Nuclear Magnetic Resonance Studies of Rate Processes and Conformations. Part XX.† Nitrogen Inversion in the Gas Phase

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The barriers to nitrogen inversion in *N*-methyl-, *N*-methyl-2,2-dimethyl-, and *N*-isopropyl-2,2-dimethyl-aziridine have been studied in the gas phase and in a variety of solvents. The barrier is found to be almost the same in the gas phase and in C_6D_{12} solution. Solvent effects are discussed. Some small coupling constants have been determined by double irradiation.

SEVERAL types of rate process have by now been studied by n.m.r. techniques, *e.g.* ring inversion,[1] nitrogen inversion,[2] and hindered internal rotation.[3] There are however very few values available for the gas phase. Using n.m.r. spectroscopy Harris and Spragg [4] have studied the hindered internal rotation in $Me_2N{\cdot}N{:}O$ in both gas and liquid phase, and found that the energy barrier is *ca.* 2 kcal mol^{-1} lower in the gas phase. Fatela *et al.*[5] have found approximately the same for benzaldehyde from i.r. data.

The rates of nitrogen inversion have been studied as a function of steric and electronic effects (for a recent review see ref. 2). However, since many different solvents have been used it is not always easy to compare the values for different compounds.

A number of theoretical calculations of the barrier to nitrogen inversion in a variety of compounds have been performed.[2] All the calculated values refer to an isolated molecule. It is hence of great interest to know the corresponding experimental values. It has normally been assumed that the value determined in an inert solvent is almost the same as the gas-phase value, but

† Part XIX, J. M. Lehn and J. Wagner, *Chem. Comm.*, 1970, 414.

[1] F. A. L. Anet and A. J. R. Bourn, *J. Amer. Chem. Soc.*, 1967, **89**, 760.

[2] J. M. Lehn in ' Topics in Current Chemistry,' ed. Springer-Verlag, Berlin, 1970, **15**, 311.

[3] G. Binsch in ' Topics in Stereochemistry,' eds. E. L. Eliel and N. L. Allinger, Wiley, New York, 1968, vol. 3.

[4] R. K. Harris and R. A. Spragg, *Chem. Comm.*, 1967, 362.

[5] W. G. Fatela, R. K. Harris, F. A. Miller, and R. E. Witkowsky, *Spectrochim. Acta*, 1965, **21**, 231.

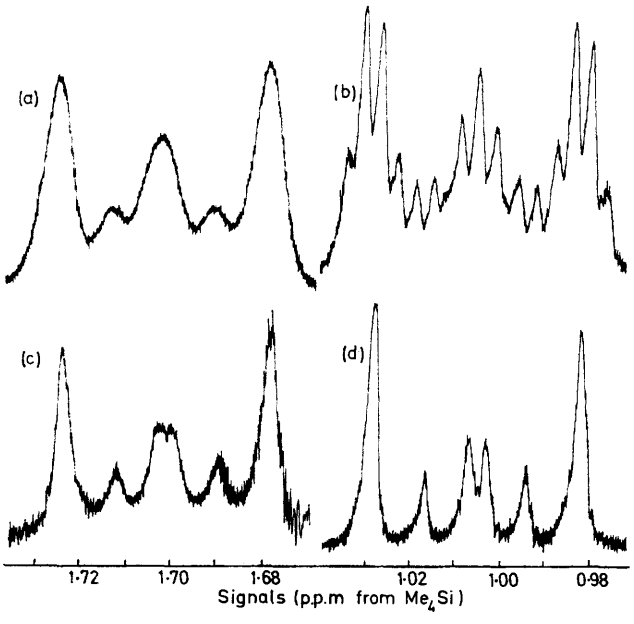
this has never been proved for this type of compound. Nitrogen-inversion barriers might be expected to be especially sensitive to medium effects because of the large difference in polarity between the pyramidal form and the planar transition state.

It may be also noted that, although the barriers determined by microwave spectroscopy are for the gas phase, their range is quite limited (<6 kcal mol^{-1}) in comparison to the large range (6—23 kcal mol^{-1}) of the barriers determined by n.m.r. spectroscopy, which allow a detailed discussion of a great variety of structural effects.[2]

In order to obtain more information on the solvent effect on nitrogen inversion we have studied the rate of nitrogen inversion in some aziridines both in the gas phase and in several solvents.

