94, 146 (1972).
(9) G. A. Olah and G. Liang, *J. Am. Chem. Soc.*, **97**, 1920 (1975).
(10) G. A. Olah, G. Liang, K. A. Babiak, T. K. Morgan, Jr., and R. K. Murray, Jr., *J. Am. Chem. Soc.*, **98**, 576 (1976).
(11) G. A. Olah and G. Liang, *J. Am. Chem. Soc.*, **98**, 7026 (1976).
(12) G. A. Olah, R. J. Spear, P. C. Hiberty, and W. J. Hehre, *J. Am. Chem. Soc.*, **98**, 7470 (1976).
(13) M. Saunders and J. Rosenfeld, *J. Am. Chem. Soc.*, **92**, 2548 (1970).
(14) J. E. Baldwin and W. D. Foglesong, *J. Am. Chem. Soc.*, **89**, 6372 (1967). For a full account of these studies see J. E. Baldwin and W. D. Foglesong, *ibid.*, **90**, 4303, 4311 (1968).
(15) Alcohol **10** was prepared by the sodium borohydride reduction of 8,9-dehydro-2-adamantanone as described by Baldwin and Foglesong.[14] However, an improved procedure for the synthesis of the precursor ketone was employed.[16]
(16) R. K. Murray, Jr., T. K. Morgan, Jr., and K. A. Babiak, *J. Org. Chem.*, **40**, 1079 (1975).
(17) R. K. Murray, Jr. and K. A. Babiak, *Tetrahedron Lett.*, 311 (1974).
(18) Chlorides **11** and **14** were prepared by refluxing the corresponding alcohols with 1 equiv of thionyl chloride in anhydrous ether for 2 h in the presence of a catalytic amount of pyridine.
(19) R. K. Murray, Jr., D. L. Goff, and T. M. Ford, *J. Org. Chem.*, in press.
(20) B. L. Jelus, B. Munson, K. A. Babiak, and R. K. Murray, Jr., *J. Org. Chem.*, **39**, 3250 (1974).
(21) D. Lenoir, R. E. Hall, and P. v. R. Schleyer, *J. Am. Chem. Soc.*, **96**, 2138 (1974), and references cited therein.
(22) G. A. Olah and G. Liang, *J. Am. Chem. Soc.*, **94**, 6434 (1972); **97**, 1987 (1975); G. A. Olah, G. Liang, and Y. K. Mo, *ibid.*, **94**, 3544 (1972).
(23) L. A. Spurlock and K. P. Clark, *J. Am. Chem. Soc.*, **94**, 5349 (1972); R. K. Murray, Jr. and T. K. Morgan, Jr., *J. Org. Chem.*, **40**, 2642 (1975).
(24) The observation that **23** → **24** suggests that substitution of any of these groups for the hydrogen at C-8 (or C-9) in **12** would also lead to a static ion.
(25) Ion **32** can also be formed from the same precursors in FSO_3H–SO_2ClF solution at −120 °C. However, in this medium the ion is only stable below −78 °C. Upon further warming, **32** is slowly transformed into a mixture of two ions. Since the ^1H NMR spectrum of the minor product is very similar to that of **17**, it is tentatively identified as the 4-methyl-2-tricyclo[4.4.0.0^{5,9}]dec-3-enyl cation. The structure of the major product has not been determined.
(26) D. Seyferth and H. M. Cohen, *J. Organomet. Chem.*, **1**, 15 (1963).
(27) G. A. Olah and G. Liang, *J. Am. Chem. Soc.*, **96**, 189 (1974).

The Effect of Carbonyl Substituents on the Barriers to Rotation in *N,N*-Dimethylamides

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Abstract: The barriers to rotation about the carbonyl–nitrogen bond were determined for 14 α-alkyl- and α-halo-substituted *N,N*-dimethylacetamides by NMR total line-shape analysis. Free energies of activation were found to be insensitive to relatively nonpolar aprotic solvents and concentrations. Regression analyses were performed with a variety of inductive and steric parameters. The best correlations with $\Delta G^{\ddagger}$ were obtained using σ_1 and v values. When amides containing substituents capable of direct resonance interaction were included in the regression analysis, the addition of σ_R^- as a third independent variable produced a reasonably good correlation. The relative importance of these effects is discussed.

