Barriers to Rotation about the Amide (N–CO) and Sulphenamide (N–S) Bonds in Methyl *N*-Arylsulphenyl-*N*-benzylurethanes. A Simple Molecular Orbital Model to Explain Substituent Effects on Sulphenamide Rotational Barriers[1]

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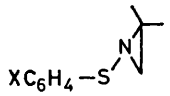
Barriers to rotation about both the N–S and N–CO bonds have been measured in a series of substituted methyl *N*-arylsulphenyl-*N*-benzylurethanes, $XC_6H_4SN(CH_2C_6H_5)CO_2CH_3$, by analysis of the temperature dependent n.m.r. spectra of the benzyl methylene protons. N–S Torsional barriers increase linearly with increasing electron demand of the substituents (σ^- substituent constant), while N–CO barriers are substituent independent. This result is inconsistent with a mechanism for S–N torsion involving $(p–d)\pi$ conjugation between the nitrogen lone pair and sulphur. An alternative rationale is proposed, based on a simple perturbational molecular orbital model. Application of the model to various experiments is discussed, with the conclusion that it adequately rationalizes all the currently available (and sometimes inexplicable) results on sulphenamides.

THE possible conjugation between a low lying vacant *d* orbital of sulphur with a nonbonding electron pair of an adjacent first row element (*e.g.* nitrogen, oxygen, or a carbanion) has often been employed to rationalize the differences in chemical reactivity of sulphur compounds and their oxygen analogues.[2] The question of the extent to which such $(p–d)\pi$ conjugation actually affects organic sulphur chemistry remains, however, quite controversial, in view of recent theoretical studies which conclude that it is insignificant.[3] *d*-Orbital conjugation provided an elegant explanation for substituent effects on the barrier to rotation about the N–S bond in substituted arenesulphenamides (XC_6H_4SNRR').[4,5] In this system, studied by Raban and his co-workers, the rate of rotation was found to decrease substantially with increasing electron-withdrawing power (Hammett σ) of a *meta*- or *para*-substituent X. This was attributed to a greater double bond character of the N–S bond in the torsional ground state, caused by partial transfer of the nitrogen lone pair into a vacant *d*-orbital on sulphur, as a result of electron attraction by the substituent X. However, further studies on sulphenamide chemistry, led to observations which could not be rationalized in terms of *d*-orbital conjugation: the absence of a substituent effect on nitrogen inversion barriers in *N*-arylsulphenylaziridines (1)[6] and *N*-arylsulphenyl-



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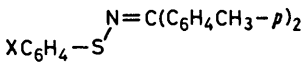

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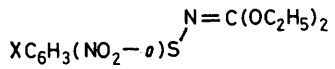
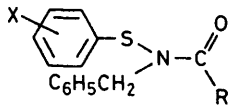


(3)

imines (2)[7] and -iminocarbonates (3)[8] is inconsistent with the $(p–d)\pi$ conjugation mechanism. The increased bond order of the N–S bond due to $(p–d)\pi$ conjugation in these systems, in the presence of an electron-withdrawing group X, might have been expected to result in a more stabilized transition state for nitrogen inversion and hence in a lower barrier.†

The present study critically examines the $(p–d)\pi$ mechanism for torsion about the N–S bond in sulphenamides, using an experimental model designed to answer this question.

The choice of a molecular system for this study is based on previous results in series (1).[6] If $(p–d)\pi$ conjugation were important in the sulphenylaziridine molecule, one would expect the planar transition state for nitrogen inversion to be more stabilized the more electronegative the substituent X. The observation that nitrogen inversion barriers are independent of the substituents on the phenyl ring can only be explained, within the framework of *d*-orbital conjugation, by assuming equal substituent effects (whether stabilizing or



(4) R = H
(5) R = C_6H_5
(6) R = OCH_3

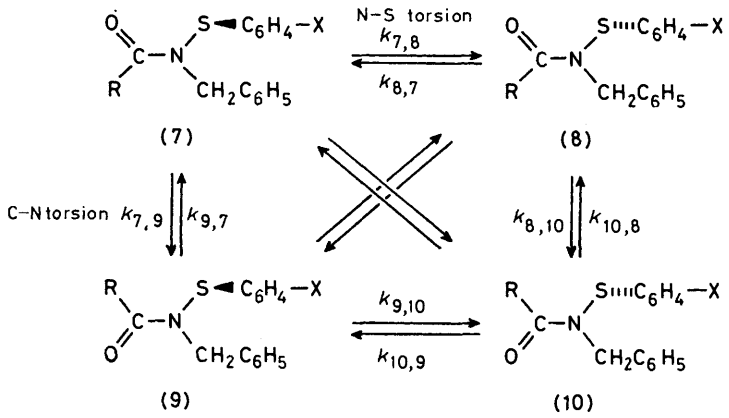
a; X = *p*-OCH_3
b; X = *p*-CH_3
c; X = H
d; X = *p*-Cl
e; X = *m*-NO_2
f; X = *p*-NO_2
g; X = 2,4-$(NO_2)_2$

destabilizing) on both the pyramidal (ground) and planar (transition) states of the inverting nitrogen atom. However, it is difficult to justify such an assumption. In the present work we have prepared a series of *N*-arylsulphenyl-*N*-benzylamides (4)—(6), and measured their barriers to rotation about the N–C and N–S bonds by the dynamic n.m.r. method.[10] In view of the uncertain conclusions drawn from the study of series (1), we have

† Such an effect was reported [9] for *para*-substituted *N*-phenylaziridines, where nitrogen inversion barriers decreased markedly with increasing Hammett σ constants of the substituents, presumably due to stabilizing $(p–p)\pi$ interaction of the nitrogen lone pair at the transition state.

aimed at a more definite assessment of the extent of *d*-orbital involvement in these compounds, using the following approach: if, in the presence of an electronegative substituent X, the nitrogen lone pair of electrons is more strongly attached to the N–S bond, because of extensive $(p–d)\pi$ conjugation, the electron density near the N–CO bond must decrease. Carboxamides exhibit substantial barriers to rotation about the N–CO bond, which have been attributed to the partial double bond character of this bond, due to conjugation of the nitrogen lone pair with the carbonyl π system.[11] Thus, reduced electron density at the N–CO bond, due to $(p–d)\pi$ conjugation, is expected to result in a *decrease* in carboxamide rotational barriers.*

Measurement of free energy barriers to rotation about the N–CO bond in series (4)—(6) should, therefore, provide evidence for or against the $(p—d)\pi$ mechanism.