RESULTS AND DISCUSSION

The N.m.r. Spectra.—*N*-Methylaziridine gives an AA'BB' system for the ring protons. The high-field part has been assigned to the *cis* and the low field to the *trans* protons.[6] The non-equivalence of these two parts has been assumed to be due to spin coupling to the *N*-methyl protons and to nitrogen.[7] For the solvent $CDCl_3$ it has been possible to resolve the quartets due to the *N*-methyl coupling for the high-field part of the AA'BB' spectrum but not for the low-field part (Figure). In the Figure is also shown the spectrum obtained while saturating the *N*-methyl signal. The high-field part gives narrow lines (half-width *ca.* 0·30 Hz) whereas the low-field signals are a little broadened (half-width *ca.* 0·40 Hz) but narrower than without decoupling by *ca.* 0·40 Hz. The line-width of the low-field methylene signals decreases by *ca.* 0·1 Hz on nitrogen irradiation, but the high-field signals and the *N*-methyl line do not change at all. We can also see from the Figure that, except for the small excess broadening of the low-field signals, the two parts of the AA'BB' system seem to be equivalent. Yonezawa *et al.*[7] have found from ^{13}C coupling satellites that the coupling constants $J_{cis}(H_cH_c)$ and $J_{cis}(H_tH_t)$ are not equal (7·0 and 5·3 Hz respectively).



N-Methylaziridine ring ^1H n.m.r. signals (at 100 MHz in $CDCl_3$): (a) low-field part without decoupling; (b) high-field part without decoupling; (c) low-field part with N–CH_3 saturation; (d) high-field part with N–CH_3 saturation

The coupling constants found for *N*-methylaziridine are given in Table 1. The constants for AA'BB' system have been calculated with the iterative program LAOCOON III.[8] In this Table the coupling constants obtained for *N*-methyl-2,2-dimethylaziridine are also given; they are all small, and it was not possible to determine all of them. The only signal that shows any fine structure without decoupling is the low-field C–CH_3 signal, which seems to be a badly resolved quintuplet. When irradiating the N–CH_3 signal this quintuplet becomes a little better resolved, which shows that there is some coupling between these protons (<0·1 Hz). Irradiation of the high-field C–CH_3 signal transforms the low-field C–CH_3 signal into a doublet with a splitting of 0·45 Hz, which must be caused by coupling to one of the methylene protons. The irradiation of the low-field methylene signal does not change the low-field C–CH_3 signal appreciably; thus these protons are probably coupled to the high-field methylene proton. This can however not be checked by double irradiation since the signals are too close together.

TABLE 1

Coupling constants in *N*-methylaziridine (I) and *N*-methyl-2,2-dimethylaziridine (II)

Compd.	$J_{gem}(H_cH_t)$	$J_{gem}(CH_{3c}CH_{3t})$	$J_{trans}(H_cH_t)$
(I)	0·47		4·13
	(1·0) [b]		(3·8) [b]
(II)		~0·3	0·45
Compd.	$J_{cis}(H_tH_t)$ [a]	$J_{cis}(H_cH_c)$ [a]	$J_{cis}(HNCH_3)$
(I)	(5·3) [b]	(7·0) [b]	0·40
(II)	<0·1	<0·1	<0·1
Compd.	$J_{trans}(HNCH_3)$	$J_{cis}(CH_3NCH_3)$	$J_{trans}(CH_3NCH_3)$
(I)	~0·2		
(II)	<0·1	<0·1	<0·1

[a] Could not be obtained with the LAOCOON program since the spectrum is not affected at all by these coupling constants. [b] Ref. 7; obtained from ^{13}C-coupling satellites.

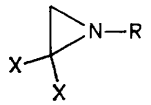
Coupling between the methylene protons and the nitrogen nucleus in *N*-methylaziridine seems to vary with solvent. In $CDCl_3$ and water the broadening of the signals due to nitrogen coupling is very small, 0·1 and 0·0 Hz for the low- and high-field signals, respectively. The corresponding values for C_6D_{12} solution are 0·5 and 0·0 Hz. In the gas phase, all the signals are broadened so much that almost all the fine structure of the signals disappears. This change of line-width with solvent can

[6] H. Saito, K. Nukada, T. Kobayashi, and K. Morita, *J. Amer. Chem. Soc.*, 1967, **89**, 6605.

[7] T. Yonezawa and I. Morishima, *J. Mol. Spectroscopy*, 1968, **27**, 210.

[8] S. Castellano and A. A. Bothner-By, *J. Chem. Phys.*, 1964, **41**, 3863.

be explained by the variation of the correlation time of the aziridine molecules. In solvents with hydrogen bonding capability the motion of the molecules is slowed down and the coupling to the nitrogen almost completely disappears due to fast nitrogen quadrupolar relaxation. In other solvents where the motion is faster, this effect is not so effective; this is even more valid for the gas phase. The large broadening of the gas-phase lines is probably partly caused by a change in the proton relaxation time.



