The E2C Mechanism in Elimination Reactions. VI.[1] Primary Hydrogen Isotope Effects on Rates of E2 Reactions of Alicyclics

David Cook, R. E. J. Hutchinson, J. K. MacLeod, and A. J. Parker*

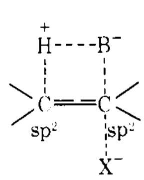
Research School of Chemistry, Australian National University, Canberra, A. C. T., Australia

Received October 2, 1973

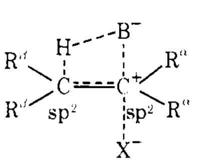
Primary hydrogen isotope effects on the rates of bimolecular elimination reactions of some cyclohexyl tosylates and bromides are small ($k^H/k^D \approx$ 2-3) for very E2C-like reactions, pass through a maximum of 6 for more E2H-like reactions, and are small again (2-3) for very E2H-like reactions. Movement from the E2C to the E2H side of the spectrum has been achieved by increasing the acidity of the substrate, by increasing the hydrogen basicity of the base, and by changing the leaving group from tosylate to bromide. Differences between k^H/k^D values, as measured by intramolecular competition *vs.* intermolecular rate comparisons, may be due to a secondary hyperconjugative isotope effect.

The primary hydrogen isotope effects, k^H/k^D, on the rates of β-eliminations promoted by weak hydrogen bases, B, but strong carbon nucleophiles, such as chloride ion (E2C-like reactions), are low at 25-75°, *i.e.*, 2.3-3.2.[2-4] They are considerably less than k^H/k^D of 5-7, commonly observed for β-elimination induced by strong hydrogen bases, such as alkoxides (E2H-like reactions).[5] This observation is true for the limited number of eliminations studied, and, although the topic has been reviewed,[6,7] a representative study of k^H/k^D through the E2C-E2H spectrum has not been made.

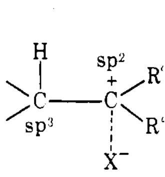
The changes in k^H/k^D can in themselves be explained by any one of several sets of variable transition states, but opinions differ as to which set to use. Certainly there must be variable transition states for E2 reactions,[8] because only in this way can we explain the large changes in k^H/k^D which are observed under different conditions. In this paper we have chosen to discuss the isotope effects in terms of the E2C-E2H spectrum of transition states. However, recent work in our laboratories on the effect of conjugative substituents[9] has caused us to reexamine our ideas[10] about the structure of the E2C extreme transition state. Although we still favor the "loose" structure I, with a well-developed double bond, and very loose C_β-H, C_α-X, C_α-B, and B-H bonds, we cannot reject structure II, which also has C_α and C_β sp^2 hybridized and also has very loose C_α-X and C_α-B bonds. The differences between II and I are that II has a poorly developed double bond, and, although the C_β-H bond in both I and II has changed from sp^3-s overlap in the reactant to p-s overlap in the transition states, it is very loose in I, but tight in II. Structure II requires some positive charge at C_α, whereas I has positive charge on hydrogen. We had previously rejected II, because we could find no evidence for positive charge at C_α.[11] Thus there are very small substituent effects at C_α in E2C-like reactions, and this contrasts markedly with the very large substituent effects at C_α in solvolysis (SN1) reactions of the same substrates, where there is positive charge at C_α.[11] However, it may be that because there are *two* anions, loosely bound to C_α in II, in what is effectively an ion triplet, $B^-C^+X^-$, the requirements from an electron-donating or -withdrawing substituent R^α in II may be much less than the requirements in the SN1 transition state III, which resembles an ion pair, C^+X^-. We will be examining the arguments for I *vs.* II in E2C-like reactions when the appropriate experiments are completed, but for the consideration of k^H/k^D values both I and II lead to the same expectation, that k^H/k^D will be small for E2C-like reactions. This is because C-H-B is bent in both transition states and C_β-H is either extensively or slightly broken in I and II, respectively.



I, E2C



II, E2C



III

The extreme E2H structure is thought to be "Elcb-like," with a poorly developed double bond, negative charge at C_β, extensive transfer of hydrogen to the base in a linear arrangement of C_β-H-B, little breaking of the C_α-X bond, and little rehybridization at C_α.[10] As eliminations become more E2H-like, the C-H-B bonds become less bent and the extent of bonding of base to hydrogen increases, so that k^H/k^D is expected to increase.[12] The k^H/k^D value may even pass through a maximum,[13,14] as the eliminations become very E2H-like; *i.e.*, the C_β-H bond is well broken and transfer of proton to base is very well advanced. Low k^H/k^D values are observed for Elcb reactions.[6]

These expectations are examined in this paper, where, either by increasing the acidity of the substrate or increasing the H basicity of the base, we have moved the transition state to a more E2H-like character.