SCHEME

RESULTS AND DISCUSSION

N.m.r. Analysis.—The system investigated in this study undergoes two torsional processes, rotations about the N–CO and N–S bonds, each of which is associated with a substantial energy of activation (Scheme). The compounds were so designed as to enable the measurement of both of these activation energies in the same molecule. This is done by monitoring the changes in the n.m.r. signals of the benzyl methylene protons in series (4)—(6) with temperature changes. The shapes of these signals change in different fashion for the two processes, and hence, the barrier measured can be readily and unequivocally assigned to one of the processes. This is the result of the different stereochemical consequences of the two rotational processes; torsion of the N–S bond brings about a degenerate racemization, *i.e.* an interconversion of enantiomers in a racemate [*e.g.* (7) ⇄ (8), (9) ⇄ (10) in the Scheme], while rotation about the carboxamide bond [(7) ⇄ (9), (8) ⇄ (10)] produces an interconversion of two diastereomers, the *syn*- and *anti*-amide isomers. When the former of these processes is slow on the n.m.r. time scale, the prochiral benzyl group 'senses' the local chiral environments in the two enantiomers, and the methylene protons are diastereotopic.[13] Eventually, coalescence of the signals arising from these protons is observed upon heating, and they become enantiotopic when the topomerization [14] is fast on the n.m.r. time scale. When carboxamide rotation is relatively slow (while N–S rotation is fast on the n.m.r. time scale) the methylene protons are enantiotopic and isochronous (*i.e.* chemical shift equivalent), as the time-averaged ground state conformation is achiral. However, the methylene groups in the *syn*- and *anti*-diastereoisomers are diastereotopic and therefore give rise to two unequally intense singlets.

A straightforward assignment of the torsional process under examination follows from the above analysis. Slow torsion about the N–S bond is observed when the initial singlet broadens symmetrically upon cooling of the sample (from its initial temperature at which *both* processes are fast relative to the n.m.r. time scale), and eventually splits into an AB quartet. Further cooling of the sample will result in eventual slow amide rotation, and further splitting of the signals into two separate AB patterns, of unequal intensities, corresponding to *syn*- and *anti*-isomers. A typical series of spectra featuring these changes is depicted in Figure 1. In this case the high field portions of the two quartets accidentally overlap. The reverse situation is shown in Figure 2, where, upon cooling, the initial singlet first splits into two unequal singlets due to slow amide rotation, and further cooling results again in the 'freezing' of both rotations as manifested by the appearance of two AB patterns. The entire process is readily followed by computer simulation (Figures 1 and 2).

The choice of methyl *N*-arylsulphenylurethanes (6) for the study of substituent effects on the amide torsional barrier was necessary since in neither of the amides (4) and (5) could this barrier be measured. In these amides no splitting of the methylene signals due to *syn*–*anti*-interconversion could be observed at sample temperatures as low as −90 °C. We assumed that this was due to an unfavourable equilibrium distribution of

* It has been demonstrated recently that π-electron withdrawal from the nitrogen atom in *para*-substituted formanilides results in reduced rotational barriers.[12]

isomers, and that the major amide isomer was the pair (9) and (10) (Scheme), where the O and S atoms are *anti* to each other and repulsive interactions between their lone pairs are at a minimum. The introduction of

determination. In fact, in some of the compounds the methoxy-singlet just broadened slightly at low temperatures, in [$^2H_8$]toluene solutions, and no splitting was observed.

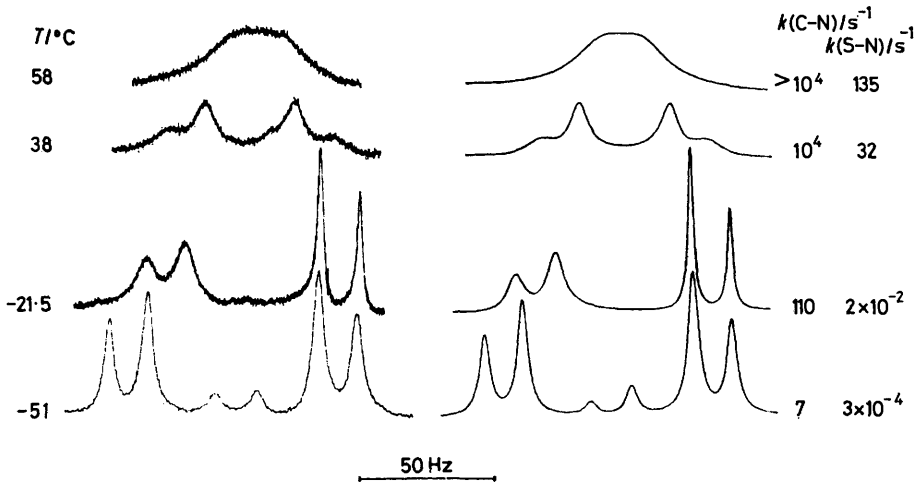


FIGURE 1 Dynamic n.m.r. spectra of the benzyl methylene protons of (6g); left: experimental; right: computed

R = OCH_3 should render these interactions more equal in the two isomers, as in *both* of them oxygen atoms are *syn* to the sulphur atom, and hence their populations should not differ substantially. This indeed was the case, and amide torsional barriers, as well as S–N torsional barriers, could be measured for series (6).

Rate constants were determined for each compound by line shape analysis,* at a number of temperatures, and $\Delta G^{\ddagger}$ values were calculated using the Eyring equation. For the purpose of analysing the substituent effects on rotational barriers we used the free energy of activation rather than the enthalpy of activation or the Arrhenius

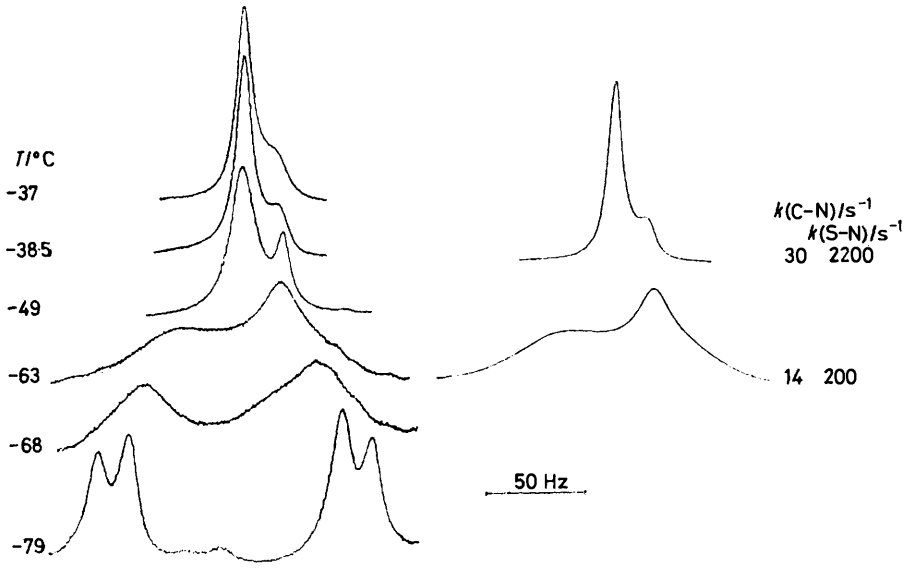


FIGURE 2 Dynamic n.m.r. spectra of the benzyl methylene protons of (6e); left: experimental; right: computed

