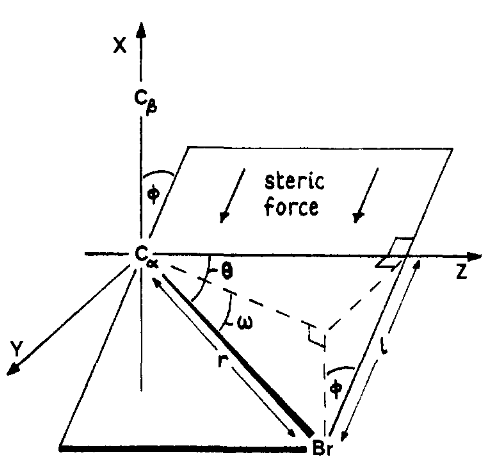

Figure 3. Distorting effect of steric force on CCBr coordinate.

bending force constants had virtually no effect on calculated KIE's. In subsequent work,[5] however, we show that this steric effect is an important feature of the model transition states and we have introduced it here for convenience.

Acknowledgment. We thank the S.R.C. for support.

Appendix. Derivation of the Steric Factor S_ω

Assume that a C_α–C_β bond and the $C_\alpha\cdots$Br bonds would lie along the axes denoted x and z, respectively, in Figure 3 in the absence of any steric pressure. Suppose then that a perturbing steric force acts perpendicularly to the z axis distorting the C–Br bond by an angle θ from the z axis in a plane making an angle ϕ with the xz plane. There is a harmonic potential for the bending of the CCBr angle from its 90° value in the unperturbed system; the deformation ω of the CCBr coordinate is the angle between the C–Br bond and the yz plane, and the harmonic energy (per C–Br bond) of the distorted system is

$$V_b = \tfrac{1}{2}F\omega^2 \qquad (7)$$

where F is the bending force constant of the undistorted system. The repulsive energy of the steric force is given by the inverse exponential expression (8), where l is the perpendicular distance

$$V_r = \alpha \exp[-\beta\,(l + l')] \qquad (8)$$

of the Br atom from the z axis and α, β, and l' are constants. The total energy V of the distorted system (per C–Br bond) is $V_b + V_r$, and differentiation with respect to displacement in the CCBr coordinate gives eq 9. This derivative may be evaluated by noting

$$\frac{dV}{d\omega} = \frac{dV_b}{d\omega} + \frac{dV_r}{dl}\,\frac{dl}{d\theta}\,\frac{d\theta}{d\omega} \qquad (9)$$

that $l = r \sin\theta$ and $\sin\omega = \sin\theta\cos\phi$. The equilibrium condition is given by eq 10.

$$\frac{dV}{d\omega} = F\omega - r(\cos\omega/\cos\phi)\alpha\beta \exp[-\beta(l + l')] = 0 \qquad (10)$$

The force constant for bending of the CCBr coordinate in the distorted system is given by the second derivative of V with respect to ω at the equilibrium position. Thus

$$\frac{d^2V}{d\omega^2} = \frac{d^2V_b}{d\omega^2} + \frac{d^2V_r}{dl^2}\left(\frac{dl}{d\theta}\,\frac{d\theta}{d\omega}\right)^2 + \frac{d^2l}{d\theta^2}\left(\frac{dV_r}{dl}\right)\left(\frac{d\theta}{d\omega}\right)^2 + \frac{d^2\theta}{d\omega^2}\left(\frac{dV_r}{dr}\,\frac{dl}{d\theta}\right) \qquad (11)$$

which when evaluated gives

$$\frac{d^2V}{d\omega^2} = F + \alpha\beta \exp[-\beta(l + l')](r(\sin\omega/\cos\phi) + \beta r^2(\cos^2\omega/\cos^2\phi)) \qquad (12)$$

At equilibrium eq 10 may be substituted into eq 12, thus enabling the force constant to be expressed by eq 13. Although F is

$$F' = F(1 + \omega\tan\omega + \beta r\omega(\cos\omega/\cos\phi)) = FS_\omega \qquad (13)$$

described above as the bending force constant for the undistorted system, the value substituted into eq 13 to obtain the modified force constant F' is that obtained *after* application of eq 3 using the distorted angle rather than a strictly undistorted angle. This procedure ensures that the S_ω describes the additional steric effect of longer range nonbonded interactions on CCBr bending force constants after the effects of geminal interactions on all bending force constants have been allowed for first.

NPE Effects in Bimolecular Nucleophilic Substitution

Christine D. Chalk, James McKenna,* and Ian H. Williams

Contribution from the Department of Chemistry, The University, Sheffield S3 7HF, England.
Received December 6, 1979

Abstract: By use of the force fields established in the two preceding papers, relative NPE effects are calculated for bromide ion exchanges (the Finkelstein reactions) for a series of simple alkyl bromides. The effects on rate constants cover a range of about 30:1, neglecting contributions (if any) from variation in rotational symmetry numbers. These calculated results are analyzed in detail and compared with related literature results, both experimental and calculated. Extension of the force fields permits computation of relative NPE effects for reaction of methyl bromide with hydroxide ion and with a series of alkoxides. Effects for alkoxides differ only slightly within the group, but the NPE contribution to the rate constant for reaction with hydroxide is nearly twice that for reaction with methoxide. Interpretations for these findings are suggested.

Introduction

Bimolecular nucleophilic substitution is one of the most intensively studied reactions in organic chemistry, and it seemed particularly important to apply in this area our procedure for computation of NPE effects outlined in the two preceding papers.[1,2]

Much of the classical work on S_N2 reactions was carried out by Ingold and his collaborators,[3-5] who conducted theoretical studies, in parallel with experimental investigations, designed to provide an understanding of the role of steric, polar, and mass

---

(1) C. D. Chalk, B. G. Hutley, J. McKenna, L. B. Sims, and I. H. Williams, preceding paper in this issue.

(2) J. McKenna, L. B. Sims, and I. H. Williams, preceding paper in this issue.

(3) C. K. Ingold, *Q. Rev., Chem. Soc.*, **11**, 1 (1957).

(4) I. Dostrovsky, E. D. Hughes, and C. K. Ingold, *J. Chem. Soc.*, 173 (1946).

(5) P. B. D. de la Mare, L. Fowden, E. D. Hughes, C. K. Ingold, and J. D. H. Mackie, *J. Chem. Soc.*, 3200 (1955).

0002-7863/81/1503-272$01.00/0

("ponderal") factors. The most detailed analysis was for Finkelstein reactions, where X and Y were isotopically or chemically different halogens and R is an alkyl group.

$$Y^- + RX \rightarrow YR + X^-$$

Both activation energies[4,5] and activation entropies[5] were estimated, relative to the values for the reaction with methyl as the group R, on the basis of potential energy surfaces constructed from empirical potentials for nonbonded interactions,[4,5] bond stretching, and bond angle bending.[5] The estimates of activation entropies included vibrational contributions, but the models used were deficient in that of necessity (in the precomputer era) only a small number of modes were allowed for and intraalkyl vibrations, for example, were ignored. Recently, other workers have used either classical[6,7] or quantum[8] mechanics to study changes in potential energy during the Finkelstein reactions and thus to obtain estimates of barrier heights ($\Delta\epsilon^\ddagger$ in our notation), but there have been no previous attempts based on an adequately complete vibrational analysis to estimate $\Delta(G - \epsilon)^\ddagger$, the nonpotential energy (NPE) components of free energies of activation.

In the sequel we outline our results for calculation of NPE effects for some bimolecular substitutions and express these conveniently as contributions to relative rate constants $k(\mathrm{R})/k(\mathrm{Me})$ where *R* is an alkyl group other than methyl in the symmetrical bromine-exchange reaction

$$Br^- + R{-}Br \rightarrow Br{-}R + Br^-$$

or where R is hydrogen or alkyl in the reaction

$$RO^- + MeBr \rightarrow ROMe + Br^-$$

Following a common type of treatment[9] of isotope effects, the relative rate constants are analyzed in terms of three multiplicative factors, MMI, EXC, and ZPE, denoting respectively contributions from changes between reactant and transition state associated with masses and moments of inertia, population of excited vibrational levels, and zero-point vibrational energies. A similar analysis for structural effects has already been used by Wolfsberg,[10] but in discussion of equilibrium rather than rate constants, for the reaction of homologous carbonyl compounds with hydrogen cyanide. We have also calculated activation entropies for the Finkelstein exchange reactions, and in principle such calculated values might usefully be checked directly against experimental values, giving additional verification of the validity of the method independent of the initially imposed requirement[1,2] that the force fields used in the computations should match appropriate experimental data. While in this case such comparisons are indeed of interest, we must note that our computations so far relate to ideal gas conditions, whereas the published experimental activation entropies, also so far (see below), are for reactions in solution. Currently, investigations of S_N2 reactions in the gas phase are being actively pursued,[11] but as yet no studies of temperature dependence on reaction rate constants, and hence of gas-phase activation entropies, have been reported.