While it is generally believed that the rotational barriers in amides are governed by steric and electronic effects, the relative magnitudes of these effects and the quantitative structural relationships used to describe them have remained virtually unexplored.[1,2] The present study has as its primary objective the identification and quantification of the factors related to the effect of carbonyl substituents on the barriers in *N,N*-dimethylamides. In order to trace these effects systematically in a set of relatively simple substituents, the activation parameters for 14 alkyl- and halo-substituted *N,N*-dimethylacetamides were determined by total line-shape analysis and then correlated with various structural and electronic quantities.

Experimental Section

The amides studied were commercially available or were prepared by the reaction of the appropriate acid halide with dimethylamine. All except *N,N*-dimethyl-2-fluoroacetamide (bp 94 °C (30 mm); yield 81%. Anal. Calcd for C_4H_8NOF: C, 45.71; H, 7.67. Found: C, 45.72; H, 7.69) have been reported previously. The purity of the amides as monitored by NMR spectroscopy exceeded 95%.

NMR spectra were obtained on a Varian A-60D spectrometer equipped with variable temperature accessory V-4341/V-6057. Spectra were calibrated by the side-banding method using a Hewlett-Packard 200CD audio oscillator and Model 522B electronic counter. For the total line-shape analysis at least three traces were run at low rf field on a 50-Hz sweep width at each temperature. Temperatures were measured with standard methanol and ethylene glycol samples and the equations of Van Geet.[3]

The limiting chemical shift difference, $\Delta\nu$, at each temperature used in the total line-shape analyses was extrapolated from a least-squares plot of $\Delta\nu$ vs. T obtained from spectra taken at four temperatures 25–50 °C below coalescence. Transverse relaxation values, T_2, were similarly extrapolated from a least-squares plot of T_2 vs. T. The T_2 values were calculated from the half-height width of the sharpest peak of the N–CH_3 doublet. The extrapolated $\Delta\nu$ and T_2 values were then used as constants in the Gutowsky–Holm equation[4] (programmed in FORTRAN IV) and τ was varied until the computer-generated curve displayed on a Honeywell Model 530 x–y plotter matched the NMR spectrum as closely as possible. For most amides the peaks of the N–CH_3 doublet were equally intense. When the intensities were slightly dissimilar the more intense peak was used for the fit. For several compounds τ values obtained by visual comparison were checked with the computer minimization of errors method described previously.[5]

Activation energies were calculated from least-squares Arrhenius plots constructed from five to nine points. The correlation coefficients for the Arrhenius plots were in all cases greater than 0.97. Free energies of activation were obtained at 25 °C from the Eyring equation (transmission coefficient = 1) and at the coalescence temperature from the approximate method[6] using $\Delta\nu$ extrapolated from four low-temperature values.

Solvents were dried over molecular sieves (Linde type 4A).

Results and Discussion

The results of the total line-shape analyses are presented in Table I, along with previously reported free energies of activation. The free energies of activation calculated from the total line-shape analysis have an associated error range of ±0.3 kcal/mol at the 90% confidence level as determined by application of the t test to three separate total line-shape analyses of compound II. In general the free energies of activation determined by the approximate method agree well with those

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Table I. Activation Parameters[a] for $XCON(CH_3)_2$

	X	T_c, K	E_a	$\Delta H^{\ddagger}$	$\Delta S^{\ddagger}$	$\Delta G^{\ddagger}_{298}$	$\Delta G^{\ddagger}_{T_{c,approx}}$	$\Delta G^{\ddagger}$, lit.	Solvent (lit.)	Lit. ref
I	CH_3							17.3, 18.1	CCl_4, neat	16, 25
								18.2, 18.6	Neat, Me_2SO	24, 24
II	CH_3CH_2[b]	325.4	16.9	16.3	−3	17.2	17.2	17.4	CCl_4	26
III	$(CH_3)_2CH$[d]	304.5	14.6	14.0	−8	16.5	16.6	16.2	o-$C_6H_4Cl_2$	26
IV	$(CH_3)_3C$[c]	210.3	14.1	13.5	10	10.5	11.2	11.9	$CHCl_3$	27
V	$(CH_3)_2ClC$	264.4	13.9	13.3	−1	13.6	13.5			
VI	$(CH_3)Cl_2C$	302.5	16.5	15.9	2	15.4	15.4			
VII	FCH_2	317.5					17.0			
VIII	F_2CH	348.1					18.8			
IX	F_3C							18.8, 18.6	$(CHCl_2)_2$, neat	28, 29
X	$ClCH_2$[d]	293.5	16.0	15.4	−4	16.4	16.5			
XI	Cl_2CH	319.9	19.1	18.5	3	17.6	17.5			
XII	Cl_3C[d]	285.3	15.3	14.7	0.4	14.9	14.8	15.0, 18.3	Neat, $(CBrF_2)_2$	7, 8
XIII	$BrCH_2$	292.2	17.3	16.7	3	15.8	15.6			
XIV	Br_2CH	317.5	16.4	15.9	−5	17.3	17.2			
XV	Br_3C[e]	277.9	13.6	13.0	−3	14.0	13.4			