In principle, carboxamide rotational barriers can be measured independently by observing the coalescence of singlets arising from the methoxy-groups of the amide diastereoisomers. In this way the complex analysis of the signals from the methylene protons, which are affected by the two different rotations, may be verified. However, the chemical shift difference between the methoxy-singlets was too small to permit accurate rate

activation energy, as the former can be determined more accurately.[15] Since the activation entropy in such intramolecular exchange reactions is known to be small,[16] $\Delta G^{\ddagger}$ is only slightly temperature dependent, and there-

* Program DNMR3, by G. Binsch and D. A. Kleier (Quantum Chemistry Program Exchange, Bloomington, Indiana), was slightly modified to accommodate the two spin, four configuration system.

fore values obtained at different temperatures may be used for comparison. The spectra chosen for simulation, for each compound, were taken at temperatures of maximum sensitivity of the line shape towards temperature changes. In simple symmetrical spectral systems these temperatures correspond to the ' coalescence ' temperatures. In our case exact coalescence is not always well defined. However, for each compound line shape analysis was carried out at least at two temperatures, each corresponding to major spectral changes due mainly to one of the torsional processes, and enabling accurate evaluation of the rate constants associated with that process.

The Scheme shows the various transformations involved in the dynamic process of (6). There are twelve first-order rate constants leading from each of the four conformations (7)—(10) to the others. The analysis becomes much simpler, however, when the following relationships are considered. Since (7) and (8) as well as (9) and (10), respectively, are enantiomeric pairs, they exist at equilibrium in equal concentrations. Hence equations (1) and (2) obtain. In an achiral environ-

$$k_{7,8} = k_{8,7} \quad (1)$$

$$k_{9,10} = k_{10,9} \quad (2)$$

ment the enantiomers react at equal rates, so that the rates of amide torsion of (7) and (8) are also equal [equations (3) and (4)].

$$k_{7,9} = k_{8,10} \quad (3)$$

$$k_{9,7} = k_{10,8} \quad (4)$$

The equilibrium constant for *syn–anti* interconversion further reduces the number of independent rate constants [equation (5), where K is the equilibrium constant

$$k_{7,9} = Kk_{9,7} \quad K > 1 \quad (5)$$

for the reaction (7) $\rightleftharpoons$ (9) as well as (8) $\rightleftharpoons$ (10), and is greater than unity, since the *anti*-conformations (9) and (10) are the more densely populated isomers, as is discussed below].

The four rate constants $k_{7,10}$, $k_{10,7}$, $k_{9,8}$, and $k_{8,9}$ for the diagonal pathways in the Scheme represent simultaneous rotations about the amide and sulphenamide bonds. The common transition state for this process by necessity has dihedral angles about the S–N and N–CO bonds near those typical of the transition states for the individual rotations (0° for the C–S–N–C dihedral angle and *ca.* 90° for the O=C–N–C angle). Consequently, the energy content of this transition state is of the order of the *sum* of the individual activation energies, and therefore the simultaneous reaction is highly improbable and the rate constants associated with it are negligibly small. Hence we obtain equation (6). The approach expressed in

$$k_{7,10} = k_{10,7} = k_{9,8} = k_{8,9} = 0 \quad (6)$$

equation (6) is justified by the excellent results obtained from the lineshape analyses, where it has been used as input. It is also supported by the results of theoretical studies of similar systems, where two relatively slow intramolecular changes take place in the same molecule. An *ab initio* SCF-MO study of the rotation–inversion potential surfaces of the carbanions $^{-}CH_2OH$ and $^{-}CH_2SH$ [3b,17] clearly demonstrated the improbability of a simultaneous rotation–inversion process. Similar results were obtained in a CNDO-SCF-MO study of rotation–inversion phenomena in *NN*-dimethylhydroxylamine, where the common transition state for a simultaneous reaction was the highest peak on the rotation–inversion energy surface.*,[18]

We are now left with three independent first-order rate constants ($k_{7,8}$, $k_{7,9}$, $k_{9,10}$) and one equilibrium constant which are required to describe the dynamic behaviour of the system. K Can be evaluated from the intensity ratio of signals due to *syn*- and *anti*-isomers at the slow exchange limit spectrum. The line shape at or below the coalescence temperature for C–N torsion is highly sensitive to changes in K, in a manner clearly distinct from its dependence on rate constants, and therefore K can be evaluated fairly easily by computer simulation. Two of the three rate constants are associated with similar topomerizations due to S–N torsion. $k_{7,8}$ And $k_{9,10}$ are the rate constants for S–N torsion of the *syn*- and *anti*-isomers, respectively. Although different, in principle, these rate constants describe very similar processes and may be expected to be of similar magnitude. The best line shape simulations were obtained using $k_{7,8} = k_{9,10}$. We tested the validity of this equation by using various other combinations of $k_{7,8}$ and $k_{9,10}$. It appears, that the line shape is very sensitive to variations in $k_{9,10}$, the rate constant for exchange of the major AB quartet (which also happens to possess the larger chemical shift $\Delta\nu_{AB}$), and therefore this rate constant is determined to a high degree of accuracy. The exchange rate for the minor isomer can be varied slightly above and below $k_{9,10}$ without affecting significantly the spectral shape.

The other parameters which determine the line shapes of the n.m.r. spectra, are the effective relaxation time, T_2, and $\Delta\nu_a$, $\Delta\nu_1$, and $\Delta\nu_2$, which describe the chemical shift differences between the methylene groups of the amide isomers, and between the methylene proton signals in the major and minor AB quartets, respectively. T_2 Was evaluated from the line width ($W_{\frac{1}{2}}$) of the methylene singlet at the fast exchange limit, according to equation (7), and its value varied between the limits

$$T_2 = 1/\pi W_{\frac{1}{2}} \quad (7)$$

0.1—0.4 s. The line shapes of the exchange broadened spectra are quite insensitive to changes in T_2, as the condition $T_2 \gg 1/\Delta\nu$ is met in all cases.[19]

The chemical shifts $\Delta\nu_a$, $\Delta\nu_1$, and $\Delta\nu_2$ were measured at several low temperatures, and plotted against the temperature. From these plots the $\Delta\nu$ values at higher

* See, however, A. H. Cowley, M. W. Taylor, M.-H. Whangbo, and S. Wolfe, *J.C.S. Chem. Comm.*, 1976, 838; this theoretical study concludes that the topomerization of $H_2N–PH_2$ is a hybrid process which comprises both N–P bond rotation and pyramidal inversion at nitrogen.

temperatures were extrapolated, and used as initial values for spectra simulation. The values were varied to give 'best fits' to observed exchange broadened spectra.