Calculations

Force Fields. The force fields required for calculation of NPE effects in the bromide-exchange reactions have been described in the two preceding papers,[1,2] as has the general program (QREL) used for the computations. For the hydroxide/alkoxide reactions transition-state models were used in which the C···Br bond (to the leaving group) was collinear with the forming C_α···O and the O–H(C) bonds and the angles HCBr were all 90°. All other coordinates in the nucleophiles involved tetrahedral angles and appropriate force constant values[12] which were unchanged between reactants and transition states.

Table I. Results Associated with Various Features of Transition-State Models in Calculated NPE Effects on the Reactivity of Alkyl Bromides with the Bromide Ion at 298 K

	transition-state model[a]						
alkyl group R	Br steric effect	γ-H steric effect	hyperconjugation	k(R)/k(Me)	MMI	EXC	ZPE
Et	+[b]	–	–	0.414	0.547	0.980	0.772
	–	–	–	0.494	0.547	1.045	0.863
i-Pr	+[c]	–	+	0.340	0.273	1.057	1.178
	+[c]	–	–	0.327	0.273	1.159	1.035
	–	–	–	0.479	0.273	1.348	1.304
t-Bu	+[d]	–	+	1.878	0.191	2.130	4.617
	+[d]	–	–	1.500	0.191	2.625	2.991
	+[e]	–	–	0.425	0.191	1.460	1.526
neo-Pe	+[f]	+	–	0.061	0.181	1.600	0.212
	+[f]	–	–	0.178	0.181	1.618	0.610
	–	–	–	0.374	0.181	2.221	0.932

[a] +, yes, –, no or irrelevant. [b] Steric factor $S_\omega = 1.17$. [c] Steric factor $S_\omega = 1.20$. [d] C_α···Br partial bond order = 0.35. [e] C_α···Br partial bond order = 0.5. [f] Steric factor $S_\omega = 1.91$.

Contributions from Rotational Symmetry Numbers. It is a trivial point that a rotational symmetry number, σ, reduces the rotational partition function ($\times 1/\sigma$); changes in σ between reactant and transition state thus provide contributions to rate constants which in principle can be assessed immediately on inspection of the two structures. We have made no allowance, however, in this series of papers for such symmetry contributions in our calculations of NPE effects in cases where at least arguably we might have done so, and we have excluded related contributions from the symmetry of internal rotors (cf. reactions of halides with different alkoxides) which in any case we regard as torsional oscillators. The Finkelstein reactions of methyl and isopropyl bromides raise a special interesting query. The transition states formally have symmetry numbers (6 and 2, respectively) twice that of the reactant halides (3 and 1); in the reactions of other homologues the symmetry number is unity for both reactant halide and transition state except for the *tert*-butyl reaction, where $\sigma = 3$ for each species. There is some doubt in our minds, however,[13] whether the transition states for the methyl and isopropyl reactions should properly be regarded as having a twofold rotational axis at right angles to the reaction coordinate; if they do not, the differences indicated above would disappear and none of the bromide-exchange reactions would have a symmetry number contribution to reactivity. The main point, however, is that in any case we are predominantly interested in this series of papers in computing NPE effects which *cannot* be determined (at least in principle; see remarks above) by simple inspection; most examples studied will have no symmetry contributions, and for any odd actual or putative exception the contribution can of course be added at choice.

Special Features of Transition-State Models. Various steric and electronic features were introduced into the basic transition-state force fields[2] in order to provide more realistic models. Table I contains relative rate constants $k(\mathrm{R})/k(\mathrm{Me})$ and contributing NPE factors calculated on the basis of various levels of sophistication in the models; the MMI terms remain unaffected since the transition-state geometries are unchanged, but the EXC

---

(6) M. H. Abraham, P. L. Grellier, and M. J. Hogarth, *J. Chem. Soc., Perkin Trans. 2*, 1365 (1975).

(7) D. F. DeTar, D. F. McMullen, and N. P. Luthra, *J. Am. Chem. Soc.*, **100**, 2484 (1978).

(8) H. B. Schlegel, K. Mislow, F. Bernardi, and A. Bottoni, *Theor. Chim. Acta*, **44**, 245 (1977) and literature cited therein.

(9) M. Wolfsberg, and M. J. Stern, *Pure Appl. Chem.*, **8**, 225 (1964).

(10) M. Wolfsberg, *Tetrahedron Lett.* 3405 (1964).

(11) W. N. Olmstead and J. I. Brauman, *J. Am. Chem. Soc.*, **99**, 4219 (1977).

(12) Geometries and force constants as given by model force field[1,2] (with the O atom treated as the C atom or the methyl group as appropriate for specification of some bending and torsional coordinates), together with the following exceptions and additions. Bond lenghts (Å): C_N–O = 1.47, O–H = 0.958, O···C_α = 1.78, C_α···Br = 2.08. Force constants: C_N–O, 5.3; O–H, 7.8; C_α···Br, O···C_α, 1.874 (all in mdyn Å^{-1}); HC_NO, CC_NO, 1.0; HC···Br, 0.59; O···C_αH, 0.492; C_NO···C_α, HO···C_α, 0.113; τ(C_NO···C_α), 0.005 (all in mdyn Å rad^{-2}). Zero-frequency reaction-coordinate modes in transition states.

(13) Cf. D. Rapp and R. E. Weston, *J. Chem. Phys.*, **36**, 2807 (1962); E. Pollak and P. Pechukas, *J. Am. Chem. Soc.*, **100**, 2984 (1978).

Table II. Carbon-Bromine Stretching Frequencies Corresponding to Different Types of Reaction Coordinates for S_N2 Bromine Exchange with Methyl Bromide

type of reactn coordinate	interactn force constant (f)	freq of C–Br stretching mode, cm^{-1}	
		sym	asym
none[a]	0	178	582
zero frequency	$F_{C\cdots Br}$	251	0
imaginary frequency	$2F_{C\cdots Br}$	308	$616i$

[a] The adduct is an intermediate not a transition state.

and ZPE terms are affected by the changes in force constants. Inclusion of the sideways steric effect of an alkyl group upon the bromine atoms in a transition state has a relative rate-retarding effect, in proportion to the size of the steric factor s_ω, primarily as a result of a decreased ZPE contribution. The reciprocal steric effect of the bromine atoms on the γ-hydrogen atoms of the neopentyl transition state is also considerably relative rate retarding ($\times^1/_3$) and is exerted almost wholly via the ZPE term since only high-frequency vibrational modes are affected. The outward steric pressure of the methyl groups on the bromine atoms in the *tert*-butyl transition state, which leads to decreased carbon–bromine partial bond orders and to reductions in low-frequency modes, involves both ZPE and EXC terms, and is considerably relative rate accelerating (×3). The overall effect of hyperconjugation is relative rate accelerating in both the isopropyl and *tert*-butyl cases, but increases in the ZPE terms are offset by relative rate-retarding decreases in the EXC terms, since low frequencies are raised while high frequencies are lowered.

Influence of the Reaction-Coordinate Mode. The effect of the reaction-coordinate mode on calculated NPE contributions to relative reactivity was investigated in a limited way by varying the value of the interaction force constant used to couple the C···Br stretching motions. If the interaction force constant is omitted, then the bromide ion–alkyl bromide adduct is not a transition state but an intermediate lying in a potential energy well, and the asymmetric carbon–bromine stretching mode is a normal mode with a positive frequency. Inclusion of a positive interaction force constant reduces the frequency of the asymmetric C···Br stretching mode but increases the frequency of the corresponding symmetric mode. The frequencies of these modes in the methyl case are presented in Table II; as the value of the interaction force constant increases from zero, so the frequency of the asymmetric C···Br stretching mode decreases to zero and then becomes imaginary, whereas that of the symmetric mode increases steadily.

Relative rate constants for S_N2 bromine-exchange reactions of a selection of alkyl bromides calculated by using different types of reaction coordinate are presented diagrammatically in Figure 1. These calculations were performed by using transition-state models which did not include any steric effects on γ-hydrogen atoms nor any allowance for hyperconjugative effects (see Table I), but the results are generally applicable. It may be seen clearly that the range of relative rate constants obtained for transition states with a zero-frequency reaction-coordinate mode is greater than either the range obtained for transition states possessing an imaginary frequency reaction-coordinate mode or the range of relative equilibrium constants. It would seem that the basis model, with a zero-frequency reaction-coordinate mode, represents an extreme in conditions, giving a maximal range of kinetic structural effects, and therefore provides a convenient basis for investigation of such effects. Variation of the reaction-coordinate frequency in the transition states affects primarily the ZPE term, while the additional low frequency asymmetric stretching mode in the intermediate affects the EXC term also.

Results. Relative NPE Effects Associated with Substrate Homology

Relative rate constants for reactions of bromide ion with alkyl bromides, with respect to that with methyl bromide as standard, have been calculated by assuming ideal gas conditions at 298 K and excluding contributions from potential energy differences between reactants and transition states, and the results are given in Table III. It is of great interest to note that NPE terms alone may contribute appreciably to relative rate constants $k(R)/k(Me)$ such that there is a factor of 30 between the fastest and slowest of the reactions considered here.

