washed with toluene and added as a toluene slurry. The flask was immersed in a water bath maintained between 20 and 35°. A solution of 303 g (2.0 mol) of (*o*-chlorophenyl)acetonitrile and 444 g (2.2 mol) of 1,3-dibromopropane in anhydrous diethyl ether (total volume 1 l.) was added at a rapid rate through the dropping funnel with vigorous stirring. Total addition time was determined by the rate of cooling. The temperature was held between 25 and 35° by cooling. The reaction can be worked up immediately or allowed to stir overnight. The mixture was cooled in ice water and 100 ml of 2-propanol was added dropwise, followed by the addition of 1.5 l. of water. The layers were separated and the aqueous layer was extracted four times with 1-l. portions of diethyl ether. The combined extracts were dried over anhydrous magnesium sulfate, filtered, concentrated, and recrystallized to yield the product. See Table I for yield and physical characteristics.

**Registry No.**—**1**, 2201-23-2; **2**, 77-57-6; **3**, 14377-68-5; **4**, 28049-59-4; **5**, 28049-60-7; **6**, 28049-61-8; **7**, 28049-62-9; **8**, 28049-63-0; **9**, 28049-64-1; **10**, 28049-65-2; **11**, 28049-66-3; **12**, 28049-67-4.

## Nitrogen Inversion in Cyclic *N*-Tosylamines

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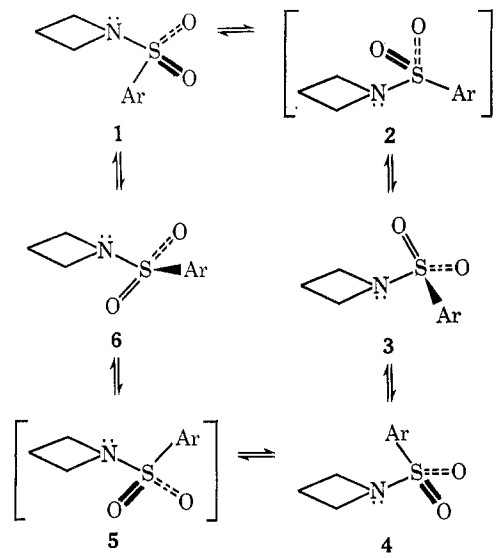
*Received September 11, 1970*

Diastereotopic protons in a sulfonamide of the type $(R)(R'CH_2)NSO_2R''$ may be brought into equivalence by an inversion about nitrogen and a rotation about the N–S bond. The rate-determining step for such a process is not specified by the simple observation of an $A_2$ to AB change in the spectrum of the indicated methylene protons. Additional evidence, such as the effects of steric bulk, conjugation, or ring size, is needed.[2] Spectral changes for the cyclic sulfonylaziridines have been attributed to hindered nitrogen inversion, but the method used does not unambiguously differentiate inversion from rotation.[3]

In order to clarify the nature of the rate-determining process for interconversions in small-ring sulfonamides, we have compared the free energies of activation for sulfonylaziridines and sulfonylazetidines. There should be little difference between the two systems for a rate-determining bond rotation. If nitrogen inversion is the slow step, however, the observed barrier should be much greater for the more highly strained three-membered rings than for the four-membered rings.[4] The available aziridine data are given in Table I. For the three sulfonylaziridines (I–III), $\Delta G^{\pm}$ is close to 12.5 kcal/mol. Because sulfonylazetidines had not previously been studied,[4] we examined the proton spectrum of *N*-tosylaziridine (VI, *p*-toluenesulfonylaziridine) down to −170°. The α-proton triplet is unchanged to −120°. Below this temperature, the resonance broadens through coalescence to two peaks ($T_c$ = −150°, $\Delta\nu$ = 12 Hz at 90 MHz). The free energy of activation is calculated to be 6.2 ± 1.0 kcal/mol at the coalescence temperature.

The set of processes that must be occurring in VI is depicted in Scheme I. The ground-state form of VI

SCHEME I




is assumed to be **1** (**4**), with the nitrogen lone pair staggered between the two sulfonyl oxygen atoms.[5] Nitrogen inversion converts **1** to **2** through an "$sp^2$" transition state. The eclipsed form **2** then returns to the ground-state form **4** by a torsional process. The pathway **1** → **6** → **5** → **4** represents the same process in the reverse direction. The question to be answered is whether the highest point on the energy surface is the inversion transition state between **1** and **2** with an $sp^2$ nitrogen or some point on the rotational itinerary between (and including) **2** and **4**.