The rate constants and $\Delta\nu$ were also estimated directly at the coalescence temperature of the AB quartet due to the major isomer, by measuring $W_{\frac{1}{2}}$, the width of the coalescence spectrum at half of its height. The rate at coalescence (k_c) and $\Delta\nu_1$ were then interpolated from computed plots of k_c and $\Delta\nu$, respectively, against $W_{\frac{1}{2}}$, in a method described previously.[20] For all the urethanes, except (6g), a spectrum corresponding to coalescence of the major AB quartet could be observed, with a relatively narrow signal, due to the minor isomer, superimposed on it. The spectrum taken at −63°, in Figure 2, represents this situation. The peak belonging to the minor isomer was removed, graphically, from the spectrum, and the resulting band was used for interpolation. Rate constants obtained by this method were always greater than those obtained by line shape analysis by 10—20%. This uncertainty in rate constants, due to the complex nature of the spectral changes, does not, however, affect the barriers to any significant extent: $\Delta G^{\ddagger}$ values calculated from the two k values fall within 0.1 kcal mol^{-1} of each other. In Table 1 we have therefore included only $\Delta G^{\ddagger}$ values associated with the rate constants obtained from line shape analysis.

Table 1 lists the results obtained from the above dynamic n.m.r. analysis. For the amide torsion two rate constants and two $\Delta G^{\ddagger}$ values are given, for the reaction from the minor to the major isomer and for the reverse reaction.

TABLE 1

Dynamic n.m.r. data and free energies of activation

		Amide rotation							Sulphenamide rotation					
Compound	σ^- [a]	K [b]	$\Delta\nu_a$/Hz	$k_{7.9}$ [c]	$k_{9.7}$ [c]	t/°C [d]	$\Delta G^{\ddagger}_{7.9}$ [e]	$\Delta G^{\ddagger}_{9.7}$ [e]	$\Delta\nu_1$ [f,j]	$\Delta\nu_2$ [f,j]	t/°C [d,g]	$k_{7.8}$ [e,h]	$k'_{7.8}$ [e,h]	$\Delta G^{\ddagger}_{7.8}$ [e]
(4d)									159 [i]		−46		360	10.5
(5d)									155 [i]		−63		352	9.7
(6a)	−0.268	4.7	16	36	7.7	−36	12.1	12.8	136	58	−85	270	309	8.7
(6b)	−0.170	4.6	16	36	7.8	−36	12.1	12.8	156	50	−76	300	355	9.1
(6c)	0.000	5.0	20	40	8.0	−35	12.1	12.8	156	50	−69.5	320	352	9.4
(6d)	0.226	6.5	19	42	6.5	−36	12.0	12.9	154	50	−68	310	350	9.5
(6e)	0.710	4.5	19	31	6.9	−38.5	12.0	12.7	100	42	−63	200	255	9.9
(6f)	1.270	8.0	20	25	3.1	−40.5	12.0	12.9	122	40	−40.5	240	280	10.9
(6g)	2.54	4.0	22	110	27.5	−21.5	12.3	13.0	−47 [i]		58	130	130	16.2

[a] Taken from H. H. Jaffé, *Chem. Rev.*, 1953, **53**, 191. [b] Equilibrium constant for *syn*→*anti* interconversion. [c] First-order rate constants in s^{-1}. [d] Temperature at which spectrum for simulation was taken. [e] Free energies of activation in kcal mol^{-1}. [f] $\Delta\nu_1$ and $\Delta\nu_2$ are the chemical shift differences in Hz between the methylene protons for the major and minor amide isomers, respectively. [g] This temperature corresponds to coalescence of the major AB quartet. [h] $k_{7.8}$ was evaluated by complete line shape analysis; $k'_{7.8}$ by interpolation according to ref. 20. [i] A single AB pattern was observed. [j] The coupling between the methylene protons in all cases was 14—14.5 Hz.

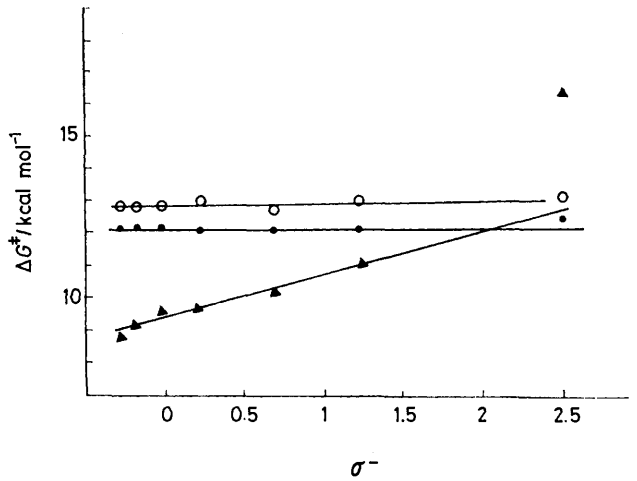


FIGURE 3 Hammett plot of rotational free energy of activation *versus* σ^- substituent constant for series (6). N–S rotation ▲; *syn*→*anti* C–N rotation ($\Delta G^{\ddagger}_{79}$) ●; *anti*→*syn* C–N rotation ($\Delta G^{\ddagger}_{97}$) ○

Substituent Effects.—Free energies of activation for S–N and C–N rotations were plotted against σ^- substituent constants (Figure 3). For the amide barrier, both $\Delta G^{\ddagger}_{7.9}$ and $\Delta G^{\ddagger}_{9.7}$ were treated. It is evident from Figure 3 that $\Delta G^{\ddagger}$ values are linearly correlated with substituent electronegativity. The substituent effect was analysed using Raban's modification of the Hammett analysis,[4a] which enables comparison of dynamic n.m.r. data obtained at different temperatures. The results are listed in Table 2. ρ' Is a temperature independent reaction constant, and ρ_{300} is a constant at 300 K for the purpose of comparison with other ρ values.[4a] For the *ortho* substituted compound (6g) the value of σ^- was estimated as twice the value for a *p*-nitro-group. However, the S–N barrier for this compound strongly deviates from the linear correlation, possibly

TABLE 2

Hammett correlations of activation free energies for series (6) [a]

Rotational process	Substituent constants	Barrier correlated	ρ' [b]	ρ_{300} [c]	Correlation coefficient
S–N	σ^-	$\Delta G^{\ddagger}_{7.8}$	−275 ±29	−0.9 ±0.1	0.978
S–N	σ	$\Delta G^{\ddagger}_{7.8}$	−341 ±74	−1.1 ±0.25	0.917
C–N	σ^-	$\Delta G^{\ddagger}_{7.9}$	16 ±6	0.05 ±0.02	−0.816
C–N	σ^-	$\Delta G^{\ddagger}_{9.7}$	6 ±13	0.02 ±0.04	0.221

[a] Determined by linear least squares analysis. Errors are standard deviations. [b] A temperature independent reaction constant, as defined in ref. 4*a*. [c] Calculated Hammett reaction constant at 27 °C, as in ref. 4*a*.

due to an additional steric interaction which is absent in other compounds. *ortho*-Substituted compounds are not expected to fit into Hammett plots,[21] and the barriers for (6g) have therefore been excluded from the least squares treatment of Table 2. For comparison, correlation of S–N barriers with Hammett σ values has also been included, though σ^- constants seem to yield a better line.