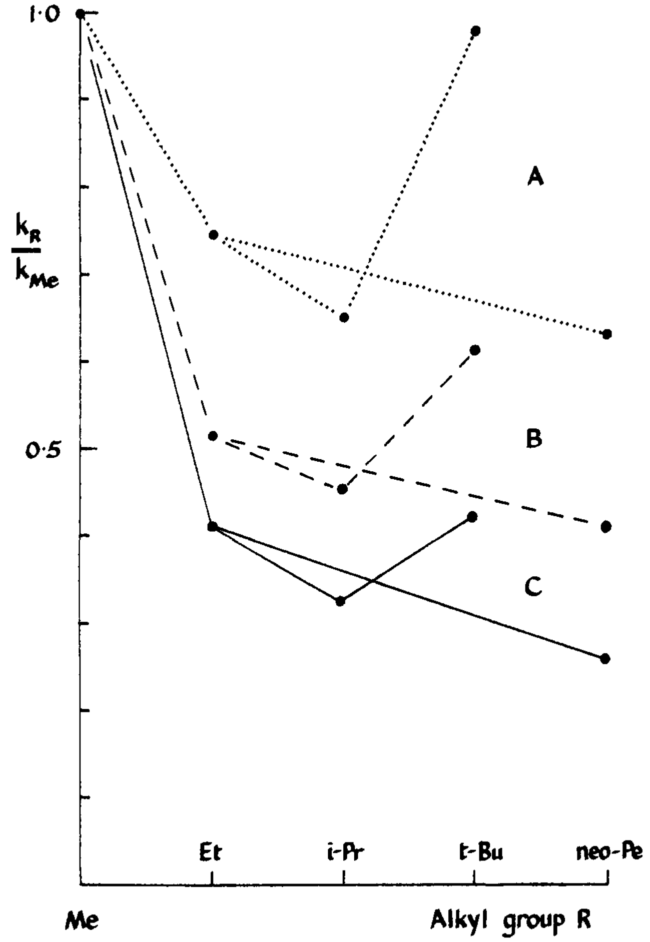

Figure 1. Effect of differing reaction coordinate modes on relative rate (or equilibrium) constants for S_N2 bromide-exchange reactions of alkyl bromide at 298 K: (A) no reaction-coordinate mode included in calculation of relative equilibrium constants ($f = 0$); (B) reaction-coordinate mode with imaginary frequency included ($f = 2F_{C\cdots Br}$); (C) reaction-coordinate mode with zero frequency included ($f = F_{C\cdots Br}$). In this and other figures, variations for the α and the β series (see: Mass and Moment of Inertia Effects subsection under Results) are shown separately.

Table III. Calculated NPE Contributions[a] to Relative Rate Constants for S_N2 Reactions of the Bromide Ion with Alkyl Bromides at 298 K

alkyl group	$k(R)/k(Me)$	MMI	EXC	ZPE
Me	1.000	1.000	1.000	1.000
Et	0.414	0.547	0.980	0.772
i-Pr	0.340	0.273	1.057	1.178
t-Bu	1.878	0.191	2.130	4.617
n-Pr (C_s)	0.172	0.375	0.992	0.462
n-Pr (C_1)	0.247	0.347	1.258	0.565
i-Bu (C_s)	0.185	0.225	1.812	0.455
i-Bu (C_1)	0.234	0.207	2.101	0.538
neo Pe	0.061	0.181	1.600	0.212

[a] All NPE calculations (including calculations of activation entropies) given in the tables exclude any contributions from rotational symmetry numbers. See text.

The factors MMI, EXC, and ZPE listed in Table III multiply together to give the relative rate constant, but the trends in these factors with alkyl homology are better observed graphically by taking logarithms.

$$\ln\,(k(R)/k(Me)) = \ln\,(MMI) + \ln\,(EXC) + \ln\,(ZPE)$$

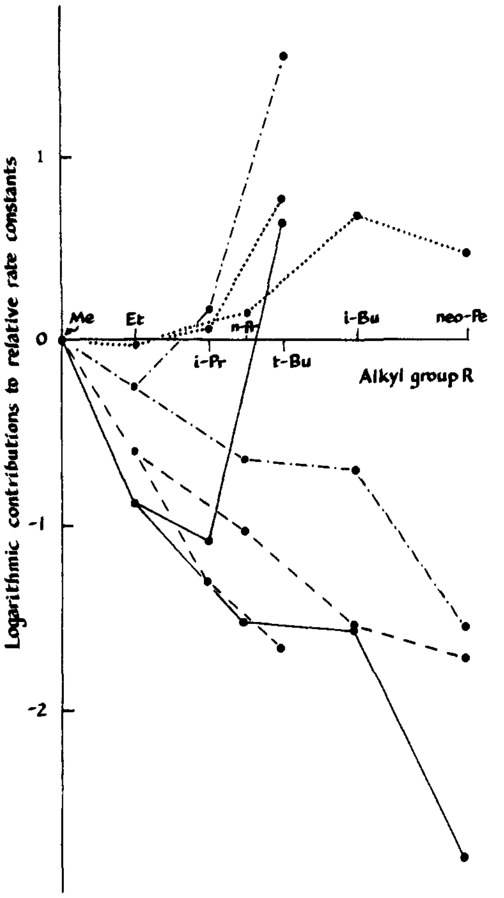

Figure 2. Logarithmic NPE contributions to relative rate constants for S_N2 bromide-exchange reactions of alkyl bromides at 298 K: solid lines, ln $(k(R)/k(Me))$; dashed lines, ln (MMI); dotted lines, ln (EXC); interrupted lines, ln (ZPE).

We may note that while these additive contributions are dimensionless, they may be expressed as energies by multiplying by RT.

$$RT \ln (k(\mathrm{R})/k(\mathrm{Me})) = [-\Delta(G^\circ - \epsilon)^\ddagger]_\mathrm{R} - [-\Delta(G^\circ - \epsilon)^\ddagger]_\mathrm{Me}$$

$$RT \ln (\mathrm{MMI}) = [-\Delta(G^\circ - E_0)_{\mathrm{trans+rot}}{}^\ddagger]_\mathrm{R} - [-\Delta(G^\circ - E_0)_{\mathrm{trans+rot}}{}^\ddagger]_\mathrm{Me}$$

$$RT \ln (\mathrm{EXC}) = [-\Delta E_\mathrm{th}{}^\ddagger + T\Delta S_\mathrm{vib}{}^\ddagger]_\mathrm{R} - [-\Delta E_\mathrm{th}{}^\ddagger + T\Delta S_\mathrm{vib}{}^\ddagger]_\mathrm{Me}$$

$$RT \ln (\mathrm{ZPE}) = [-\Delta E_\mathrm{zp}{}^\ddagger]_\mathrm{R} - [-\Delta E_\mathrm{zp}{}^\ddagger]_\mathrm{Me}$$

Figure 2 is a plot of the logarithms of the NPE contributions in Table III against alkyl homology, points referring to different alkyl groups being separated along the horizontal axis of this diagram for reasons of clarity only, since there is no horizontal scale. The points plotted in Figure 2 for n-propyl and isobutyl refer to equilibrium gaseous mixtures of C_s and C_1 symmetry reactant conformers and are mole fraction weighted averages of energetic contributions. The mole fractions of the C_s conformers were taken as 0.37 and 0.47, respectively, for n-propyl and isobutyl bromides. We now discuss variations with structure of the three components of the relative NPE effects.

Mass and Moment of Inertia Effects. The MMI term decreases in value from unity, for the methyl standard, to 0.181 for the neopentyl case, and hence is relative rate retarding. MMI is a simple function of the masses and moments of inertia for the reactants and transition states for two reactions, given algebraically by eq 1, where M is a molecular mass, I is a principal moment

$$\mathrm{MMI} = \left(\frac{M_\mathrm{R}{}^\ddagger}{M_\mathrm{R}{}^\mathrm{r}}\frac{M_\mathrm{Me}{}^\mathrm{r}}{M_\mathrm{Me}{}^\ddagger}\right)^{3/2}\left(\frac{(I_xI_yI_z)_\mathrm{R}{}^\ddagger}{(I_xI_yI_z)_\mathrm{R}{}^\mathrm{r}}\frac{(I_xI_yI_z)_\mathrm{Me}{}^\mathrm{r}}{(I_xI_yI_z)_\mathrm{Me}{}^\ddagger}\right)^{1/2} \quad (1)$$

of inertia, and the superscript r refers to reactants. It is instructive to consider the quantitative implications of both factors separately, and again this is best illustrated graphically by taking logarithms. The logarithms of the ratio of masses and of the ratio of products of principal moments of inertia (PPMI) for the reactants and the transition state in the case of each alkyl group are plotted in Figure 3. It is clear from the downward trend of each plot that the differences between reactants and transition state in mass and in moments of inertia are greatest for the case of methyl and diminish with increasing alkyl homology. The mass increase arising from association of an alkyl bromide with bromide ion is proportionately less as the mass of the alkyl group becomes greater; hence the translational factor decreases steadily with increasing alkylation, from unity for methyl to 0.755 for neopentyl, and becomes more relative rate retarding.