Results

Approximate primary kinetic hydrogen isotope effects ($k_D{}^H/k_D{}^D$) were obtained by intramolecular competition in the reactions of cyclohexyl-*trans-2-d* tosylate (IV), cyclohexyl-*trans*-2-*d* bromide (V), and *cis*-1,2-dibromocyclohexane-*1-d* (VI) with a variety of bases. The reactions and symbolism are shown in Figure 1. The product olefins were isolated by preparative vpc, and analyzed for H and D content by mass spectrometry in the vicinity of the molecular ion. Results are presented as k^H/k^D in Table I. We note that the k^H/k^D values in Table I may only approximate the true primary kinetic isotope effects ($k_H{}^H/k_D{}^D$ of Figure 1) for elimination from substrates IV, V, and VI. All results are probably a little lower than the true primary values. This is because, like most workers in this area,[15] we have assumed that two sources of secondary isotope effect are negligible, *i.e.*, that $k_D{}^H = k_H{}^H$. In VI, there may be a secondary isotope effect of α deuterium *vs.* α hydrogen on the leaving tendency of bromide ion, as the hybridization at C_α changes.[6] In IV and V there may be a secondary isotope effect due to hyperconjugative interactions of C-H *vs.* C-D with either a positive charge at C_α (*cf.* transition state II) or with the well-developed double bond between C_α and C_β[6] in transition states like I. Even if allowance had been made for these secondary isotope effects, it would not change the conclusions about primary isotope effects which can be drawn from Table I or Figure

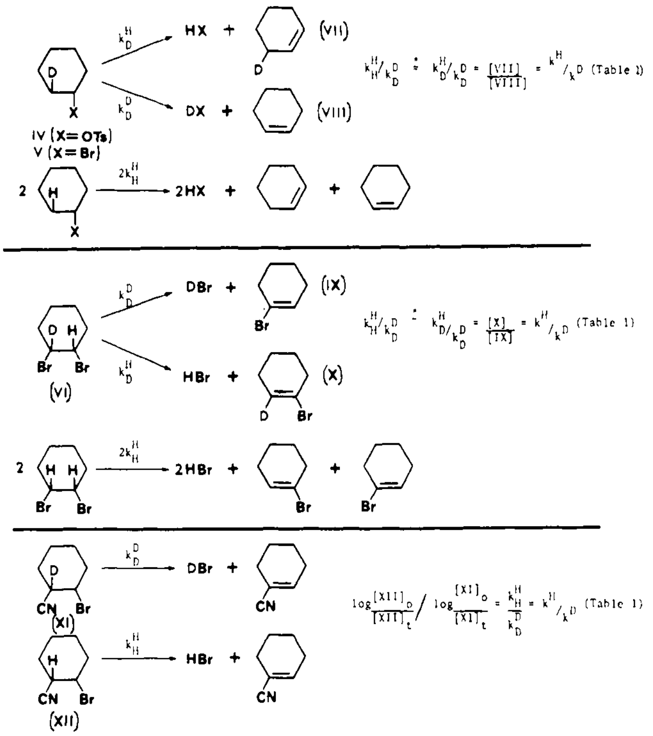


Figure 1. Kinetic isotope effects in E2C reactions. The approximate equalities marked with an asterisk are assumed equal for the purposes of this paper.