The results show that S–N torsional barriers increase with increasing electron-withdrawing power of the substituents, in the same manner observed previously for other sulphenamides.[4a] The amide barriers, however, show no substituent dependence, within experimental error, regardless of whether the *syn* ⟶ *anti* or the *anti* ⟶ *syn* transformation is used for comparison. As discussed earlier, this observation cannot be rationalized in terms of *d*-orbital conjugation, and must be taken as evidence against the $(p$–$d)\pi$ mechanism for S–N torsion. It also rules out other possible mechanisms involving ground state stabilization by conjugation of the nitrogen lone pair with vacant antibonding orbitals ($n \longrightarrow \sigma^*$ conjugation). In the following sections we develop an alternative mechanism to account for these, as well as previous conflicting observations.

Perturbational Molecular Orbital (PMO) Analysis.— Restricted rotation about the N–S bond in sulphenamides, and particularly the effect of polar substituents on its barrier, may be attributed to the four electron π interaction of the lone pairs on sulphur and nitrogen.

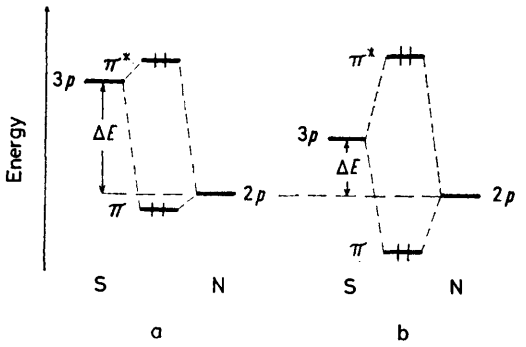


FIGURE 4 Schematic diagram of the four electron interaction between lone pairs on S and N at the transition state for rotation about the N–S bond: (a) without substituent; (b) with an electronegative substituent: smaller ΔE and greater interaction

One of the two lone pair orbitals on sulphur is a hybrid orbital with considerable *s* character, and lies in the C–S–N plane. The other one is nearly a pure $3p$ orbital.[22] The former, due to its *s* character and greater stability, does not effectively participate in π overlap, and therefore its interaction with the nitrogen lone pair is unimportant relative to that of the latter. We now focus on the π interaction between the *p*-lone pair on sulphur and the nitrogen lone pair (Figure 4).* If overlap is not neglected the four electron interaction has a net destabilizing effect, since both the bonding and antibonding molecular orbitals (MOs) are filled.[23] In the torsional ground state conformation the lone pair orbitals are nearly orthogonal to each other, and hence the interaction is minimal. It is quite substantial, however, in the transition state, when the orbitals are parallel, and is responsible for at least a major part of the observed barrier.

The interacting orbital on sulphur, being a $3p$ orbital, is higher in energy than the $2p$ nitrogen orbital (and even more so when the lone pair orbital on nitrogen is a hybrid orbital with less *p* character). The effect of substituents on the sulphenyl phenyl ring is to vary the $3p$ energy level through conjugation across the aromatic π system. The stronger the electron demand by the substituent (as measured by its Hammett σ value), the lower the energy level of the sulphur $3p$ orbital (Figure 4). Evidence for this effect is found in the results of recent photoelectron spectroscopic studies.[24]

It is known from simple PMO theory [23,25] that the two electron interaction between two levels depends on the energy separation (ΔE) between them (Figure 4). The smaller ΔE, the greater the stabilizing effect of the resulting bonding MO. We propose that in the present system the same is true also for the *destabilizing* effect of the four electron π interaction; the smaller ΔE, the greater the interaction (as discussed in the following paragraph). Thus, an electron-withdrawing substituent X will increase the barrier to S–N rotation by decreasing ΔE and hence increasing the destabilizing interaction *at the rotational transition state*. This is in accord with experiment,[4a] although, perhaps, contrary to chemical intuition: one might have expected electron withdrawal from either the S or N end of the S–N bond to result in reduced electron density and hence in reduced lone pair repulsion at the transition state.

Solution of the 2×2 interaction problem without neglect of overlap, leads to expression (8) for the four electron destabilizing energy (DE) where $e_0 = (e_1 + e_2)/2$, the mean of the orbital energies, S_{12} is the overlap integral between orbitals ϕ_1 and ϕ_2, and H_{12} is the interaction matrix element.[23]

$$DE = \frac{4(e_0 S_{12}^2 - H_{12} S_{12})}{1 - S_{12}^2} \qquad (8)$$

Equation (8) shows that DE is not directly related to ΔE, the energy gap ($\Delta E = e_1 - e_2$). In fact, when commonly used to discuss repulsive interactions, equation (8) is taken to mean that lower orbital energies (*i.e.* more negative e_0) results in smaller DE (weaker destabilization). Strictly speaking, this is true only when S_{12} and H_{12} are constant. However, little is known on the variation of S_{12} and H_{12} with changes in conformation or structure, and their effect on DE is often not taken into account.* Clearly, for an accurate estimate of DE, the

* The type of hybridization of the nitrogen lone pair orbital depends on the particular compound. In the present study it is essentially a pure $2p$ orbital.

* The importance of changes in H_{12} when estimating DE can be demonstrated by substitution of two common approximations for H_{12} into equation (8). Substituting $H_{12} = kS_{12}$, results in the same dependence of DE on e_0 as above. However, substituting the equally useful approximation $H_{12} = CS_{12}(e_1 + e_2)$, results in the *opposite* dependence on e_0: this time a lower e_0 will produce a *greater* DE.

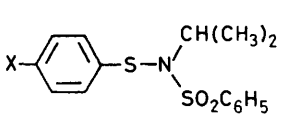
behaviour of e_0, S_{12}, and H_{12} must be studied explicitly in each molecular system. For the present model we assume that lowering the energy of the sulphur lone pair in the presence of an electronegative X (*i.e.* reducing the gap ΔE) results in an increase in the overlap integral S_{12}, as the orbital energies approach each other. This increase is dominant over the decrease in e_0, and results in a greater destabilizing interaction at the transition state for rotation.* With this assumption, this simple model rationalizes the numerous available observations in sulphenamide chemistry (as discussed below), and we feel justified to make the assumption because of the strong experimental support.