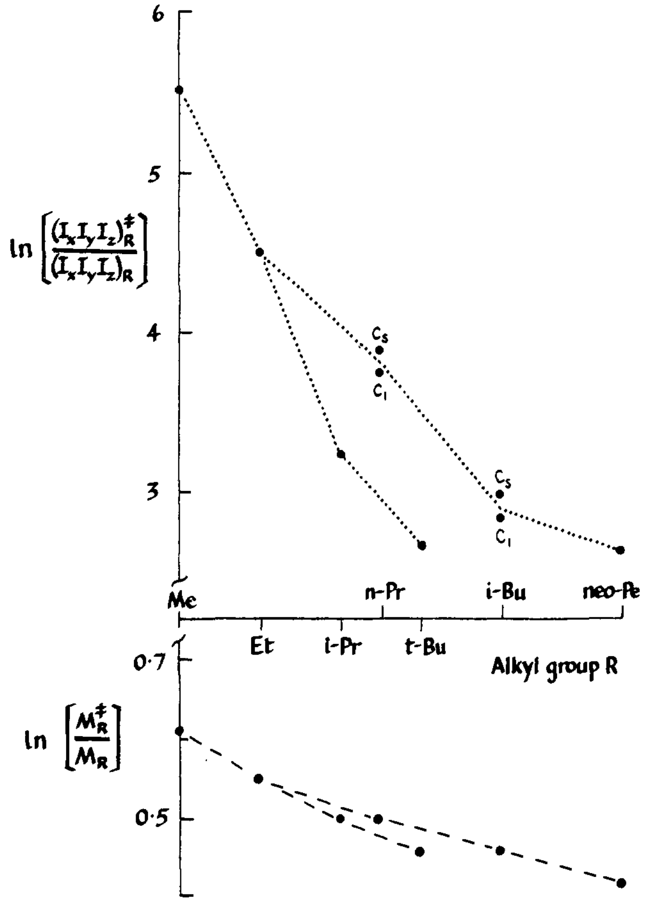

Figure 3. Logarithmic ratios of masses and of products of moments of inertia for reactants and transition states for S_N2 bromide-exchange reactions of alkyl bromides.

The moments of inertia of methyl bromide have very low values, because the molecule consists of a single heavy atom with a light group attached, and so the center of mass is located near to the heavy atom. Association of the molecule with a bromide ion is akin to formation of a diatomic molecule from two monatomic species, because the adduct (the S_N2 transition state) is like a dumbell having two heavy atoms joined by a light connecting group; the moments of inertia about the dumbell axis remain very small, but about axes perpendicular to this axis the moments of inertia are very large because the two heavy atoms are each located as far away as possible from the center of mass. Association of two atoms to form a diatomic molecule generates two moments of inertia in a system previously possessing none. By analogy, association of methyl bromide with bromide ion generates two large moments of inertia in a system previously possessing only small moments of inertia.

The effect of alkyl homology upon the moments of inertia of alkyl bromides may be assessed qualitatively by considering the distribution of the extra mass about the center of mass of the $C_\alpha \cdots Br$ subsystem, which is close to the bromine atom. The product of principal moments of inertia (PPMI) increases with increasing alkylation, but for a given additional mass the increase is less if the mass is distributed compactly about C_α (cf. the α-methylated alkyl groups isopropyl and *tert*-butyl) than if the mass is contained in a more extended alkyl chain (cf. the β-methylated alkyl groups *n*-propyl, isobutyl, and neopentyl); for a given alkyl group the increase in the PPMI over that for methyl is roughly dependent on the separation of the center of mass of the alkyl group from the bromine atom.

The effect of alkylation on the moments of inertia of transition states for S_N2 bromine exchange of alkyl bromides may be similarly assessed by consideration of the distribution of mass about the center of mass of the approximately linear Br···C···Br subsystem, located close to C_α. The PPMI again increases with increasing alkylation, the more so for alkylation distributed distantly from C_α than for alkylation distributed compactly about C_α, with the increase being roughly dependent on the separation of the center of mass of the alkyl group from C_α. However, the transition-state structures are such that these separations from C_α are less than the corresponding separations from Br in the reactants, and hence the increase in the PPMI over that for methyl is less in the transition states than in the reactants. Thus the increase in the PPMI from reactant to transition state becomes smaller with increasing alkylation, as may be seen from Figure 3, and this diminution is more marked within the α series of alkyl groups (Me, Et, *i*-Pr, *t*-Bu) than within the β series (Et, *n*-Pr, *i*-Bu, neo-Pe). The α series comprises molecules having relatively more compact distributions of mass ("centripetal" distributions?) whereas the β series comprises molecules having increasingly more distant distributions of mass ("centrifugal" distributions?). The ratio of the PPMI, between reactant and transition state, for any alkyl group as over methyl, determines the rotational factor in the above equation, which decreases from unity for the methyl standard to 0.240 for *tert*-butyl and 0.239 for neopentyl. The near equality of these rotational contributions to the relative rate constants for neopentyl and *tert*-butyl demonstrates the importance of the *distribution* of mass in determining kinetic structural effects in these reactions of alkyl bromides; other things being equal, an increase in mass leads to a relative rate retarding rotational contribution, but addition of a greater mass distant from the center of mass may be equivalent to addition of a lesser mass close to the center of mass of the unalkylated system.

Excitational and Zero-Point Energy Effects. The importance of both the EXC and ZPE terms in determining kinetic isotope effects is well-known, although the contributions of EXC to secondary isotope effects are small and associated discussions tend to major on the ZPE contributions.[9] However, inspection of Table III and Figure 2 shows that for these (secondary?) kinetic structural effects the contributions of EXC and ZPE are indeed both important and that the overall value of a relative rate constant greatly depends on the nature of the interplay of these two terms. An interesting structural distinction between the α- and β-methylated series of alkyl groups is revealed: along the α series the EXC and ZPE terms act in the same direction, being slightly relative rate retarding for ethyl but considerably relative rate accelerating (~×10) for *tert*-butyl, whereas along the β series the EXC and ZPE terms act in opposite directions, with ZPE tending to dominate. The manner in which these trends arise may be understood by examining the calculated frequencies and normal coordinates for representative cases: we present results here for the methyl standard case, for ethyl, and for *tert*-butyl and neopentyl as the terminal cases of the α and β series, respectively. For the purpose of analysis it was found useful to classify the vibrational modes of each species into three categories: first, the carbon–bromine stretching modes together with the extra vibrational modes in the transition states involving the additional bromine atom, second, the five valence angle bending modes about the α-carbon atom in the reactants and the corresponding modes in the transition states, and, last, all the rest of the vibrational modes, including torsions. Correlation of individual modes between reactant and transition state may be achieved, and frequency changes may be related to structural effects in the transition states.

Table IV. Frequencies of Selected Vibrational Modes of Reactants and Transition States for S_N2 Bromine-Exchange Reactions of Alkyl Bromides

		freq, cm^{-1}	
alkyl group	descriptn of mode	reactant	transition state
methyl	extra Br–C–Br (deg)		180
	C–Br sym str	613	251
	H–C–Br (deg)	942	1112
	H–C–H (deg)	1381	1345
	H–C–Br	1411	1243
ethyl	extra Br–C–Br	-	176
		-	185
	C–Br sym str	563	209
	C–C–Br	288	392
	CH_2 rock	778	847
	CH_2 twist	1176	1183
	CH_2 def	1238	1297
	CH_2 wag	1349	1281
tert-butyl	extra Br–C–Br (deg)	-	119
	C–Br sym str	562	178
	C–C–Br	261	441
	C–C–Br (deg)	308	230
	C–C–C (deg)	401	446
neopentyl	extra Br–C–Br	-	132
		-	147
	C–Br sym str	677	219
	C–C–Br	152	582
	CH_2 rock	732	879
	CH_2 twist	1156	1198
	CH_2 def	1195	1244
	CH_2 wag	1255	1335

Frequencies of modes for reactants and transition states in the four cases under consideration and in the first two categories only mentioned above are listed in Table IV.

The excitational term EXC, which describes the contribution from the variable population statistics of vibrational states above the lowest vibrational energy level to the relative rate constant, is given below, where the quantities Π_R for each species are products over all the vibrational modes ($3N - 6$ for reactants, $3N - 7$ for transition states).

$$\mathrm{EXC} = \frac{\Pi_R \; \Pi_{Me^\ddagger}}{\Pi_{R^\ddagger} \; \Pi_{Me}}$$

$$\Pi_R = \prod_i [1 - \exp(-hc\nu_i/kT)]_R$$

These quantities are presented in Table V for the four reactions considered here. The value of EXC is determined by changes in low-frequency vibrational modes, between reactant and transition state, for a reaction relative to the methyl standard reaction; the important modes are bending and stretching modes involving bromine atoms and skeletal bending modes involving carbon atoms. Formation of a "loose" transition state by reduction in force constants associated with low-frequency modes results in a relative rate-accelerating EXC term; conversely, formation of a "tight" transition state involving increases in vibrational frequencies leads to a relative rate-retarding EXC term.