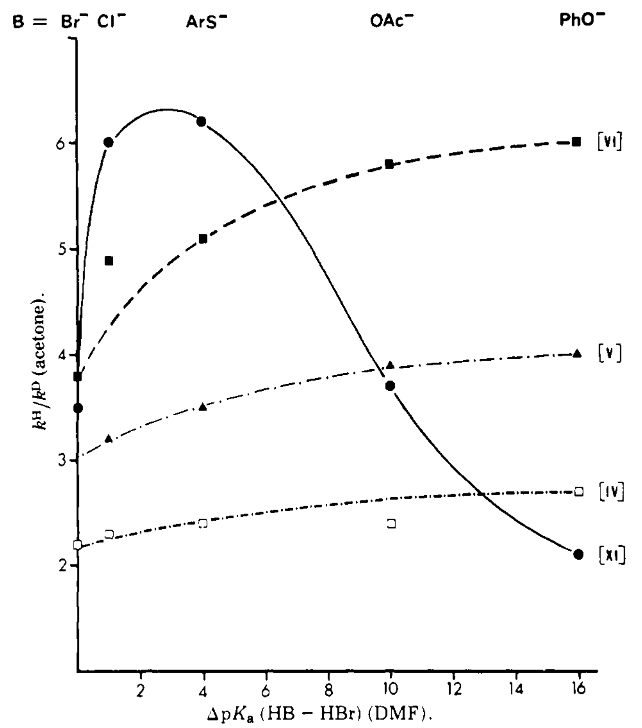


Figure 2. Variation of primary isotope effects with change of base strength for reactions of bases shown with substrates IV, V, VI, and XI in acetone. Data from Table I.

2, because the secondary effects are small ($k_H^H/k_D^H \cong$ 1.0–1.2). The k^H/k^D values for reaction of *cis*-2-bromocyclohexyl cyanide-*1-d* in Table I are believed to be "true" primary isotope effects (*i.e.*, k_H^H/k_D^D of Figure 1).

We are currently investigating the secondary isotope effects shown in Figure 1[16] and note that the hyperconjugative effect in reactions of IV and V is measurable and of mechanistic significance. Whether this hyperconjugative effect is due to interaction with positive charge at C_α or interaction with a developing allylic double bond is yet to be decided.

Table I
Primary Kinetic Hydrogen Isotope Effects k^H/k^D on Rates of Elimination at 75°

X in NBu_4X	E2H[d] → E2C	k^H/k^D: $C_6H_9D(H)$-CNBr XI and XII[a,d]	$C_6H_9DBr_2$ VI[a]	C_6H_{10}-DBr V[a]	C_6H_{10}-DOTs IV[a]
		A. NBu_4X in Acetone			
PhO^-	↓	2.1	6.0[b]	4.0	2.7
OAc^-		3.7	5.8[b]	3.9	2.4
$4\text{-}NO_2C_6H_4S^-$		6.2	5.1	3.5	2.4
Cl^-	↓	6.0	4.9	3.2	2.3
Br^-	E2C	3.5	3.8		2.2
	B. Alkoxide in Conjugate Alcohol				
	E2H				
KOBu-*t*	↓	1.7	6.0[b]	3.8	2.8
NaOEt	E2C	4.4[c]	5.9[b]	3.2	2.3

[a] Numbers refer to structures in Figure 1. [b] Extrapolated from measurements at 50°, where k^H/k^D was 0.8 greater. [c] Extrapolated from 4.9 at 24° obtained by measuring relative rates of reaction of XI and XII. [d] Arrows show movement from E2H to E2C with change of substrate or base. [d] At 50°.

Reaction mixtures were sampled at appropriate stages of reaction, to minimize the effect of substitution and subsequent elimination from the inverted product. Thus for reaction of bromide and chloride ion with IV, the olefins were analyzed over the first 10 and 30% of reaction, respectively, where k^H/k^D was constant, but, for other bases, analysis was over a greater portion of reaction.

Approximate k^H/k^D values for reactions of XI and XII were obtained by comparing the rates of dehydrobromination of *cis*-2-bromocyclohexyl cyanide-*1-d* to 1-cyanocyclohexene with those for *cis*-2-bromocyclohexyl cyanide (XII). Stopped-flow methods, with *p*-nitrophenol as indicator of base consumed, were used for reactions with NBu_4OAc in acetone and NaOEt in ethanol. For the reaction of XI and XII with bromide ion, total bromide, by titration, and loss of XI or XII by vpc analysis were used to follow the elimination and elimination plus substitution reactions respectively. Rate constants are in Table II. The values of k^H/k^D which are in Table I were obtained by competitive experiments, at 50°, using an excess of mixed XI and XII over base and analyzing the unreacted XI and XII by mass spectrometry at suitable stages of reaction. For reactions of Cl^-, $4\text{-}NO_2C_6H_4S^-$, and Br^- with XI and XII it was important to analyze before one half-life, because bromide ion induced dehydrobromination was a competing reaction. For reaction of XI and XII with bromide ion, vpc analysis of the dehydrobromination product showed only 1-cyanocyclohexene, with no 3-cyanocyclohexene during the first 10% reaction. This confirmed that neither elimination into the branch away from the cyano group nor substitution followed by elimination from the inverted bromide was a competing reaction.