Application of the PMO Model to Experimental Observations.—Consider again the possible transformations in series (6), as depicted in the Scheme. As discussed earlier, the simultaneous rotation about both the S–N and N–CO bonds (the diagonal pathway in the Scheme) is a highly unlikely process, and therefore rotations take place only consecutively. It then follows that while carboxamide rotation is in progress, near its transition state, the local geometry of the molecule at the S–N bond *must correspond to the ground state conformation* with respect to rotation about this bond. The key to understanding the absence of a substituent dependence of amide rotational barriers in (6), according to this model, lies in the fact that substituents affect sulphenamides *at the* S–N *torsional transition state*, when the lone pair orbitals overlap. Since amide rotational barriers reflect the difference between the free energies of the molecule at the transition and ground states for this rotation, and since *both* of these states occur while the local conformation at the S–N bond corresponds to the *substituent independent* S–N torsional ground state, there can be no substituent effect on amide rotational barriers in this system. This result is, of course, in agreement with the experimental findings of this study.

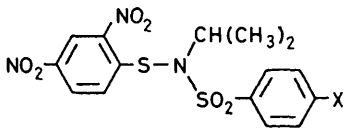
The same explanation holds also for other systems where a second function, capable of undergoing a slow conformational change, is adjacent to a sulphenamide bond. Thus the results of studies on the analogous systems (1)—(3), mentioned in the introduction, are now readily understood. In series (1), for instance, inversion of the nitrogen pyramid occurs while the rest of the molecule assumes a conformation corresponding to the ground state for S–N torsion. The result is that the entire nitrogen inversion process is independent of substituents on the phenyl ring, as the latter have a significant effect only on the S–N torsional transition state. In a similar way planar inversion of nitrogen in (2) and (3) is substituent independent, as it occurs while the S–N function rests at its torsional ground state.

The non-symmetric nature of the S–N bond with respect to substitution on the sulphur and nitrogen ends is accounted for by this model. While electron-demanding substituents X on the sulphenyl phenyl ring in series (6), as well as in (11),[4a] substantially increase S–N torsional barriers, the opposite effect is found in series (12): an electronegative X in (12) causes a *decrease* in the barrier, resulting in a positive Hammett reaction constant.[4a] This becomes obvious from Figure 4: electron withdrawal from the nitrogen end stabilizes the nitrogen lone pair orbital and thus *increases* ΔE, contrary to the effect of electron withdrawal from sulphur.

Further results which fit neatly into the framework of the proposed model are measurements of the rates of conformational changes in the *N*-arylsulphenylaziridine series (1).[6] While only nitrogen inversion barriers were measured directly in this series, an upper limit was determined for the S–N torsional barriers. These were found to be substantially smaller than those measured



(11)



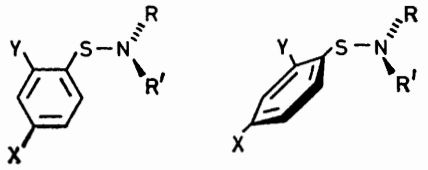
(12)

for acyclic sulphenamide analogues, a result which could not be adequately accounted for by the $(p$–$d)\pi$ model.[6] The unusually low rotational barriers may be attributed to the strain associated with the three-membered aziridine ring, which forces the nitrogen atom to hybridize such that the lone pair occupies an orbital with substantial *s* character. Consequently, there is less effective π overlap between this orbital and the sulphur *p* lone pair orbital at the torsional transition state, resulting in lower barriers than in acyclic analogous sulphenamides.

A recent report by Raban and Yamamoto on torsional barriers in trinitrobenzenesulphenamides [26] sheds more light on the ground state structure for S–N torsion. The introduction of a third nitro-group at the 6 position of 2,4-dinitrobenzenesulphenamides [*e.g.* (12; X = CH_3) and related compounds] resulted in a remarkable *decrease* in rotational barrier. This was attributed to steric inhibition of conjugation due to the presence of the bulky nitro-groups at the *ortho*-positions of the sulphenyl phenyl ring at the ground state. It was concluded, that as long as one of the *ortho*-positions remains unsubstituted, the ground state conformation of arenesulphenamides (13) must hold the phenyl ring within the N–S–C plane. This result is at odds with the $(p$–$d)\pi$ mechanism,[26] for the latter requires a ground state in which the phenyl ring is perpendicular to the N–S–C plane (14), in order to enable conjugation of the nitrogen lone pair with the aromatic π system through a vacant *d*-orbital on sulphur.[4a,26] However, these findings agree with the present model, and hence provide further support for it. Since the substituent effect on S–N torsion is a transition state effect, the structure of the ground state is practically immaterial for the barrier,

* A referee suggested that variation in orbital coefficients, when taken into account properly, might have the opposite effect to variation in S_{12}. The exact changes in S_{12}, H_{12}, and the orbital coefficients (C_1, C_2) associated with changes in substitution may be studied, along with the validity of our assumption, by SCF–MO calculations. Such calculations on model systems are under way, and will be the subject of a future publication.

as long as it does not vary with the substituents. However, the conclusion that (13) correctly represents the torsional ground state, where the sulphur p lone pair is conjugated with the π system, suggests that the preferred orientation of the phenyl ring at the transition state might be the same. Conjugation of the lone pair on sulphur with the π system is required in this model for



(13) (14)

effective interaction between the substituents and the lone pair.

Synthesis and Structural Assignment.—The amides (4)—(6) were prepared by the reaction of an arenesulphenyl chloride with the enolate of the appropriate *N*-benzylamide, obtained by proton abstraction with n-butyl-lithium according to reaction (9).

$$C_6H_5CH_2NHCOR + ArSCl \xrightarrow[C_6H_6]{Bu^nLi} C_6H_5CH_2NCOR \quad (9)$$
$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad SAr$$
$$R = H,\ C_6H_5,\ CH_3O$$

Some analytical and spectral data are shown in Table 3. In the above reaction a conceivable pathway might be *O*-alkylation to yield a sulphenylated imidoester (15) instead of *N*-alkylation. However, this product may be

TABLE 3

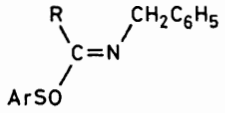
Physical properties

Compound	M.p. (°C)	Carbonyl $\nu_{max.}$/cm^{-1} [a]	δ (p.p.m.) [b] OCH_3	CH_2	Analysed for [c]
(4d)	61—62	1 670		4.6 (s)	C,H,Cl,N,S
(5d)	134—136	1 670		4.84 (s)	C,H,Cl,N,S
(6a)	Red liquid [d]	1 710	3.72 (s) 3.74 (s)	4.62 (s)	C,H,N,S
(6b)	Yellow liquid [d]	1 710	3.72 (s)	4.62 (s)	C,H,N,S
(6c)	Yellow liquid [d]	1 710	3.74 (s)	4.64 (s)	C,H,N,S
(6d)	45—47	1 710	3.74 (s)	4.66 (s)	C,H,Cl,N,S
(6e)	42—44	1 720	3.78 (s)	4.72 (s)	C,H,N,S
(6f)	109—111	1 710	3.76 (s)	4.72 (s)	C,H,N,S
(6g)	131—133	1 720	3.76 (s)	4.4—5.1 [e] (ABq)	C,H,N,S