[a] In kcal/mol, except for $\Delta S^{\ddagger}$, which is given in cal/deg·mol. Unless noted otherwise, values are for 30% (v/v) solutions in ClC_6H_5. [b] 10% in CCl_4. [c] 30% in $C_6H_5CH_3$. [d] 10% in ClC_6H_5. [e] 30% in CH_3COCH_3.

determined by total line-shape analysis. For the $(CH_3)_3C$ derivative the poorer agreement is almost surely a result of the low coalescence temperature and the consequently poorer resolution and higher solution viscosity. Because of ^{19}F–^1H coupling for the fluoro derivatives, the free energies of activation for the fluoro derivatives were determined only by the approximate method. All of the free energies of activation also agree with literature values within experimental error. (Note, however, that the value of 18.3 kcal/mol reported for the Cl_3C derivative[7] does not agree with the other literature value[8] nor with the value determined here.)

In order to evaluate the sensitivity of the free energy of activation to solvent and solution concentration, the approximate method was used to determine $\Delta G^{\ddagger}$ for the CH_3CH_2 and $ClCH_2$ derivatives in three solvents (ClC_6H_5, $C_6H_5CH_3$, and CCl_4) and at several concentrations in the range 10–30%. The values obtained were in agreement with those in Table I to within ±0.2 kcal/mol. This insensitivity to solvent (at least to relatively nonpolar aprotic solvents) and concentration is also reflected in the agreement with the literature values (obtained in a variety of solvents) shown in Table I.

The activation energy and the derived parameters $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ are notoriously less reliable than free energies of activation.[1,2] The entropies of activation for the rotational process in amides are thought to have values close to zero.[1,2] The $\Delta S^{\ddagger}$ values in Table I range from −8 to +10 cal/deg·mol with an average value of −0.5 cal/deg·mol. There is no obvious relationship to the nature of the substituent. Because of the greater reliability of $\Delta G^{\ddagger}$ and (since $\Delta S^{\ddagger}$ is small) the parallelism between $\Delta G^{\ddagger}$ and E_a, the effect of substituents on the rotational barrier will henceforth be discussed in terms of the free energy of activation.

A number of trends in $\Delta G^{\ddagger}$ are apparent from Table I. For the alkyl substituents, $\Delta G^{\ddagger}$ varies $CH_3CH_2 > (CH_3)_2CH > (CH_3)_3C$; for the fluoro derivatives the barrier varies $FCH_2 < F_2CH = F_3C$; for the chloro and bromo derivatives the disubstituted amides (e.g., X = Cl_2CH) have higher barriers than the monosubstituted compounds, which in turn have higher barriers than the trisubstituted species. Comparisons within the halogen series reveal that for each series—mono-, di-, and trisubstituted—the barriers vary F > Cl > Br.

These qualitative trends can be rationalized with the steric and electronic effect models.[1,2] The steric model for rotational barriers in amides assumes that an increase in size of substituent at the carbonyl carbon or nitrogen will result in greater repulsive forces in the planar ground state relative to the transition state and will therefore produce a decrease in rotational barrier. Because the electronic effects of the alkyl substituents, CH_3CH_2, $(CH_3)_2CH$, and $(CH_3)_3C$, are similar, the trend in barriers for these derivatives can be easily rationalized with this model. The increase in size of the substituent can also be used to explain the fact that the barriers for the trichloro and tribromo derivatives are lower than those for the disubstituted derivatives.