Allowance was made for imperfect deuteration of our substrates, *e.g.*, cyclohexanol-*trans-2-d* (1.2% d_2, 94.2% d_1, 4.6% d_0); cyclohexyl bromide *trans-2-d* (0.8% d_2, 87.3% d_1, 11.9% d_0); *cis*-1,2-dibromocyclohexane-*1-d* (2.3% d_2, 84.0% d_1, 13.7% d_0); and *cis*-2-bromocyclohexyl cyanide-*1-d* (0.5% d_2, 93.0% d_1, 6.5% d_0) in the calculation of k^H/k^D values.

Solvolysis was always <5% of all bimolecular reactions with bromide ion, including solvolysis of XI or XII in the presence of the base 2,6-lutidine in acetone at 94°. Reac-

Table II
Rate Constants (M^{-1} sec^{-1}) for Dehydrobromination of Labeled and Unlabeled *cis*-2-Bromocyclohexylcyanides (RBr) with Bases in Acetone

[RBr], 10^2 *M*	Base	[Base], 10^2 *M*	[Lut],[e] 10^2 *M*	Temp, °C	Log *k*, 1-D	Log *k*, 1-H	k^H/k^D [c]
3.75	NBu_4Br	5.00	4.3	94.0	−2.545[a]	−2.101[b]	3.61
2.50	NBu_4Cl	2.51	3.54	39.8	−2.764	−1.939	6.71
0.50	NBu_4OAc	5.15		22.2	+1.534[d]	+1.935[d]	2.52
0.020	NaOEt[f]	5.08		24.2	+1.172[d]	+1.859[d]	4.87

[a] Reaction is 67% dehydrobromination, 33% substitution. The rate constant is for loss of RBr, *i.e.*, for the combined reactions. [b] Reaction is 87% dehydrobromination, 13% substitution; *cf.* footnote *a*. [c] The ratio of the rate constants for dehydrobromination at the temperature shown. [d] In the presence of 10^{-4} *M* *p*-nitrophenol as indicator. [e] Lut is 2,6-lutidine. [f] Solvent is ethanol.

tions with bases other than bromide ion were less than 1% influenced by solvolyses.

A serious discrepancy exists between our k^H/k^D values for reactions of *trans*-2-*d*-cyclohexyl tosylate with both NaOEt in ethanol and with KOBu-*t* in *tert*-butyl alcohol, *vs.* those reported by Finley and Saunders.[15] Finley and Saunders reported k^H/k^D of 4.47 and 7.53 for NaOEt and KOBu-*t*, respectively, at 50°, whereas we find 2.6 and 3.1 at 50°. Professor Saunders has pointed out to us that the results can be reconciled if it is realized that the Finley and Saunders'[15] values of k^H/k^D are really an intermolecular rate comparison $k_H{}^H/(k_D{}^H + k_D{}^D - k_H{}^H)$ in Figure 1, whereas our values of k^H/k^D in Table 1 are an intramolecular product comparison $k_D{}^H/k_D{}^D$. We both assume that $k_H{}^H = k_D{}^H$, but any error in this assumption is much more serious for Finley and Saunders than for us. "True" values for k^H/k^D (*i.e.*, $k_H{}^H/k_D{}^D$) for the reaction of IV with NaOEt and KOBu-*t* at 50°, respectively, can be determined by applying our intramolecular values (*i.e.*, $k_D{}^H/k_D{}^D$) to the data reported by Finley and Saunders ($k_H{}^H$ and $k_D{}^H + k_D{}^D$) to give values of 2.9 and 3.5, respectively. The comparison of intermolecular and intramolecular data also enables the secondary hyperconjugative isotope effects ($k_H{}^H/k_D{}^H$) to be calculated as 1.11 and 1.18. Thus these secondary isotope effects are by no means negligible in a mechanistic sense. As noted above, our approximate primary isotope effects of 2.6 and 3.1 respectively, are not far from the "true" values, and trends are unchanged, but the Finley and Saunders values[15] of 4.47 and 7.53 are very misleading as indicators of $k_H{}^H/k_D{}^D$.