Addition of a bromide ion to an alkyl bromide increases the total number of vibrational modes by 3; simply, the extra bromine atom may vibrate in directions parallel or perpendicular to the new C_α···Br bond, corresponding to a C_α···Br stretching mode and two Br···C_α···Br bending modes. However, since the adduct is a transition state and not an intermediate, the antisymmetric combination of C_α···Br stretching modes constitutes the reaction-coordinate mode which, in the present examples, has a zero frequency and is omitted from considerations of the EXC term. The net effect of the bonding changes about C_α is that the frequency of the symmetric C_α···Br stretching mode is decreased from its reactant value and that two extra bending modes of low frequency are present in the transition state. Inspection of Table V reveals that EXC contributions from these modes ("extras + stretch") for ethyl, *tert*-butyl, and neopentyl are all relative rate accelerating

Table V. Analysis of Excitational Contributions to Relative Rate Constants for S_N2 Bromine-Exchange Reactions of Alkyl Bromides at 298 K

alkyl group R	category of vibratnal modes	$\pi_R{}^r$	$\pi_R{}^{\ddagger}$	EXC
methyl	extras + stretch	0.948 171	0.236 774	1.0000
	α bends	0.975 350	0.985 224	1.0000
	rest	0.999 998	0.999 998	1.0000
	total	0.924 797	0.233 275	1.0000
ethyl	extras + stretch	0.933 884	0.214 843	1.0855
	α bends	0.728 148	0.829 137	0.8871
	rest	0.679 607	0.667 959	1.0174
	total	0.462 137	0.095 856	0.9797
tert-butyl	extras + stretch	0.933 590	0.109 359	2.1318
	α bends	0.314 623	0.309 605	1.0265
	rest	0.365 096	0.375 060	0.9734
	total	0.107 239	0.012 699	2.1302
neopentyl	extras + stretch	0.961 982	0.156 198	1.5379
	α bends	0.500 067	0.919 525	0.5493
	rest	0.036 097	0.019 064	1.8935
	total	0.017 386	0.002 738	1.5997

Table VI. Analysis of Zero-Point Energy Contributions to Relative Rate Constants for S_N2 Bromine-Exchange Reactions of Alkyl Bromides at 298 K

alkyl group R	category of vibratnal modes	$\Sigma_R{}^r$, cm^{-1}	$\Sigma_R{}^{\ddagger}$, cm^{-1}	Δ_R, cm^{-1}	ZPE
methyl	extras + stretch	613.3033	611.2202	−2.0831	1.0000
	α bends	6057.4165	6156.8375	99.4210	1.0000
	rest	8941.0056	8936.1790	−4.8266	1.0000
	total	15611.7254	15704.2367	92.5113	1.0000
ethyl	extras + stretch	562.8583	570.2049	7.3466	0.9775
	α bends	4828.4890	5000.2521	171.7631	0.8398
	rest	22266.6074	22287.0851	20.4777	0.9408
	total	27657.9547	27857.5421	199.5874	0.7723
tert-butyl	extras + stretch	561.9367	414.9571	−146.9796	1.4185
	α bends	1680.3388	1793.7508	113.4120	0.9668
	rest	49392.1312	48884.2502	−507.8810	3.3665
	total	51634.4067	51092.9581	−541.4486	4.6168
neopentyl	extras + stretch	677.5171	497.8426	−179.6745	1.5350
	α bends	4490.3912	5237.6584	747.2672	0.2095
	rest	58488.8363	58656.3964	167.5331	0.6597
	total	63656.7446	64391.8704	735.1258	0.2121

with respect to methyl; in fact the overall values of the EXC terms for *tert*-butyl and neopentyl are very nearly given by these contributions. In the transition states for ethyl and neopentyl the sideways steric pressure of the alkyl groups on the bromine atoms leads to higher frequencies for the bending modes about C_α ("α bends") and therefore to relative rate-retarding contributions to EXC, the effect being most marked for neopentyl. The further weakening of the $C_\alpha\cdots Br$ partial bonds in the *tert*-butyl transition state, resulting from the outward steric pressure of the methyl groups on the bromine atoms, leads to a very slightly relative rate-accelerating contribution to EXC. The methyl groups substituting C_α in ethyl and *tert*-butyl have little associated vibrational structure, only some relatively high-frequency modes involving hydrogen atoms, and hence the contributions to EXC from these modes (the "rest"), are close to unity. However, the vibrational structure of the alkyl group substituting C_α in the case of neopentyl gives rise to a relative rate-accelerating contribution to EXC which counterbalances the relative rate-retarding contribution from the α bends. In particular, the frequencies of two low-frequency modes involving the substituting *tert*-butyl group, a torsional mode and a skeletal rocking mode, are further decreased in the neopentyl transition state and together account for this relative rate-accelerating contribution from the "rest" of the modes to the EXC term.

The zero-point energy term ZPE is given as in eq 2, the quantity

$$\mathrm{ZPE} = \exp[hc/2kT(\Delta_{\mathrm{Me}} - \Delta_{\mathrm{R}})] \qquad (2)$$

$$\Delta_R = \Sigma_R{}^{\ddagger} - \Sigma_R{}^{r} = \Big(\sum_j^{3N-7} \nu_j{}^{\ddagger} - \sum_i^{3N-6} \nu_i{}^{r}\Big)_R$$

Δ_R for each reaction being the difference between the sums of the frequencies of the reactant and the transition state. Table VI contains the contributions to ZPE from the three categories of vibrational modes for the four reactions presently under consideration. The principal zero-point energy effect on the rate constant for the standard methyl reaction is an intrinsically rate retarding one due to an increase in the frequencies of the α bends between reactant and transition state. Sideways steric pressure of the alkyl group on the bromine atoms in the ethyl and neopentyl transition states restricts bending motions about the α-carbon atom and leads to increased frequencies for these vibrational modes. Since these increases are greater than for the methyl reaction, they give rise to relative rate-retarding ZPE contributions; the more retarding contribution occurs in the neopentyl case, for which the steric pressure is larger. The reciprocal steric pressure of the bromine atoms on the γ-hydrogen atoms in the neopentyl transition state also leads to increased frequencies for bending modes involving these atoms and consequently to a relative rate-retarding ZPE contribution from the "rest" of the vibrational structure. By contrast, hyperconjugation involving the γ-hydrogen atoms in the *tert*-butyl transition state results in decreased frequencies and a relative rate-accelerating ZPE contribution from the methyl groups in this case. Just as the extra bending modes involving the additional bromine atom and the symmetric carbon–bromine stretching mode in the *tert*-butyl and neopentyl transition states have low frequencies and give rise to relative rate-accelerating contributions to EXC, so these modes also give rise to relative rate-accelerating contributions to ZPE, because the loss in the frequencies of the carbon–halogen stretching modes is greater than the gain in the frequencies for the extra two modes.

Effect of Vibrational Structure. The most serious shortcoming of the calculations of Ingold and co-workers[5] was probably the neglect of the vibrational structure of the alkyl groups; these workers treated the reactants and transition states for the bromine-exchange reactions as simple derivatives of methane, substituted by structureless masses, for the purpose of their vibrational calculations. The role of intraalkyl vibrations in determining kinetic structural effects may be assessed by removing some or all of the degrees of vibrational freedom from the alkyl groups of both reactants and transition states in our model calculations.

First, a set of calculations was performed in which all vibrational coordinates other than those about the α-carbon atoms were omitted; the coordinates remaining were the bond stretches involving C_α and the angle bends with C_α at the apex. The calculation of the MMI term for the reactions was unaltered, but the assumption of vibrationally structureless alkyl groups affected the EXC and ZPE terms, as may be seen from the results presented in Table VII compared to those in Table III. A marked difference in behavior between the α series and the β series of alkyl groups was found, which may be seen readily from the plot of logarithms of relative rate constants against alkyl homology given in Figure 4; the *presence* of the intraalkyl vibrational structure is relative rate accelerating along the α series, mainly via the ZPE term, whereas along the β series the counterbalancing of an accelerating tendency on EXC and a retarding tendency on ZPE

Table VII. Calculated NPE Contributions to Relative Rate Constants for S_N2 Reactions of the Bromide Ion with Alkyl Bromides Containing Vibrationally Structureless Alkyl Groups at 298 K

alkyl group R	k(R)/ k(Me)	MMI	EXC	ZPE
Me	1.000	1.000	1.000	1.000
Et	0.367	0.547	0.930	0.722
i-Pr	0.148	0.273	0.978	0.555
t-Bu	0.451	0.191	1.883	1.254
n-Pr (C_s)	0.270	0.375	0.956	0.753
n-Pr (C_1)	0.230	0.347	0.948	0.698
i-Bu (C_s)	0.175	0.225	1.010	0.771
i-Bu (C_1)	0.176	0.207	1.018	0.831
neo-Pe	0.058	0.181	0.749	0.429