At room temperature, the α protons of VI are equivalent, so all processes must be rapid on the nmr time scale. When the temperature is lowered to −170°, the α protons become nonequivalent. So long as only one rotamer is present, it is possible to observe only one set of spectral changes. If the changes in the aziridine II spectrum had been due to a rate-determining N–S rotation, the azetidine VI should have exhibited spectral coalescence with similar kinetics. The difference of over 6 kcal/mol between the barriers for II and VI cannot therefore be explained in terms of a slow torsional process. For a rate-determining nitrogen inversion, a considerably lower barrier is expected of the four-membered ring; *cf.* V *vs.* VIII. The spectral changes for

(1) (a) Alfred P. Sloan Foundation Fellow, 1968–1970. This work was supported by the National Science Foundation (Grant GP-9257), the Advanced Research Projects Agency of the Department of Defense through the Northwestern University Materials Research Center, and the Petroleum Research Fund administered by the American Chemical Society (Grant 2970-A4, 5). (b) National Science Foundation Undergraduate Research Participant, 1969–1970. (c) National Science Foundation Trainee, 1966–1967; National Institutes of Health Fellow, 1968–1970.

(2) M. Raban, G. W. J. Kenney, Jr., J. M. Moldowan, and F. B. Jones, Jr., *J. Amer. Chem. Soc.*, **90**, 2985 (1968); M. Raban and F. B. Jones, Jr., *ibid.*, **91**, 2180 (1969).

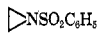
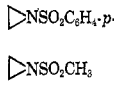
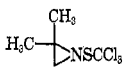
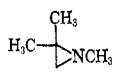
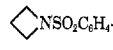
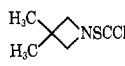
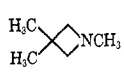
(3) (a) F. A. L. Anet and J. M. Osyany, *ibid.*, **89**, 352 (1967); (b) F. A. L. Anet, R. D. Trepka, and D. J. Cram, *ibid.*, **89**, 357 (1967).

(4) The factors that influence the inversion barrier have been discussed by J. B. Lambert, *Top. Sterochem.*, in press; J. M. Lehn, *Fortschr. Chem. Forsch.*, **15**, 311 (1970); A. Rauk, L. C. Allen, and K. Mislow, *Angew. Chem., Int. Ed. Engl.*, **9**, 400 (1970).

(5) S. Wolfe, A. Rauk, and I. G. Csizmadia, *J. Amer. Chem. Soc.*, **91**, 1567 (1969). Arguments analogous to those presented here would still apply if **3** (**6**) were the stable rotamer.

TABLE I

ACTIVATION PARAMETERS FOR N-SUBSTITUTED AZIRIDINES AND AZETIDINES

| | Compd | Solvent | $\Delta G^{\ddagger}$ ($T_c$), kcal/mol | Process | Source |
|---|---|---|---|---|---|
| I |  | $CDCl_3$ | 12.4 (−30)[a] | Inversion | *b* |
| II |  | $CDCl_3$ | 12.4 (−30)[a] | Inversion | *b* |
| III |  | $CDCl_3$ | 12.8 (−25)[a] | Inversion | *c* |
| IV |  | $CH_2Cl_2$–$CFCl_3$ | 9.1 (−87) | Inversion | *d* |
| V |  | $CDCl_3$ | 18.9 (∼+60) | Inversion | *e* |
| VI |  | $CHClF_2$ | 6.2 (−150) | Inversion | This work |
| VII |  | $CH_2Cl_2$ | 12.1 (−30) | Rotation | *d* |
| VIII |  | $CFCl_3$ | 8.9 (−93) | Inversion | *f* |

[a] Calculated from the reported rate data and the equation $\Delta G^{\ddagger} = RT(23.76 + \ln T/k)$. [b] Reference 3b. [c] Reference 3a. [d] Reference 6. [e] M. Jautelat and J. D. Roberts, *J. Amer. Chem. Soc.*, **91**, 642 (1969). [f] J. M. Lehn and J. Wagner, *Chem. Commun.*, 148 (1968).