Discussion

We have used successful Swain-Scott plots[17] of log k^E *vs.* log k^S, where k^E is the rate constant for elimination and k^S is the rate constant for substitution, with a variety of bases reacting with the same substrate to identify very E2C-like reactions.[1,10] Successful Brønsted plots of log k^E *vs.* pK_a identify very E2H-like reactions. Movement from E2C to E2H through the E2C-E2H spectrum of transition states is shown by increasing deviation from the Swain-Scott plot and increasing adherence to the Brønsted plot.[1]

Thus for reaction of cyclohexyl tosylate with a large number of bases, log k^E *vs.* log k^S is linear and of unit slope.[1] The plot is less satisfactory for reactions of cyclohexyl bromide and is a scatter diagram for reaction of *cis*-1,2-dibromocyclohexane with the same bases. The Brønsted plot is reasonable for the latter reactions but very poor for reactions of cyclohexyl tosylates.[1] The greatest deviations from a Swain-Scott plot of unit slope are shown for reaction of these three substrates with strong hydrogen bases, such as *tert*-butoxide, ethoxide, phenoxide, and acetate ion, which have log k^E greater than predicted by the substitution rate, whereas reactions of chloride or mercaptides continue to give reasonable Swain-Scott plots of near unit slope, even for reactions with *cis*-1,2-dibromocyclohexane. The conclusion was that cyclohexyl tosylate, a very weakly acidic compound, with a "loose" leaving group was a very E2C-like substrate, that cyclohexyl bromide with a "tighter" leaving group was a slightly more E2H-like substrate, and that the more acidic *cis*-1,2-dibromocyclohexane was an even more E2H-like substrate.[1] Following this reasoning, *cis*-2-bromocyclohexyl cyanide would be the most E2H-like substrate of the four, because it has the most acidic β hydrogen.

In summary, dehydrotosylations of cyclohexyl tosylate with most bases are thought to be very E2C-like, and dehydrobrominations of cyclohexyl bromide and of *cis*-1,2-dibromocyclohexane are increasingly E2H-like. The E2H-like character for any one of these substrates is greatest in the order of base strength $OPh^- > OEt^-$, $OAc^- > SPh^- > Cl^- > Br^-$. Dehydrobrominations of the acidic *cis*-2-bromocyclohexyl cyanide are quite E2H-like with most bases, except perhaps chloride and bromide ion.

This picture of movement toward E2H through the E2C-E2H spectrum with increasing acidity and "tightness" of the substrate and increasing hydrogen basicity, but decreasing carbon nucleophilicity, of the base, is strongly supported by the primary kinetic hydrogen isotope effects recorded in Table I. Table I is arranged so that for reactions in acetone the degree of E2H character required by the eliminations decreases both down the series of bases and across the series of substrates. The same arrangement is used for the reactions of the alkoxides in alcohols. Thus the dehydrobromination with phenoxide ion in acetone of *cis*-2-bromocyclohexyl cyanide is the most E2H-like reaction (k^H/k^D = 2.1 at 50°) and the dehydrotosylation of cyclohexyl tosylate with bromide ion in acetone is the most E2C-like reaction (k^H/k^D = 2.2 at 75°) of those studied. Values of k^H/k^D of about 6 at 75° have been obtained for dehydrobromination of *cis*-1,2-dibromocyclohexane with phenoxide ion in acetone and of *cis*-2-bromocyclohexyl cyanide with chloride ion. These are eliminations which are intermediate between the extremes of E2H and E2C in Table I.

The observation in Table I that k^H/k^D values pass through a maximum both for reactions of PhO^-, OAc^-, OEt^-, and *t*-BuO^-, with movement across the E2C-E2H spectrum, as the acidity of the substrate increases and also for reaction of *cis*-2-bromocyclohexyl cyanide as the basicity of the base increases, is in accord with conventional ideas[18] about proton transfer between acids and bases of different strengths. If there were at one extreme an E2C transition state like II, with little transfer of the proton to a very weak base, this would have a low isotope effect. There would be increased transfer to a stronger base and thus the isotope effect would increase as the reaction becomes more E2H-like. With extremely strong bases and acidic substrates, proton transfer to the base is almost completed and again a low isotope effect is observed.[13] The very low sensitivity of k^H/k^D to change of base on the E2C side of the spectrum, *i.e.*, reactions of cy-

Table III
Comparison of Kinetic Probes into Positions in the E2C–E2H Spectrum. Reactions at 75° in Acetone[b]

A. Response of Probe to Change of Base

Base		Substituent effects in *cis*-2-$RC_6H_{10}Br$[c] $\Delta_R \log k_B$[d] (CN – H)	Substituent effects in *cis*-2-$RC_6H_{10}Br$[c] $\Delta_R \log k_B$[d] (Br – H)	Leaving group effects in $C_6H_{11}X$, $\Delta_X \log k_B$[e] (OTs – Br)	Isotope effects in *cis*-2-$RC_6H_{10}Br$ k^H/k^D R = Br[f]	Isotope effects in *cis*-2-$RC_6H_{10}Br$ k^H/k^D R = CN[f,j]
NBu_4Br	E2C	1.3[a]		1.4	3.8	3.5
NBu_4Cl	↓	2.2[a]	0.43	1.0	4.9	6.0
NBu_4SAr	↓		1.1	0.4	5.1	6.2
NBu_4OAc	↓	5.4[a]	2.0	0.1	5.8	3.7
NaOEt[g]	E2H	6.3[a]	2.0[a]	0.0	5.9	4.4