[a] I.r. spectra of solids were measured in KBr pellets. Liquids were measured as thin films. [b] Taken at room temperature in $CDCl_3$ solution. [c] Analyses agreed within 0.4% of the calculated values for each element. [d] These compounds were viscous liquids which could not be crystallized. [e] At room temperature this spectrum features an exchange broadened AB quartet.

ruled out for the following reasons. (a) *N*-Alkylimines possess very substantial barriers to *syn–anti* interconversion, which are usually greater than 19 kcal mol^{-1},[27] whereas amide barriers measured for series (6) amounted to only 12 kcal mol^{-1}. (b) The imine bond stretching frequency in the i.r. spectrum of Schiff's bases and imidoesters ranges between 1 640 and 1 690 cm^{-1},[28] while compounds of series (6) absorb at 1 710—1 720 cm^{-1}, typical of the carbonyl stretching band for urethanes.[28]

Assignment of the *anti*-structures (9) and (10) to the major isomer observed at low temperatures in the n.m.r. spectra of the urethanes (6) is based on the analogy between these compounds and the amides (4d) and (5d). It was concluded earlier that in the latter compounds the predominant conformation is the *anti*-amide isomer, while the *syn*-isomer is not observed. The data in Table 1 show that the chemical shifts ($\Delta\nu_1$) for the methylene protons of (4d) and (5d) almost equal those of the major isomer in compounds of series (6), while they differ substantially from the corresponding chemical



(15)

shifts ($\Delta\nu_2$) for the minor isomer. We may conclude that the conformation of (4d) and (5d) is analogous to that of the major isomer of (6). This assignment is also supported by the observation that $\Delta\nu_1$, the chemical shift for the AB quartet due to the major isomer, is substantially greater than that for the minor isomer, $\Delta\nu_2$ (Table 1). Since the different chemical shifts for the methylene proton signals arise mainly from their different spatial relationship with the anisotropic carbonyl group,* we expect this effect to be stronger (*i.e.* greater $\Delta\nu$) the closer the methylene group is to the carbonyl. This situation exists in (9) and (10), and hence their structure is assigned to the major isomer.

In this connection it may be of interest to note that the difference between $\Delta\nu_1$ and $\Delta\nu_2$ is considerably smaller in non-aromatic solvents, such as $CDCl_3$ and $CHFCl_2$. This indicates that the unusually large chemical shifts observed here for constitutionally equivalent (though, of course, stereochemically different) protons arises, at least in part, from different average orientations of the aromatic solvent molecules with respect to these protons.

EXPERIMENTAL

N.m.r. spectra were measured on a Varian XL-100-15 spectrometer, operating at 100 MHz. Temperatures were controlled by a Varian variable temperature control unit and calibrated with methanol or ethylene glycol spectra as described in the Varian users manual. Unless stated, all dynamic n.m.r. measurements were made in 7—10% [$^2H_8$]toluene solutions. M.p.s are uncorrected. Microanalyses were performed by the Weizmann Institute microanalytical laboratory. Column chromatographs were

* In other sulphenamides, including *NN*-dialkylarenesulphenamides and *N*-benzyl- or *N*-isopropyl-*N*-arylsulphonylarenesulphenamides [4b] the chemical shift difference between diastereotopic groups is much smaller, and in some cases too small to be resolved. The introduction of the carbonyl function in compounds (4)—(6) resulted in an enormous increase in $\Delta\nu$ values, and hence we conclude that interaction of the protons with this group is the main cause for the change.

run over Merck 7734 silica gel, using solutions of 10—25% acetone in light petroleum (fraction boiling 60—70°).

Theoretical spectra were computed with a CDC-6600 computer using a local modification of program DNMR3 (see footnote on p. 319) and plotted on a Calcomp plotter. Experimental and theoretical spectra were visually compared to obtain ' best fits '.

Arenesulphenyl chlorides were prepared as described in the literature.[4a] *N*-Benzylformamide and *N*-benzylbenzamide for the syntheses of (4d) and (5d) were prepared by standard procedures, and had m.p. 58—60 and 103—105°, respectively.

Methyl N-*Benzylurethane*.—This intermediate was prepared in two methods. *Method A*. This is based on the Curtius rearrangement.[29] A mixture of phenylacetohydrazide (13.5 g, 0.09 mol), water (135 ml), concentrated hydrochloric acid (9 ml), and ether (90 ml) was mechanically stirred and cooled in an ice–salt bath. A solution of sodium nitrite (6.8 g) in water (30 ml) was added dropwise over 20 min. After the addition the ether layer was separated and the aqueous layer extracted twice with portions (50 ml) of ether. The combined ether solution was washed successively with sodium hydrogencarbonate solution (100 ml) and with water (100 ml) and then dried over calcium chloride for 10 min. Methanol (40 ml) was added to the solution and the ether distilled off on a water-bath through a short fractionating column. The remaining solution was refluxed for 20 min, after which the methanol was distilled off. The residue crystallized after cooling, and weighed 9.1 g (0.055 mol, 61%) after filtration. This material was almost pure product (n.m.r.), and after recrystallization from chloroform–hexane had m.p. 60–61° (lit.,[30] 65°).

Method B. Into a well stirred solution of benzylamine (25 ml, 24.5 g, 0.229 mol) in CH_2Cl_2 (150 ml), cooled in a water-bath, was added dropwise a solution of methyl chloroformate (8.1 ml, 10 g, 0.105 mol). The mixture was stirred for 1 h and then filtered. The filtrate was washed twice with 5% HCl solution and then successively with sodium hydrogencarbonate and with sodium chloride solutions and dried over magnesium sulphate. The product solidified after removal of the solvent *in vacuo*, and weighed 16.2 g (0.098 mol, 94%). After recrystallization from chloroform–hexane it had m.p. 60—61°.