In order to explain the other trends delineated above the electronic model must be invoked. According to this model, withdrawal of electron density from the carbonyl carbon results in stabilization of the ground state and destabilization of the transition state in which the carbon is relatively more electrophilic.[2] The net result is an increase in the barrier to rotation. Hence, the increase in barrier from bromo to chloro to fluoro—$BrCH_2 < ClCH_2 < FCH_2$; $Br_2CH < Cl_2CH < F_2CH$; $Br_3C < Cl_3C < F_3C$—can be attributed to an increase in electronegativity of the halogen in the same order. Moreover, the increase in barrier from the monohalo to dihalo compounds can also be ascribed to the greater electron-withdrawing power of the dihalo groups. Apparently, then, the barrier-lowering effect due to an increase in size from monohalo to dihalo substituent is outweighed by the barrier-increasing electronic effect. The transition from di- to trisubstitution for chloro and bromo apparently involves the predominance of the steric effect. For the fluoro derivatives there is no difference in the barriers for the F_2CH and F_3C derivatives, probably because of the small size and high electronegativity of fluorine.

Thus, the barriers to rotation in this series of amides can be rationalized in terms of only two models—the steric and inductive models. The two effects are clearly operative in each derivative and their disentanglement is not easy. However, in the methyl series the inductive effect remains relatively constant and the effect of size is clearly visible; in the methylchloro series—CH_3Cl_2C, $(CH_3)_2ClC$—size remains approximately the same and the electron-withdrawing effect due to progressive substitution of chlorine is apparent (note, however, that the barrier for the Cl_3C derivative is lower than that for the CH_3Cl_2C derivative).

In order to place these observations about the effect of size and electron-withdrawing ability on a more quantitative basis and also to determine what other factors might influence the rotational barriers, linear multiple correlations of $\Delta G^{\ddagger}$ with a variety of substituent parameters were performed. The results of a selected set of these correlations are presented in Table II. The steric parameters used were Charton's υ values,[9] E_s values,[10] and van der Waals radii calculated for a variety of different conformations of the substituent. The inductive effect

Table II. Regression Analysis Results

Series	Dependent variable	Independent variable	r^a	F^b	S^c	n^d
(VII-XV)	$\Delta G^{\ddagger}$	σ_I	0.05	0.02	1.9	9
		υ	0.67	5.7	1.4	9
		σ_I, υ	0.993	213	0.24	9
	E_a	σ_I, υ	0.929	12.7	0.98	7
(VII-XV, II-IV)	$\Delta G^{\ddagger}$	σ_I, υ	0.901	19.4	1.06	12
		$\sigma_I, \upsilon, \sigma_R^\circ$	0.902	11.6	1.11	12
	E_a	σ_I, υ	0.83	7.5	1.3	10
(II-XV)	$\Delta G^{\ddagger}$	σ_I, υ	0.908	25.8	0.98	14
(I-XV)	$\Delta G^{\ddagger}$	σ_I, υ	0.906	27.3	0.96	15
(I-XV + others)	$\Delta G^{\ddagger}$	σ_I, υ	0.71	9.9	1.6	22
		$\sigma_I, \upsilon, \sigma_r^-$	0.903	26.4	0.99	22

[a] Correlation coefficient. [b] F value. [c] Standard error of the estimate. [d] Number of data sets in correlation.

parameters utilized included σ_I values[11] calculated from the pK_a of substituted acetic acids, σ_I values obtained from ^{19}F chemical shifts in α-substituted fluorotoluenes,[12] and σ^* values.[10] The $\sigma_I(pK_a)$ values were obtained from the pK_as[13] of the appropriate substituted acetic acids by means of the least-squares relationship developed by Charton.[11] The pK_as for three acids could not be found in the literature and these were therefore estimated by analogy with similar acids.[13] The acids and their estimated pK_as are $Br_2CHCOOH$, 1.30; $(CH_3)_2ClCCOOH$, 2.78; CH_3Cl_2CCOOH, 1.08.

Of the possible combinations of steric and inductive parameters, $\sigma_I(pK_a)$ and υ gave the best correlation for the nine derivatives that constitute the halogen series (compounds VII-XV). This correlation is significant above the 99.9% confidence level[14] and predicts $\Delta G^{\ddagger}$ for each compound within ±0.4 kcal/mol of the experimental value! The correlation of E_a with $\sigma_I(pK_a)$ and υ had a lower correlation coefficient and F value.