(I) X = H; R = Me
(II) X = R = Me
(III) X = Me; R = Pr^i

In the low-temperature spectrum of the aziridine (III) in some solvents the isopropyl methyl signals show an extra splitting into two narrow doublets, the shift being *ca.* 2 Hz in $CDCl_3$ solution. This must be due to non-equivalence of the two methyl groups due to the fact that the nitrogen, when the inversion is slow, can be looked upon as an asymmetric centre. It is only for the solvents toluene, methanol, and chloroform that this splitting has been observed; for methanol the non-equivalence is so small that it is only revealed as a broadening of the signals.

Nitrogen Inversion Barriers.—In Table 2 are given the chemical-shift differences for coalescing signals, the coalescence temperature, and the free energy of activation at the coalescence temperature. The free energy of activation is calculated at coalescence from equation (1) where T_c is the coalescence temperature and τ_c is

$$\Delta G_c^{\ddagger} = 4{\cdot}576T_c[10{\cdot}32 + \log (T_c \cdot \tau_c)] \quad (1)$$

given by equation (2), where $\delta\nu$ is the limiting chemical-shift difference. This gives $\Delta G^{\ddagger}$ values which are *ca.*

$$\tau_c = 2^{\frac{1}{2}}/(\pi \cdot \delta\nu) \quad (2)$$

0·1 kcal mol^{-1} smaller than those obtained from a total line-shape analysis, when $\delta\nu$ is in the order of 10 Hz and $T_2 = 0{\cdot}3$ s [*e.g.* (II) in $(CH_3)_8Si_4O_4$ $\Delta G_c^{\ddagger} = 17{\cdot}49$ and 17·63 kcal mol^{-1}, from coalescence temperature and total line-shape, respectively]. This error will decrease with increasing shift and T_2.[9] Equation (2) is also used for (I), which consists of a coalescing AA'BB' system. Though not strictly valid for this case the error is not more than 0·1 kcal mol^{-1}. Dahlqvist *et al.*[10] have, for a more strongly coupled system, found $\tau_c = 0{\cdot}0124$ from total line-shape analysis and 0·0090 with the simple formula. This gives an energy difference of 0·25 kcal mol^{-1} at a coalescence temperature of 400 K. It is therefore possible to use these values for comparison even though they are not exactly correct.

The purpose of this work was to see if the values obtained in inert solvents may be used as an approximation for the gas-phase values. For (I) we found no difference in the inversion barrier ($\Delta G^{\ddagger}$) between the gas phase and C_6D_{12} solution, but for (II) and (III) the barrier was found to be 0·2 kcal mol^{-1} higher in solution than in the gas phase. Hence, for this type of compound, the values found for solutions in inert solvents are almost the same as for the gas phase.

TABLE 2

Chemical shift difference (in p.p.m.) between exchanging signals, coalescence temperature (°C), and free energy of activation (kcal mol^{-1}) for aziridines (I)—(III) in various solvents

		(I)			(II)			(III)		
Solvent	MHz	$\delta\nu$ [a]	T_c	$\Delta G_c^{\ddagger}$ [c]	$\delta\nu$ [b]	T_c	$\Delta G_c^{\ddagger}$ [c]	$\delta\nu$ [b]	T_c	$\Delta G_c^{\ddagger}$ [c]
Gas	100	0·81	117	19·03	0·101	53	17·13	0·13	43	16·43
C_6H_{12}	60	0·74	108	19·02	0·088	48	17·27	0·107	38	16·59
C_6D_{12}	100				0·088	56	17·39	0·107	45	16·66
Toluene	60	0·854	112	19·10						
	100				0·103	60	17·49	0·058	38	16·65
$(CH_3)_8Si_4O_4$	60							0·107	41	16·85
	100	0·74	112	19·20	0·088	58	17·49			
$(CD_3)_2SO$	60	0·575	125	20·1	0·130	69	18·15	0·155	54	17·22
	100				0·130	77	18·26	0·155	59	17·17
$CDCl_3$	100	0·697			0·070	76	18·69	0·077	60	17·69
Formamide	60	0·563	135	20·7	0·112	96	19·81	0·137	77	18·23
	100				0·112	104	19·84			
Glycerol	60	0·525	145	21·2						
Methanol	100				0·116	97	19·5	0·125	82	18·57
D_2O	60	0·481	>150	~23				0·150	106	20·1
	100				0·124	>100	~23			
Acetone	100				0·131	72	17·98	0·152	56	17·03

[a] Ring methylene signals. [b] Ring methyl signals. [c] The relative errors between different solvents are believed to be less than 0·1 kcal mol^{-1} and the absolute errors less than 0·2 kcal mol^{-1}.

[9] T. Drakenberg and D. Forsén, unpublished data.
[10] K. I. Dahlqvist, S. Forsén, and T. Alm, *Acta Chem. Scand.*, 1970, **24**, 651.