N-*Aryl*-N-*benzylsulphenylamides* (4) *and* (5) *and Urethanes* (6).—n-Butyl-lithium (20% solution in hexane) was added dropwise from a syringe to a stirred solution of the appropriate *N*-benzylamide (or urethane) (0.01 mol) in anhydrous benzene (80 ml) over 10 min under nitrogen. The addition was continued until a distinct colour change was observed, an indication that an equivalent amount of reagent had been added. The mixture was stirred for another 30 min and an arenesulphenyl chloride (0.01 mol) dissolved in benzene (25 ml) was added to the mixture and allowed to react for at least 30 min. The mixture was washed successively with solutions of 10% sulphuric acid, 5% sodium hydrogen carbonate, and water, dried ($MgSO_4$), and the solvent removed *in vacuo*. The amides (4d) and (5d) were crystallized from ethanol and ethyl acetate, respectively. The urethanes (6a—g) were purified by chromatography over silica gel. Those which were solids (Table 3) were then crystallized from chloroform–hexane mixtures.

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REFERENCES

[1] Portions of this work have appeared in preliminary form, D. Kost and A. Zeichner, *Tetrahedron Letters*, 1975, 3239; D. Kost and M. S. Sprecher, *ibid.*, 1977, 1089.

[2] (*a*) G. Cilento, *Chem. Rev.*, 1960, **60**, 146; (*b*) K. A. R. Mitchell, *ibid.*, 1969, **69**, 157; (*c*) D. J. Cram, ' Fundamentals of Carbanion Chemistry,' Academic Press, New York, 1965, pp. 71—84; (*d*) S. Oae in ' The Chemistry of Sulfur Compounds,' eds. N. Kharasch and C. Y. Meyers, Pergamon, New York, vol. 3, 1970.

[3] (*a*) J.-M. Lehn and G. Wipff, *J. Amer. Chem. Soc.*, 1976, **98**, 7498; (*b*) F. Bernardi, I. G. Csizmadia, A. Mangini, H. B. Schlegel, M.-H. Whangbo, and S. Wolfe, *ibid.*, 1975, **97**, 2209; (*c*) A. Streitwieser, jun., and J. E. Williams, *ibid.*, p. 191; (*d*) N. D. Epiotis, W. R. Cherry, F. Bernardi, and W. J. Hehre, *ibid.*, 1976, **98**, 4361.

[4] (*a*) M. Raban and F. B. Jones, jun., *J. Amer. Chem. Soc.*, 1971, **93**, 2692; (*b*) M. Raban, G. W. J. Kenney, jun., and F. B. Jones, jun., *ibid.*, 1969, **91**, 6677; (*c*) M. Raban, E. H. Carlson, S. K. Lauderback, J. M. Moldowan, and F. B. Jones, jun., *ibid.*, 1972, **94**, 2738.

[5] Reviews on sulphenamides: (*a*) F. A. Davis, *Internat. J. Sulfur Chem.*, 1973, **8**, 71; (*b*) C. Brown and B. T. Grayson, *Mechanisms of Reactions of Sulfur Compounds*, 1970, **5**, 93.

[6] D. Kost and M. Raban, *J. Amer. Chem. Soc.*, 1976, **98**, 8333.

[7] (*a*) F. A. Davis, W. A. R. Slegeir, and J. M. Kaminski, *J.C.S. Chem. Comm.*, 1972, 634; (*b*) F. A. Davis and E. W. Kluger, *J. Amer. Chem. Soc.*, 1976, **98**, 302; (*c*) C. Brown, R. F. Hudson, and B. T. Grayson, *J.C.S. Chem. Comm.*, 1978, 156. These authors analysed substituent effects on the barrier in terms of stabilizing interactions between the nitrogen lone pair orbital and various vacant antibonding orbitals.

[8] C. O. Meese and W. Walter, *Chem. Ber.*, 1976, **109**, 3129. In this study equal barriers were measured for (3) when X = H and when X = NO_2.

[9] J. D. Andose, J.-M. Lehn, K. Mislow, and J. Wagner, *J. Amer. Chem. Soc.*, 1970, **92**, 4050.

[10] Reviews: (*a*) G. Binsch, *Topics Stereochem.*, 1968, **3**, 97; (*b*) L. M. Jackman and F. A. Cotton, ' Dynamic Nuclear Magnetic Resonance Spectroscopy,' Academic Press, New York, 1975.

[11] Reviews on n.m.r. studies of amides: (*a*) W. E. Stewart and T. H. Siddall, III, *Chem. Rev.*, 1970, **70**, 517; (*b*) ref. 10*b*, p. 203.

[12] C. H. Yoder, J. A. Sandberg, and W. S. Moore, *J. Amer. Chem. Soc.*, 1974, **96**, 2260.

[13] A review on prochiral groups: W. B. Jennings, *Chem. Rev.*, 1975, **75**, 307.

[14] G. Binsch, E. L. Eliel, and H. Kessler, *Angew. Chem. Internat. Edn.*, 1971, **10**, 570.

[15] H. Kessler, *Angew. Chem. Internat. Edn.*, 1970, **9**, 219.

[16] J.-M. Lehn, *Topics Current Chem.*, 1970, **15**, 311.

[17] S. Wolfe, L. M. Tel, and I. G. Csizmadia, *Canad. J. Chem.*, 1973, **51**, 2423.

[18] (*a*) D. Kost and M. Raban, *J. Org. Chem.*, 1976, **41**, 1748; (*b*) D. Kost and M. Raban, *Progr. Theor. Org. Chem.*, 1977, **2**, 20.

[19] L. M. Jackman and S. Sternhell, 'Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry,' Pergamon, London, 1969, 2nd edn., p. 55.

[20] D. Kost and A. Zeichner, *Tetrahedron Letters*, 1974, 4533.

[21] L. P. Hammett, ' Physical Organic Chemistry,' McGraw-Hill, New York, 1970, 2nd edn., p. 357.

[22] W. L. Jorgensen and L. Salem, ' The Organic Chemist's Book of Orbitals,' Academic Press, New York, 1973, p. 42.

[23] N. D. Epiotis, W. R. Cherry, S. Shaik, R. L. Yates, and F. Bernardi, *Topics Current Chem.*, 1977, **70**, 1.

[24] C. N. R. Rao, *Tetrahedron*, 1976, **32**, 1561; F. Bernardi, G. Distefano, A. Mangini, S. Pignataro, and G. Spunta, *J. Electron Spectroscopy and Related Phenomena*, 1975, **7**, 457.

[25] M. J. S. Dewar and R. C. Dougherty, ' The PMO Theory of Organic Chemistry,' Plenum, New York, 1975.

[26] M. Raban and G. Yamamoto, *J. Amer. Chem. Soc.*, 1977, **99**, 4160.

[27] Ref. 10*b*, p. 244.

[28] D. H. Williams and I. Fleming, ' Spectroscopic Methods in Organic Chemistry,' McGraw-Hill, London, 1973, 2nd edn., pp. 59—60.

[29] P. A. S. Smith, *Org. Reactions*, 1946, **3**, 382.

[30] P. C. de la Saulniere, *Ann. Chim.*, 1942, **17**, 353.