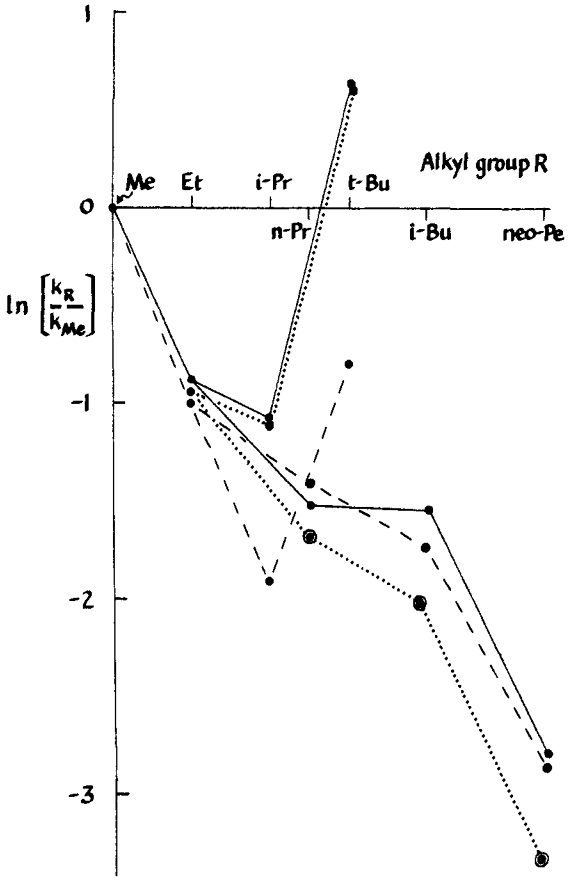

Figure 4. Effect of vibrational structure on logarithms of relative rate constants for S_N2 bromide-exchange reactions of alkyl bromides at 298 K: solid lines, all vibrational coordinates included; dotted lines, all torsional coordinates excluded; dashed lines, all intraalkyl vibrational coordinates excluded; concentric circles, skeletal torsions only excluded.

results in little overall contribution. These effects may be deduced also from the results in Tables V and VI: the category of vibrational modes labeled "the rest" in these tables is constituted almost entirely by the intraalkyl vibrations. The accelerating ZPE effect of the intraalkyl vibrations in the α series is shown by the large contribution to ZPE from the "rest" of the modes for *tert*-butyl in Table VI, while the counterbalancing effect in the β series is shown by the contributions to EXC and ZPE, of values greater than and less than unity, respectively, from the "rest" of the modes for neopentyl, in Tables V and VI, respectively.

A second set of calculations was performed in order to investigate which elements of the vibrational structure of the alkyl groups were important in determining the trends noted above. In these calculations *all* torsional coordinates *only* were omitted, and the results contained in Table VIII suggest that, while the presence of the torsional modes in the molecules of the α series has virtually no effect on their relative reactivity for S_N2 bromine exchange, the torsional modes have a relative rate-accelerating effect, manifested mostly by the EXC term, for the molecules of the β series in this reaction. This finding may be rationalized by inspection of the frequencies in Table IX for the reactants and transition states for *tert*-butyl and neopentyl, being representative of the α and β series, respectively. The frequencies of the methyl torsions in both the *tert*-butyl and neopentyl molecules are little changed as between reactant and transition state, but the frequency of the neopentyl skeletal torsional mode is markedly decreased in the transition state and gives rise to a relative rate-accelerating contribution to the EXC term. The fact that the methyl torsional modes have virtually no effect upon the relative reactivity of the molecules of the β series in S_N2 bromine exchange is supported by the results of a set of calculations in which only skeletal torsional modes were omitted from the full set of vibrational coordinates. The results in Table X show that overall values of relative rate constants are little changed from the values obtained from the calculations omitting *all* torsional coordinates.

Table VIII. Calculated NPE Contributions to Relative Rate Constants for S_N2 Reactions of the Bromide Ion with Alkyl Bromides Excluding All Torsional Coordinates at 298 K

alkyl group R	k(R)/ k(Me)	MMI	EXC	ZPE
Me	1.000	1.000	1.000	1.000
Et	0.389	0.547	0.960	0.741
i-Pr	0.329	0.273	1.048	1.150
t-Bu	1.842	0.191	2.109	4.574
n-Pr (C_s)	0.191	0.375	1.002	0.509
n-Pr (C_1)	0.185	0.347	1.069	0.497
i-Bu (C_s)	0.127	0.225	1.368	0.414
i-Bu (C_1)	0.134	0.207	1.438	0.448
neo-Pe	0.036	0.181	1.058	0.188

Table IX. Frequencies of Torsional Vibrations of Reactants and Transition States for *tert*-Butyl and Neopentyl Bromides in S_N2 Bromine Exchange

	torsional freq, cm^{-1}	
alkyl bromide	reactant	transition state
tert-butyl	278	277
	274 (deg)	284 (deg)
neopentyl	84	53
	230	230
	230	235
	233	237

Table X. Calculated NPE Contributions to Relative Rate Constants for S_N2 Reactions of Bromide Ion with the β Series of Alkyl Bromides from which Torsional Coordinates C_α-C_β Only Are Excluded

alkyl group R	k(R)/ k(Me)	MMI	EXC	ZPE
Me	1.000	1.000	1.000	1.000
n-Pr (C_s)	0.183	0.375	0.994	0.490
n-Pr (C_1)	0.188	0.347	1.084	0.500
i-Bu (C_s)	0.128	0.225	1.375	0.413
i-Bu (C_1)	0.135	0.207	1.454	0.449
neo-Pe	0.036	0.181	1.070	0.188

The results of these investigations do point to the important role of torsional vibrations, especially of modes involving C_α-C_β, in determining NPE effects in S_N2 reactivity. Unfortunately, it is just these coordinates for which there is the greatest uncertainty in regard to the appropriate values for transition-state force constants.[2] In this work the assumption has been made that torsional force constant values are unchanged between reactants and transition states, but a more sophisticated treatment would be desirable. However, for molecules exhibiting rotational isomerism transition-state torsional force constants were transferred from one rotamer only, such that inevitably these force constants were changed between reactant and transition state for another rotamer. This consideration explains the kink at *n*-propyl in the

Table XI. Calculated Entropies[a] of Activation for S_N2 Reactions of the Bromide Ion with Alkyl Bromides at 298 K

alkyl group R	$-\Delta S^{\ddagger}$, cal deg^{-1} mol^{-1}	$-\delta_R\Delta S^{\ddagger}$, cal deg^{-1} mol^{-1}
Me	25.8300	0.00
Et	27.2055	1.38
i-Pr	28.5135	2.68
t-Bu	27.0925	1.26
n-Pr (C_s)	28.1219	
n-Pr (C_1)	27.5059	
n-Pr[b]	27.7338	1.90
i-Bu (C_s)	27.4426	
i-Bu (C_1)	27.2182	
i-Bu[b]	27.3237	1.49
neo-Pe	28.4654	2.64

[a] Standard state at 1 atm. [b] Weighted average.

line joining results for the full vibrational calculations for the β series in Figure 4, because the values of the torsional force constants for the transition state are the same as those for the gauche conformer rather than the anti conformer reactant.

Entropies of Activation: Comparison of Theoretical and Experimental Values. Entropies of activation for S_N2 reactions of bromide ion with alkyl bromides have also been computed, and are given in Table XI together with relative values with the reaction of methyl bromide as standard. Just as the model transition states for these reactions were used to calculate kinetic isotope effects in agreement with observed values, so it would also be very satisfactory to achieve similar accord between calculated and observed activation entropies. However, these are intrinsically more likely than isotope effects to depend on phase and gas-phase activation entropies for these reactions are presently unavailable. The solvent dependence of activation entropies for S_N2 halide exchanges may be illustrated by the results of Cook and Parker:[14] for reaction of chloride ion with alkyl bromides in acetone the values of $\Delta S^{\ddagger}$ for the *tert*-butyl and neopentyl bromides were −2.5 and −8.5 cal deg^{-1} mol^{-1}, respectively, whereas in dimethylformamide the corresponding values were −10.1 and −2.7 cal deg^{-1} mol^{-1}.

Entropies of formation of gas-phase *adducts* between bromide ions and alkyl bromides have been measured,[15] but comparison with our calculated values[16] indicates that these adducts have asymmetric structures quite different from the symmetric structures of analogous S_N2 transition states.