both *N*-tosylamines II and VI may therefore be confidently attributed to a rate-determining nitrogen inversion. The barrier for VI (6.2 kcal/mol) constitutes the lowest value yet measured for nitrogen inversion in a four-membered ring.[4]

A contrasting case is given by the trichloromethylthio compounds IV and VII.[6] Here the aziridine has a lower barrier than the azetidine. The authors consequently assigned the rate-determining step for the three-membered ring to inversion, but for the four-membered ring to bond rotation.[6] When bonded atoms both possess lone pairs, as in the sulfenamides IV and VII, the torsional operation can have a high energy barrier.[2,5] The sulfonamide bond (N—$SO_2$) is therefore expected to have a much lower torsional barrier, because one atom (sulfur) is devoid of lone-pair electrons.

Scheme I may be unnecessarily complex. The conversion of **1** to **3** may involve only a single maximum on the inversion–rotation energy surface. The transition state would then possess both inversional and rotational character. Our data certainly do not exclude such an operation. Nonetheless, we would conclude that such a transition state between **1** and **3** should still have a larger proportion of inversion character.

The extremely low magnitude of the barrier to nitrogen inversion in VI deserves further comment. Some time ago, Traylor[7] remarked that the barrier in sulfonamides might be lowered by $(p\text{–}d)_\pi$ overlap between the nitrogen lone pair and the empty orbitals on sulfur.[8] The *N*-tosyl compound VI has a barrier approximately 3 kcal/mol lower than the corresponding *N*-methyl compound VIII. Since the electron-withdrawing ability of the sulfonamide group ($\sigma_I$ = 0.60) would raise the barrier with respect to that of an *N*-methyl compound ($\sigma_I$ = 0.0),[3b] the observed lowering must be due to a strong conjugative effect.[4] Overlap is strongest at the transition state because the lone pair is p hybridized. Donation of the nitrogen 2p lone pair to empty orbitals on sulfur therefore provides a mechanism for the increased rate of inversion of sulfonamides. Since other proposed examples of $(p\text{–}d)_\pi$ acceleration of atomic inversion could alternatively be explained in terms of an inductive rate enhancement by electropositive substituents,[4] the sulfonamides assume an important position in the question of d-orbital conjugation. It should be noted that the specific acceptor orbitals on sulfur cannot really be determined. The d orbitals are convenient for discussion, but other empty low-lying orbitals may also be important. The present observations with *N*-tosylazetidine are at the limit of the dnmr method. It is therefore expected that hindered nitrogen inversion will not be observed in larger ring sulfonamides without imposing specific constraints.[9]

### Experimental Section

Nmr spectra were taken at 90 MHz on a Bruker HFX-10 spectrometer[10] and at 60 MHz on Varian A-60 and T-60 spectrometers.

**3-(*p*-Toluenesulfonamido)propyl *p*-toluenesulfonate** was prepared from 3-aminopropanol according to the method of Vaughan, *et al.*,[11] mp 117–118° (lit.[11] 116–119°).

***p*-Toluenesulfonylazetidine (*N*-tosylazetidine, VI)** was prepared in quantitative yield from the above ditosylate by the method of Vaughan, *et al.*,[11] mp 118–119° (lit.[11] 119.0–121.5°).

**Registry No.**—VI, 7730-45-2.

(6) J. M. Lehn and J. Wagner, *Chem. Commun.*, 1298 (1968).

(7) T. G. Traylor, *Chem. Ind. (London)*, 649 (1963).

(8) Low inversion barriers for *N*-sulfonyl compounds have also been discussed by K. Murayama and T. Yoshioka, *Tetrahedron Lett.*, 1363 (1968).

(9) W. N. Speckamp, U. K. Pandit, P. K. Kower, P. J. van der Haak, and H. O. Huisman, *Tetrahedron*, **22**, 2413 (1966).

(10) We thank the National Science Foundation for an equipment grant that made possible the purchase of this instrument.

(11) W. R. Vaughan, R. S. Klonowski, R. S. McElhinney, and B. B. Millward, *J. Org. Chem.*, **26**, 138 (1961).