The combination of $\sigma_I(pK_a)$ and υ also produces the best correlation for the series comprised of the halogen and methyl (II-IV) derivatives. However, the correlation coefficient (0.901) is lower, as is the F value (19), although the correlation is still significant at the 99.9% confidence level. The addition of σ_R°[15] as a third independent variable did not significantly improve the correlation.

Correlation of $\Delta G^{\ddagger}$ with $\sigma_I(pK_a)$ and υ for the series composed of the halogen, methyl, and methylchloro derivatives (compounds II-XV) produced a correlation coefficient of 0.908 and an F value of 25.8 (CL = 99.9). Addition of the $\Delta G^{\ddagger}$ value obtained by Reeves et al.[16] for the parent compound (I) to this series resulted in a similar correlation coefficient and F value. Use of the higher values for I shown in Table I produced poorer correlations.

Because the inductive effect and steric parameters produce reasonably good correlations with $\Delta G^{\ddagger}$ for α-substituted dimethylacetamides, the same parameters were tried for correlations with other carbonyl-substituted amides. The other amides chosen and their $\Delta G^{\ddagger}$ (kcal/mol) are $XCON(CH_3)_2$: X = C_6H_5, 15.5;[17] CH_2=CH, 16.7;[18] CN, 21.4;[19] F, 18.1;[19] Cl, 16.5;[19] Br, 15.7;[19] OCH_3, 14.8.[5] Values for σ_I for the substituents F, Cl, Br, CN, and C_6H_5 were estimated by multiplying σ_I for CH_2X by the ratio of σ_I for CH_2X to σ_I for CH_2CH_2X.[11] (The ratio of 2.55 was the average value for X = Cl, Br, C_6H_5, and CN and was used to calculate σ_I for X = F and OCH_3.) The υ values for CH_2=CH and CN were obtained from Charton's earlier work.[20] Following Charton's assumption[21] about the conformations of CH_2X groups, the van der Waals radius of oxygen was used to calculate a υ value of 0.32 for the OCH_3 group. The correlation of $\Delta G^{\ddagger}$ of all 22 compounds with $\sigma_I(pK_a)$ and υ produced the low correlation coefficient and F value of 0.71 and 9.9, respectively. Since the substituents added (X = C_6H_5, CH_2=CH, CN, F, etc.) are all capable of direct resonance interaction with the carbonyl group, this poor correlation is not surprising. In order to account for this interaction a resonance parameter was used as a third independent variable. Of the parameters R,[22] σ_R°, σ_R(Ba), σ_R^+, and σ_R^-,[15] σ_R^- gave the best correlation. The σ_R^- value for the vinyl group was calculated with the Taft relationship[15] from the pK_a of p-vinylanilinium ion.[23] Tabulated σ_R^- values[15] were used for the substituents CF_3, C_6H_5, CN, F, Cl, Br, and OCH_3, and a value of 0.12 was estimated for the CHF_2 group. For all other groups σ_R^- was taken as zero. The resulting correlation with $\sigma_I(pK_a)$, υ, and σ_R^- had a correlation coefficient of 0.903, and an F value of 26.4 (CL = 99.9). The mean value of the residuals was 0.8 kcal/mol and, therefore, on the average this correlation will produce the experimental value of $\Delta G^{\ddagger}$ to within ±0.8 kcal/mol.

Finally, it is of some value to compare the coefficients of the inductive, steric, and resonance parameters in the regression equations $\Delta G^{\ddagger} = a\sigma_I + b\upsilon + c\sigma_R^- + h$. For the halogen series the coefficients for the $\sigma_I(pK_a)$, υ correlation are a = 7.14, b = −7.22 (h = 17.4); for the halogen, methyl, methylchloro series the coefficients for the $\sigma_I(pK_a)$, υ correlation are a = 3.17, b = −5.76 (h = 19.5); and for all 22 amides the coefficients are a = 1.975, b = −4.66, c = 7.20 (h = 18.9). The ranges of the $\sigma_I(pK_a)$ and υ values used in the correlations are approximately the same and therefore the coefficients for the halogen series indicate the comparable importance of the inductive and steric effects (as measured and correlated with σ_I and υ). The addition of the methyl and methylchloro derivatives to the halogen series leads to an increase in the relative magnitude of the steric coefficient. For all 22 amides the steric coefficient is also larger than the inductive coefficient.[30] The resonance coefficient is even larger but considering the smaller range resonance values the relative importance of the resonance effect is probably similar to that of size.

