227 (1968)).

(35) G. M. Whitesides and J. D. Roberts, *J. Amer. Chem. Soc.*, **87**, 4882 (1965).

(36) G. M. Whitesides, B. A. Pawson, and A. Cope, *ibid.*, **90**, 634 (1968).

the dotted lines 5, 7, 6, and 8 belong to the other isomer, (AB)<sub>2</sub>. The exchange scheme is treated as the superposition of two simultaneous processes: (i) geometric isomerization between quartets, (AB)<sub>1</sub> ⇌ (AB)<sub>2</sub>, *i.e.*, exchange between magnetic sites 1 and 5, 3 and 7, 2 and 6, and 4 and 8; and (ii) exchange of diastereotopic fluorines within an isomer, *i.e.*, in one isomer (AB)<sub>1</sub> ⇌ (BA)<sub>1</sub> exchanges magnetic sites 1 with 2, and 3 with 4, and in the other isomer, (AB)<sub>2</sub> ⇌ (BA)<sub>2</sub> exchanges lines 5 with 6 and 7 with 8. An 8 × 8 kinetic transfer matrix is then constructed in which each element contains terms which are exchange contributions from both processes,  $[K_{mn}(ii)]/\tau + [K_{mn}(i)]/a\tau$ , where  $K_{mn}$  is the kinetic exchange term for matrix element  $mn$ ,  $i$  and  $ii$  refer to exchange processes described above,  $\tau$  is the preexchange lifetime, and  $a$  is a variable which allows weighting of the two types of exchange. To take account of the coupling to X (*i.e.*,  $\alpha$  and  $\beta$  spins of X), calculations

are performed on two separate 8 × 8 matrices corresponding to the two spin states of X and are summed to give the complete line shape.

The low intensity outer portions of the low temperature ABX patterns were observable only for the *m*-difluoromethyltrityl cation. For the other cations, even though the outer lines were not observed, they were included in the line-shape calculations.  $J_{F-F}$  for these other cations could not be measured directly, but was reasonably approximated to be the same as in the former, 301.5 Hz.

The chemical shift nonequivalence between diastereotopic fluorines was observed to increase markedly with decreasing temperature at temperatures below coalescence (~1.1 Hz/deg). Fortunately the change was linear in temperature and chemical shifts at temperatures above coalescence could be obtained by extrapolation of the linear relationship.

## Nuclear Magnetic Resonance Study of the Conformation of 1,3-Dithiolanes<sup>1</sup>

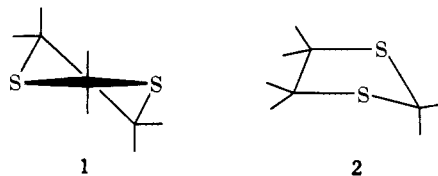
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Contribution from the Department of Chemistry, University of Illinois at the Medical Center, Chicago, Illinois 60612, and Chemical Physics Section, Abbott Laboratories, North Chicago, Illinois 60064 Received January 20, 1971

**Abstract:** The AA'BB' spin systems of the ring methylene protons of some 1,3-dithiolanes were analyzed. The geminal and vicinal coupling constants are reported and when compared to those previously reported for the corresponding 1,3-dioxolanes indicate that the sulfur hetero rings are more puckered than the oxygen isosteres. Application of the Lambert "R" factor determines approximate ring torsional angles for the 1,3-dithiolanes ( $\pm 49^\circ$ ) and the corresponding 1,3-dioxolanes ( $\pm 42^\circ$ ).

Since conformational analysis of five-membered heterocyclic rings by standard spectroscopic methods (nmr, Raman, and infrared) has been complicated and hampered by the facile interconversions which occur between the numerous nearly equienergy conformers, relatively limited information is available on this subject.<sup>3,4</sup> Although the conformations of 1,3-dioxolanes<sup>5-14</sup> and 1,3-oxathiolanes<sup>15,16</sup> have been examined by nmr spectroscopy, the only conformational data available for the 1,3-dithiolane system are based on the vibrational spectra of a series of 1,3-dithiolanes<sup>17</sup>

and X-ray analysis of 2,2'-bis-1,3-dithiolane.<sup>18</sup> These data indicate that the 1,3-dithiolane ring exists preferentially in a C<sub>2</sub> "half-chair" (1) rather than a C<sub>s</sub> "envelope" conformation (2).<sup>19</sup> However, Eliel<sup>14</sup> and Wilson<sup>16</sup> have since cautioned against considering one conformation as "preferred" and suggest a highly flexible five-membered ring with a large number of minimum energy conformations which are intermediate between the classical forms 1 and 2. Eliel<sup>14</sup> further specifies that only the most bulky substituents show signs of specific steric interactions.



### Results

The nmr spectra of a series of 1,3-dithiolanes have been examined to define the ring geometry of this system. The magnitudes of the vicinal and geminal coupling constants of the C-4,5 methylene protons have been determined by iterative computer analysis. The nmr spectra of such ring systems are amenable to analysis since the sulfur atoms insulate the hydrogen atoms

(18) L. B. Brahmé, *Acta Chem. Scand.*, **8**, 1145 (1954).

(19) For convenience, only a single representative conformation of 1 and 2 from each of the 10 possible conformers in the pseudorotation circuit is shown, and no attempt is made to imply that these are the "preferred" conformations of each type.

(1) Abstracted in part from the Ph.D. dissertation of L. A. Sternson, University of Illinois at the Medical Center, Chicago, Ill., 1970.

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