Using a model neglecting all alkyl group vibrational structure, Ingold and co-workers[5] calculated relative entropies of activation in remarkable agreement with experimental values obtained for these reactions in acetone.[17] However, these and other experimental results obtained by this group have been criticized[18] for their failure to allow for incomplete dissociation of lithium halides (occurring as both reactant and product) in acetone and additionally because it has been shown that reactions of *tert*-butyl halides in acetone proceed not by S_N2 but rather by elimination–addition[19] or ion-pair[20] mechanisms. Cook and Parker[14] attempted to reevaluate relative entropies of activation for S_N2 reactions of chloride ion with the same alkyl bromides under conditions for which the above criticisms would be invalid, and Abraham[6] has done likewise for the symmetric bromide exchanges in acetone, but recently DeTar[7] has argued that Cook and Parker's data for the *tert*-butyl reaction in acetone still do not exclusively represent a substitution reaction. Hence there remains considerable doubt regarding the correct experimental values of activation entropies for some of the series of S_N2 reactions in solution.

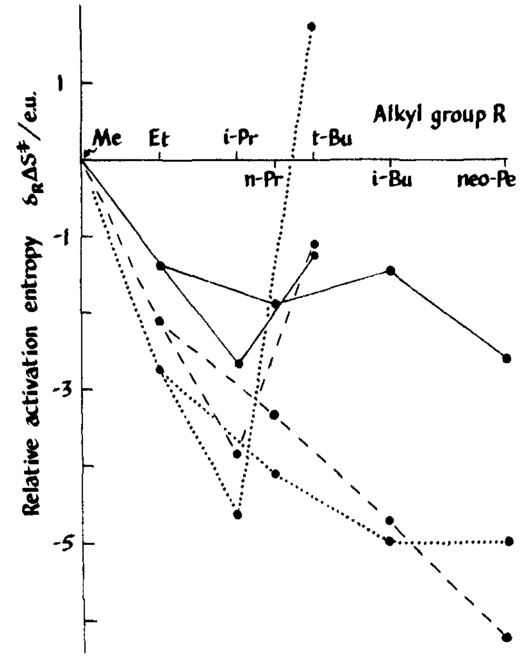

Figure 5. Comparison of calculated and experimental relative entropies of activation for S_N2 bromide-exchange reactions of alkyl bromides at 298 K: solid lines, calculated values, this work; dashed lines, calculated values, Ingold; dotted lines, experimental values, Abraham.

Despite the limited expectations from the foregoing considerations, we felt it nevertheless desirable to examine such comparisons as could be made between calculated and experimental values, and our calculated relative entropies of activation are plotted in Figure 5 together with Ingold's calculated results[5] and Abraham's suggested[6] experimental values. It may be seen that the calculated ideal gas values do at least show the same overall trends as the experimental solution values: along the α series the results become increasingly more negative to isopropyl but less negative for *tert*-butyl, and along the β series there is an overall trend to increasingly negative values. A correlation coefficient of only 0.71, however, was obtained for linear regression between our calculated values and the experimental values suggested by Abraham,[6] but this was raised to 0.88 if the values for *tert*-butyl (see comments above) were omitted.

Entropies of Activation: Comparison with Ingold's Theoretical Results. It is also of interest to compare our calculations of relative entropies of activation with those[5] of Ingold and co-workers, and the comparison is illustrated in Figure 5. The relative translational and rotational entropies of activation together determine the value of the MMI contribution, and our calculated values for this agree closely with the earlier values, allowing for the fact that slightly different C–C and C–H bond lengths were used. However, the earlier values of translational and rotational entropies for each molecular species are all in error because the given expressions for these quantities under the stated conditions have incorrect constant terms; further, the symmetry numbers used in the previous work do not correspond to the transition-state geometries specified.[21] It is a fortuitous cancellation of these errors which results in the previously calculated[5] relative translational and rotational entropies of activation agreeing with our values. The differences between our total relative entropies of activation and those of the earlier workers therefore arise from the vibrational term.

---

(14) D. Cook and A. J. Parker, *J. Chem. Soc. B*, 142 (1968).

(15) R. C. Dougherty, *Org. Mass. Spectrosc.*, **8**, 85 (1974).

(16) J. McKenna and I. H. Williams, unpublished results.

(17) P. B. D. de la Mare, *J. Chem. Soc.*, 3180 (1955).

(18) (a) S. Winstein, L. G. Savedoff, S. G. Smith, I. D. R. Stevens, and J. S. Gall, *Tetrahedron Lett.*, **9**, 24 (1960); (b) L. G. Savedoff, *J. Am. Chem. Soc.*, **88**, 664 (1966).

(19) S. Winstein, S. G. Smith, and D. Darwin, *Tetrahedron Lett.*, **16**, 24 (1959).

(20) F. G. Bordwell and T. G. Mecca, *J. Am. Chem. Soc.*, **94**, 2119 (1972).

(21) For the stated conditions[5] of temperature 298.1 K and standard concentration 0.0446 mol L^{-1} ≡ 1 atm, the constant term in the expression for translational entropy in entropy units should be not 0.515 but 25.973 and similarly in the expression for rotational entropy not −3.686 but +11.589. Aside from any consideations of the propriety of including symmetry numbers for transition states of symmetric reactions, the transition states for ethyl, *n*-propyl, isobutyl, and neopentyl all have C_s symmetry but were all given symmetry numbers of 2 by Ingold and co-workers.

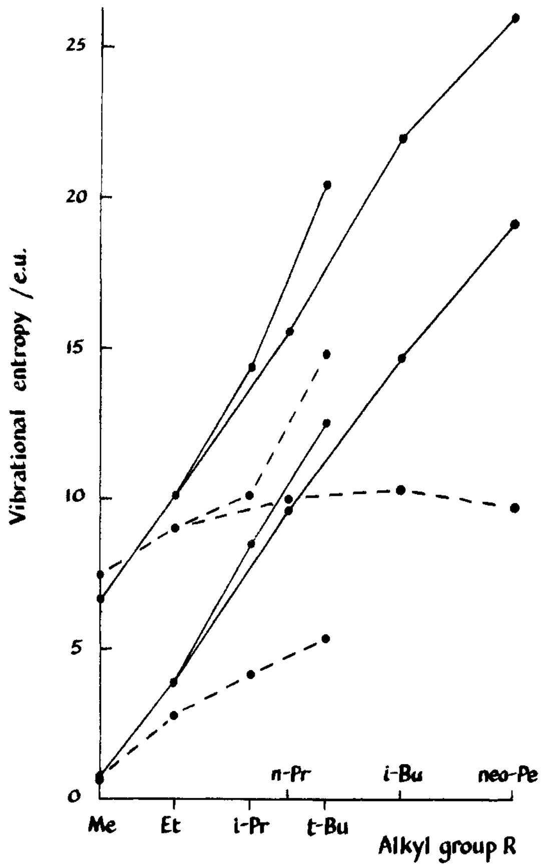

Figure 6. Vibrational entropies calculated for reactants and transition states for S_N2 reactions of bromide ions with alkyl bromides at 298 K: lower dashed lines, reactants, Ingold; upper dashed lines, transition states, Ingold; lower solid lines, reactants, this work; upper solid lines, transition states, this work.

Vibrational entropies for reactants and transition states for these reactions, as calculated by ourselves and by Ingold and co-workers,[5] are plotted in Figure 6. The neglect of intraalkyl vibrations explains why the vibrational entropy as previously evaluated for each alkyl bromide is less than our value, calculated as it is on the basis of a model force field designed specifically for satisfactory reproduction of entropy-rich low-frequency vibrational modes.[1] Remarkably, in view of this consideration, the previous method[5] of calculating the vibrational frequencies of the transition states tends to *overestimate* the entropy, since the value given for the vibrational entropy of the methyl transition state is greater than ours. Inspection of the published potential energy contour diagram for the methyl transition state suggests that the stretching force constant for the $C_\alpha\cdots Br$ partial bond has a value of about only 0.94 mdyn Å^{-1}. Using a force constant even larger than this at about 1.03 mdyn Å^{-1}, we calculated[2] a secondary deuterium kinetic isotope effect $k(H)/k(\alpha\text{-}d_3)$ of 1.300 as compared to observed inverse or much smaller normal isotope effects for analogous substitutions of methyl halides, and we concluded that such a "loose" transition state was inappropriate. Thus it would seem that the methyl transition state as used by the earlier workers is also too loose and has associated with it too much vibrational entropy.

The effect of the vibrational structure of the alkyl groups on the relative entropies of activation is demonstrated by the results, presented in Table XII, of a set of calculations from which all intraalkyl vibrational coordinates were omitted. These calculations therefore resemble those of Ingold and his co-workers[5] in that the only vibrational modes considered are those directly involving the α-carbon atom; each reaction may be regarded as being the S_N2 bromine exchange of a "pseudomethyl" bromide in which the alkyl groups substituting C_α are structureless masses. Table XII also lists the previously calculated activation entropies. The correlation coefficient for linear regression between the two sets of results is 0.98, suggesting that the pattern of the earlier results was substantially determined by neglect of intraalkyl vibrations.