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References and Notes

(1) W. E. Stewart and T. H. Siddall, III, *Chem. Rev.*, **70**, 517 (1970); H. Kessler, *Angew. Chem., Int. Ed. Engl.*, **9**, 219 (1970).
(2) L. M. Jackman in "Dynamic Nuclear Magnetic Resonance Spectroscopy", L. M. Jackman and F. A. Cotton, Ed., Academic Press, New York, N.Y., 1975, Chapter 7.
(3) A. Van Geet, *Anal. Chem.*, **42**, 679 (1970).
(4) H. S. Gutowsky and C. H. Holm, *J. Chem. Phys.*, **25**, 1228 (1956).
(5) C. H. Yoder, A. Komoriya, J. E. Kochanowski, and F. H. Suydam, *J. Am. Chem. Soc.*, **93**, 6515 (1971).
(6) D. Kost, E. H. Carlson, and M. Raban, *Chem. Commun.*, 656 (1971)
(7) O. A. Gansow, J. Killough, and A. R. Burke, *J. Am. Chem. Soc.*, **93**, 4297 (1971).
(8) T. Drakenberg, K.-I. Dahlquist, and S. Forsen, *Acta Chem. Scand.*, **24**, 694 (1970).
(9) M. Charton, *J. Am. Chem. Soc.*, **97**, 1552 (1975).

(10) R. W. Taft in "Steric Effects in Organic Chemistry", M. S. Newman, Ed., Wiley, New York, N.Y., 1956, Chapter 13.
(11) M. Charton, *J. Org. Chem.*, **29**, 1222 (1964).
(12) W. A. Sheppard, *Tetrahedron*, **27**, 945 (1971).
(13) H. C. Brown, D. H. McDaniel, and O. Häflinger in "Determination of Organic Structures by Physical Methods", E. A. Braude and F. C. Nachod, Ed., Academic Press, New York, N.Y., 1955, Chapter 14.
(14) N. R. Draper and H. Smith, "Applied Regression Analysis", Wiley, New York, N.Y., 1967.
(15) S. Ehrenson, R. T. C. Brownlee, and R. W. Taft, *Prog. Phys. Org. Chem.*, **10**, 1 (1973).
(16) L. W. Reeves, R. C. Shaddick, and K. N. Shaw, *Can. J. Chem.*, **49**, 3683 (1971).
(17) L. M. Jackman, T. E. Kavanagh, and R. C. Haddon, *Org. Magn. Reson.*, **1**, 109 (1969).
(18) R. F. Hobson and L. W. Reeves, *J. Magn. Reson.*, **10**, 243 (1973).
(19) E. A. Allan, R. F. Hobson, L. W. Reeves, and K. N. Shaw, *J. Am. Chem. Soc.*, **94**, 6604 (1972).
(20) M. Charton, *Prog. Phys. Org. Chem.*, **10**, 81 (1973).
(21) M. Charton, *J. Am. Chem. Soc.*, **91**, 615 (1969).
(22) C. G. Swain and E. C. Lupton, Jr., *J. Am. Chem. Soc.*, **90**, 4328 (1968).
(23) A. M. Shur and A. P. Donya, *Izv. Vyssh. Uchebn. Zaved., Khim. Khim. Tekhnol.*, **11**, 298 (1968).
(24) R. C. Newman, Jr., and V. Jonas, *J. Am. Chem. Soc.*, **90**, 1970 (1968).
(25) T. Drakenberg, K.-I. Dahlquist, and S. Forsen, *J. Phys. Chem.*, **76**, 2178 (1972).
(26) G. Isaksson and J. Sandström, *Acta Chem. Scand.*, **21**, 1605 (1967).
(27) W. Walter, E. Schaumann, and H. Paulsen, *Justus Liebigs Ann. Chem.*, **727**, 61 (1969).
(28) S. Ng, *J. Chem. Soc. A*, 1586 (1971).
(29) K. H. Abramson, P. T. Inglefield, E. Krabower, and I. W. Reeves, *Can. J. Chem.*, **44**, 1685 (1966).
(30) A. correlation (described as "not exceptional") of $\Delta G^{\ddagger}$ for four amides vs. σ^* and E_s gave the approximate values of 1 and 2 for the coefficients of these parameters in the regression equation.[24] (Note that E_s values decrease with an increase in size.)