There is some uncertainty in the above discussion because we have only evaluated $\Delta G^{\ddagger}$ from the coalescence temperature. We have however for one solution of (II) in $(CH_3)_8Si_4O_4$, used the total line-shape analysis to evaluate also $\Delta S^{\ddagger}$ and $\Delta H^{\ddagger}$. The evaluation covers a temperature interval of 50° and gives: $\Delta H = 16{\cdot}87$ kcal mol^{-1}, $\Delta G^{\ddagger} = 17{\cdot}63$ kcal mol^{-1}, and $\Delta S^{\ddagger} = +2{\cdot}3$ cal mol^{-1} K^{-1}. The entropy of activation is small, which one could expect for this type of exchange, so the variation of $\Delta G_c^{\ddagger}$ probably reflects very well the variation of $\Delta H^{\ddagger}$.

We can see from Table 2 that solvent effects (with cyclohexane as the standard solvent) are largest for (II) and smallest for (III), except for DMSO where (I) is most affected. That the solvent effect is least for (III) can probably be explained by the fact that approach is so hindered that interaction with the solvents is diminished. If it is the steric hindrance to solvation of the compound that determines the effect of the solvent on the inversion barrier, the largest effect should be found for (I) and not for (II). Hence other factors must also be involved. The fact that the effect of Me_2SO is largest for (I) is probably also due to the steric effect.

The solvent can be divided into three groups, non-polar, polar, and protic. The three non-polar solvents C_6D_{12}, toluene, and $(CH_3)_8Si_4O_4$ give small and similar solvent effects, within 0·2 kcal mol^{-1}. The polar but non-protic solvents Me_2SO and acetone increase the barrier by 0·5—1·0 kcal mol^{-1}. The protic solvents $CDCl_3$, formamide, alcohol, and water increase the barrier by varying amounts depending on the proton-donating strength of the solvent. For water the increase is *ca.* 4, 5, and 3 kcal mol^{-1} for (I), (II), and (III), respectively. The values for (I) and (II) are estimated from line broadening. From this it can be seen that it is necessary to take the solvent effect into account when comparing inversion barriers for different compounds.

CONCLUSION

From the above discussion it can be concluded that the inversion barriers for tertiary amines obtained in inert solvent solution are almost the same as in the gas phase. The values found from $CDCl_3$ solution (the most used solvent) are too high by 5—10%. The absolute effects are hence not very large so these values can be used for comparison with theoretically calculated values. In a study of other effects, *e.g.* steric or electronic, it may however be necessary to take account of a solvent effect of 5%, since the other effects are often smaller than this.

EXPERIMENTAL

The compounds (I), (II), and (III) were prepared by Dr. J. Wagner [11] and were used without further purification. The purity of the compounds was checked by n.m.r.; no signals due to impurities were found. The compounds did however decompose at higher temperature. For (II) we used the same sample for solution as for gas-phase studies; a small amount of decomposition products were present in the solutions.

The tubes for gas-phase study were sealed under high vacuum while cooling with liquid nitrogen. For (I) a normal 5 mm tube was used, and for (II) and (III) 12 mm tubes were used. A small amount of Me_4Si was added to these samples for locking.

The sample tubes with solvent were usually not sealed [except for (I) in C_6D_{12} and water]. The concentration was 1M. All gas-phase spectra were recorded on a Varian XL-100 spectrometer, and for the liquid phase either the XL-100 or a Varian A-60 spectrometer was used.

The sample temperature was measured either with a calibrated capillary with methanol and water (molar ratio 1 : 2) inserted in the sample tube,[12] or with the Varian standard glycol sample. The difference between these two methods was found to be $<2°$ for the 5 mm tubes. For the 12 mm tubes the Varian standard glycol sample was found to give values 6° too low at *ca.* 40 °C.

For a solution of (II) in $(CH_3)_8Si_4O_4$ a total line-shape analysis was performed. Evaluation of the rate constants was made by means of an iterative curve fitting program, STEPIT (J. P. Chandler, Physics Dept. Indiana University); the experimental lines were digitized by hand (two spectra at each temperature). The temperature was measured with the internal methanol capillary 'thermometer', which gives relative errors less than 0·2°. The values found for $\Delta G^{\ddagger}$, $\Delta H^{\ddagger}$, and $\Delta S^{\ddagger}$ are thought to be accurate to $\pm 0{\cdot}1$ kcal mol^{-1}, $\pm 0{\cdot}8$ kcal mol^{-1}, and ± 3 cal mol^{-1} K^{-1}, respectively. For a more thorough description of this type of line-shape analysis see ref. 12.

We thank Dr J. Wagner for the generous gift of the aziridines.

[1/1622 *Received, September 6th,* 1971]

[11] J. Wagner, Ph.D. Thesis, Strasbourg, 1970.
[12] T. Drakenberg, K. I. Dahlqvist, and D. Forsén, *Acta Chem. Scand.*, 1970, **24**, 694.