Table XII. Calculated Relative Entropies of Activation for S_N2 Reactions of the Bromide Ion with Alkyl Bromides Containing Vibrationally Structureless Alkyl Groups at 298 K

	$-\delta_R\Delta S^{\ddagger}$, cal deg^{-1} mol^{-1}	
alkyl group R	this work	Ingold
Me	0.00	0.00
Et	1.56	2.11
i-Pr	2.92	3.82
t-Bu	1.55	1.12
n-Pr	2.34	3.31
i-Bu	3.11	4.72
neo-Pe	4.55	6.25

Solvation Effects on Activation Entropies. As a development of the considerations discussed in the previous section, we have made further comparisons between our calculated gas-phase activation entropies and published experimental values for Arrhenius *A* factors for the same reactions in solution. The equation for interconversion of the Eyring and Arrhenius parameters can be shown to be

$$\Delta S^{\ddagger}/R = \ln A - \ln (kT/h) - \tfrac{1}{2}$$

where $\Delta S^{\ddagger}$ is expressed in relation to a standard state of 1 mol L^{-1} if the rate constant (for the bimolecular reaction) and hence the parameter *A* is, as normal, in units L mol^{-1} s^{-1}. The conversion to a standard state of 1 atm (corresponding to our calculated values of $\Delta S^{\ddagger}$) is given by

$$(\Delta S^{\ddagger})_{1\,\mathrm{atm}} = (\Delta S^{\ddagger})_{1\,\mathrm{mol\,L^{-1}}} - R(\ln RT + 1)$$

where *R* in the term ln *RT* has a value of 0.082054 L atm deg^{-1} mol^{-1} and *R* outside the bracket has whatever units are desired for $\Delta S^{\ddagger}$. The difference between the value thus derived for experimental $\Delta S^{\ddagger}$ and our calculated gas-phase value gives the contribution $\Delta S_{\mathrm{solv}}{}^{\ddagger}$.

For the S_N2 reaction of bromide ion with methyl bromide in acetone at 298 K the value[17] of log *A* is 10.7; hence $\Delta S^{\ddagger} = -23.47$ cal deg^{-1} mol^{-1} and $\Delta S_{\mathrm{solv}}{}^{\ddagger} = -23.47 - (-25.83) = 2.36$ cal deg^{-1} mol^{-1}. This positive contribution could be interpreted in terms of reduced strength of solvation associated with charge distribution in the transition states. Ingold and his co-workers calculated[5] $\Delta S_{\mathrm{solv}}{}^{\ddagger} = -11.15$ cal deg mol^{-1} for this reaction in acetone but the negative value, which it is difficult to rationalize physically, is in error since an incorrect value for the translational entropy of the bromide ion was employed in the calculation, and the fact was overlooked that the experimentally derived and theoretical activation entropies referred to different standard states.

For reaction of chloride ion with methyl bromide in acetone[14,22] (log $A = 12.0$) and in dimethylformamide[14] (log $A = 12.8$) one derives the quantities $\Delta S_{1\,\mathrm{atm}}{}^{\ddagger} = -17.53$ and -13.87 cal deg^{-1} mol^{-1}, respectively (at 298 K). We have not got a theoretical gas-phase value, but it is unlikely to differ much from that for the bromide-exchange reaction. Certainly, $\Delta S_{\mathrm{solv}}{}^{\ddagger}$ is 3.66 cal deg^{-1} mol^{-1} more positive for the reaction in dimethylformamide than in acetone, a result which accords with extrapolation of the charge-distribution argument given above to take note of the greater polarity of dimethylformamide[23] ($D = 3.82$) than of acetone[23] ($D = 2.88$).

Results. Relative NPE Effects Associated with Base Homology

The results for these calculations are shown in Table XIII, and two features are immediately striking. One is the similarity of overall effects for different alkoxides, but the marked increase for hydroxide. The other is the degree of opposition, particularly for hydroxide, between the MMI contributions on the one hand

---

(22) E. D. Hughes, C. K. Ingold, and J. D. H. Mackie, *J. Chem. Soc.*, 3173 (1955).

(23) "CRC Handbook of Chemistry and Physics", 50th ed., CRC Press, Cleveland, Ohio, 1969, p E 70.

Table XIII. Calculated NPE Contributions to Relative Rate Constants for S_N2 Reactions of Methyl Bromide with Hydroxide or Alkoxide Ions at 298 K

alkyl group R in the alkoxide ion	k(R)/k(Me)	MMI	EXC	ZPE
H	1.856	189.9	0.054	0.180
Me	1.000	1.000	1.000	1.000
Et	0.996	0.362	2.269	1.213
i-Pr	0.992	0.196	3.672	1.380
t-Bu	0.989	0.135	4.872	1.499

and those from ZPE and EXC on the other. We encountered a similar pattern of results in calculations for E2 reactions with ethyl chloride and a range of homologous bases, and we give a detailed analysis of these results in the following paper:[24] the calculations on substitutions were in fact prompted by the results on eliminations. Much of our analysis of the elimination results is transferable to those for substitutions, so only brief interpretative comments are here in order.

Loss of translational and rotational entropy in association is less for the lighter nucleophiles, and this is particularly true for loss of rotational entropy in the reaction with hydroxide, which not only is a relatively very light rotor but also has only two moments of inertia. These considerations in essence underly the variation of the MMI term. The opposition for EXC and ZPE is related to the relatively higher frequencies in the new vibrational modes of the transition states the lighter the mass of the associting base, and again the hydroxide–methoxide transition is the most marked.

If we leave the hydroxide result aside, because of the relatively very large change in mass distribution and structure between hydroxide and methoxide, and concentrate attention on the results for the series of alkoxides, it is evident that base homology is very much less effective in inducing overall relative NPE effects than in substrate homology as studied in the Finkelstein calculations. The difference seems to be due to the fact that substrate alkylation is associated with changes in geometry and force constants around the reaction site, whereas base homology is not in our calculations.

Acknowledgment. We thank the S.R.C. for support.

---

[24] C. D. Chalk, J. McKenna, L. B. Sims, and I. H. Williams, following paper in this issue.

NPE Effects in Bimolecular Elimination

Christine D. Chalk, James McKenna,* Leslie B. Sims, and Ian H. Williams

Contribution from the Department of Chemistry, The University, Sheffield S3 7HF, England.

Received December 6, 1979

Abstract: A force field for the transition states of E2 reactions between hydroxide and alkoxide bases and simple chloroalkanes has been developed by calibration against typical experimental kinetic isotope effects observed in such reactions and forms the basis of calculations of NPE effects. No allowances are made for steric effects associated with alkylation in the substrate or base. With this model force field only slight NPE contributions to relative reactivity are observed from homology among substrates (ethyl vs. isomeric propyl chlorides) or among alkoxide bases. A more substantial difference is observed in a comparison of hydroxide and methoxide ion promoted eliminations from ethyl chloride.

Introduction

As part of a survey of the role of nonpotential energy (NPE) effects in reactivity, we have previously discussed some bimolecular nucleophilic substitutions[1] and we now report the results of calculations for some simple examples from another very important class of organic reactions, namely, bimolecular elimination.[2]

NPE effects, like kinetic isotope effects, may be analyzed[1] in terms of three multiplicative factors, MMI, EXC, and ZPE, describing contributions (relative to a standard reaction) from masses and moments of inertia, population of excited vibrational energy levels, and vibrational zero-point energies, respectively. If a reaction involves changes in vibrational modes having average to high frequencies, then the ZPE term would be expected to dominate the vibrational contributions to NPE effects. However, as the frequencies involved in any changes become lower, so the importance of EXC will increase, until for very low frequencies it will become the dominant term. This behavior arises because of the inverse exponential dependence on frequency of the vibrational partition function. The exponential character of EXC may be contrasted with the linear relationship between ZPE and frequency changes and underlies a hypothesis that for suitable systems EXC could take extremely large values which could have substantial accelerating or retarding effects on reactivity. Some possible implications of this hypothesis have already been suggested for enzymic catalysis,[3a] and our calculations[3b] on simple enzyme models and on reactions within solvent cages do indeed show large and dominant EXC contributions. For gas-phase type calculations of the usual reactions of normal small molecules, however, a more even balance between the three factors may be expected. This was found to be the case for calculations on some S_N2 substitutions,[1] and another such pattern is now described for E2 eliminations.

Calculations

All calculations were performed by using program QREL and previously described methods.[1,4,5] The simplest reaction studied was the hydroxide ion promoted elimination from chloroethane to yield ethylene, and a suitable transition-state model for this parent system was found which enabled kinetic isotope effects to be calculated within the ranges of observed values. More complex

---

[1] C. D. Chalk, J. McKenna, and I. H. Williams, preceding paper in this issue.

[2] W. H. Saunders, Jr., and A. F. Cockerill, "Mechanisms of Elimination Reactions", Wiley, New York, 1973.

[3] (a) D. B. Cook and J. McKenna, *J. Chem. Soc., Perkin Trans. 2*, 1223 (1974). (b) C. D. Chalk and J. McKenna, unpublished results.

[4] C. D. Chalk, B. G. Hutley, J. McKenna, L. B. Sims, and I. H. Williams, preceding paper in this issue.

[5] J. McKenna, L. B. Sims, and I. H. Williams, preceding paper in this issue.

0002-7863/81/1503-281$01.00/0