Exo–Endo vs. Equatorial–Axial Equilibria. Assessment of Steric Crowding in the Endo Cavity

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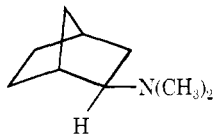
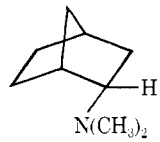
Abstract: ^{13}C NMR methods were used to determine the relative amounts of *exo*- and *endo*-*N*-alkyl-2-azanorbornane conjugate acid (where the alkyl group is methyl, ethyl, isopropyl, or *tert*-butyl). It is found that the N proton and the methyl, ethyl, and isopropyl groups all have similar ability to usurp the exo position. Steric effects in the endo cavity are too small to discriminate between moderately sized substituents and a solvated proton. This contrasts with an analogous study of *N*-alkyl-4-*tert*-butylpiperidinium ions in which the alkyl groups on the nitrogen reside in an equatorial configuration and the solvated N proton is relegated to the axial position.

The theme song of those who sing the praises of classical norbornyl cations is entitled "Crowding in the Endo". The lyrics create images of an endo 2-tosylate impaling itself on an endo 6 proton.[1] We recently set forth the proposition that if an endo leaving group is inhibited by special steric or solvation effects, then other functionalities within the endo cavity should display modified behavior as well.[2] Accordingly, we measured the pK_as and the rates of NH proton exchange, nitrogen inversion, and amine quaternization for *exo*- and *endo*-2-dimethylaminonorbornane (Ia and Ib). The two compounds

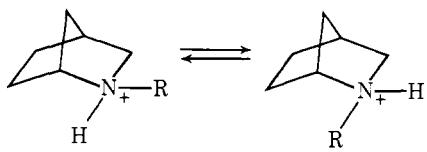


Ia

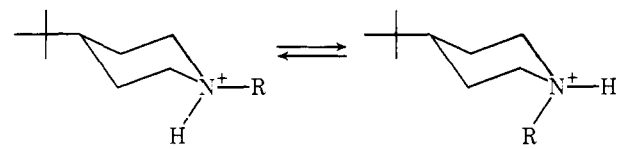


Ib

differ only slightly as would be expected if the endo dimethylamino group were not subjected to unusual steric or solvation effects.[2] In the present communication we extend this line of reasoning by considering the configurational equilibria of *N*-alkyl-2-azanorbornanes (II where R = methyl, ethyl, isopropyl, and *tert*-butyl). "Crowding in the endo" should surely favor configuration IIa. For reference purposes we also evaluated analogous equilibria for *N*-alkyl-4-*tert*-butylpiperidines (III).



IIa IIb



IIIa IIIb

Experimental Section

Synthesis of *N*-Alkyl-2-azanorbornanes (II). The four *N*-alkyl derivatives of 2-azanorbornane were prepared by known methods:[3] cyclopentanecarboxylic acid to the acid chloride to *N*-alkylcyclopentanecarboxamide to *N*-alkylaminomethylcyclopentane to the *N*-chloro compound to *N*-alkyl-2-azabicyclo[2.2.1]heptane (II). The Hofmann–Löffler–Freytag reaction was carried out with a Rayonet reactor using 2735-Å light for 18 h at 35–40 °C. The only major departure from the literature procedure[3] consisted of using NaOCl for N-chlorination of the *tert*-butyl system (*N*-chlorosuccinimide did not give product). Yields were poor even with this modification, and the product required purification on a 6-ft SE-30 analytical GLC column. Suitable NMR, IR, and mass spectra as well as analytical data were obtained for many of the synthetic intermediates[4] and all four final products. Two of the four *N*-alkyl-2-azanorbornanes (the isopropyl and *tert*-butyl derivatives) are new compounds boiling at 150–155 °C (140 mm) and about 54 °C (6 mm), respectively.

Anal. Calcd for $C_9H_{17}N$: C, 77.63; H, 12.31; N, 10.06. Found: C, 77.44; H, 12.20; N, 10.31.

Anal. Calcd for $C_{10}H_{19}N$: C, 78.36; H, 12.50. Found: C, 78.11; H, 12.47.

Synthesis of *N*-Alkyl-4-*tert*-butylpiperidine (III). The parent amine, 4-*tert*-butylpiperidine, was prepared by hydrogenating the substituted pyridine with the aid of 5% Pd on carbon.[5] Compounds III (R =

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