B. Response of Probe to Change of Substituent or Leaving Group

RX	Change of base, $\Delta_B \log k_{RX}$ (OAc – Cl)[h]	Isotope effects, k^H/k^D B = Cl^-[i]	Isotope effects, k^H/k^D B = OAc^-[i]
$C_6H_{11}OTs$	0.41	2.3	2.4
$C_6H_{11}Br$	1.26	3.2	3.9
cis-1,2-$C_6H_{10}Br_2$	3.0	4.9	5.8
cis-2-$BrC_6H_{10}CN$	4.5[a]	6.0	3.7

[a] Extrapolated to 75° from a rate constant (M^{-1} sec^{-1}) for one of the reactions measured within 50° of 75°, by assuming an entropy of activation close to zero. The other rate constant was measured at 75°. [b] Rate constants from this work or ref 1. [c] R is CN, H, or Br. [d] This is the difference in the logarithm of the rate constants for dehydrobromination by the appropriate base B, from a pair of substrates, differing only in the substituents, R, shown in parentheses. [e] Difference in rate constant (as log k) for dehydrotosylation and dehydrobromination of cyclohexyl tosylate and bromide using the appropriate base, B. [f] Primary kinetic isotope effect k^H/k^D for dehydrobromination of the protium and *trans-2-d* labeled substrates, having R as Br or CN, as shown. [g] Solvent is ethanol. [h] Difference in rates of elimination from the substrate RX shown, using acetate and chloride as base. [i] Primary kinetic hydrogen isotope effect, for elimination from the substrate shown, using chloride or acetate as base, as indicated. [j] At 50°.

clohexyl tosylate and cyclohexyl bromide, coupled with the much greater sensitivity of the E2H side, *e.g.*, reactions of *cis*-2-bromocyclohexyl cyanide, agrees with More O'Ferrall's conclusions[12] about k^H/k^D values in bent E2C-transition states, like I or II, *vs.* linear C–H–B arrangements, as in the extreme E2H-like structures. He noted that both bending and stretching vibrations must be accounted for when considering bent C–H–B bonds in transition states and predicted a significant reduction in k^H/k^D from the "normal" value of 6–7, for reactions in which C–H–B is not linear. The extent of the decrease was expected to be only mildly dependent on the degree of asymmetry in the bent transition state. Thus he predicted that the small values of k^H/k^D should persist over a wide range of substrate and base reactivity in E2C-like reactions. All of More O'Ferrall's expectations[12] have now been realized by the E2C-like reactions shown in Table I, but the results do not allow us to distinguish between the bent structures I and II, for very E2C-like reactions. The increased k^H/k^D shown in Table I as reactions become more E2H-like is due either to increased transfer of the proton from substrate to base and increased linearity of C–H–B if II is the extreme E2C-like structure, or to increasing linearity of C–H–B and a tightening of the C_β–H bond, if I is the extreme E2C-like structure.

The changes in k^H/k^D with increasing acidity and E2H-like character of the substrate, RX, and increasing basicity and E2H-like properties of the base B are shown in Figure 2. We can say qualitatively that k^H/k^D passes through a maximum, as ΔpK_a (RX – HB) becomes less positive. In Figure 2 we have plotted k^H/k^D in acetone *vs.* ΔpK_a (HB – HBr) in DMF[1,19] for the four substrates whose acidities decrease in the order XI > VI ≫ V > IV. We do not know the pK_a of these substrates in acetone, but we do know qualitatively their relative acidities, and we know that they are weaker acids than HCl or HBr in acetone and that cyclohexyl tosylate is a weaker acid than phenol in acetone. Thus the difference ΔpK_a (RX – HB) is positive for reaction of Cl^- or Br^- with all four substrates, RX, and for reaction of PhO^- with cyclohexyl tosylate. It becomes less positive as pK_a of RX decreases and ΔpK_a (HB – HBr) increases. As shown, k^H/k^D is less than the maximum of 6 for situations where ΔpK_a (RX – HB) is clearly positive, and the ratio increases to a maximum and in some cases then decreases as ΔpK_a (RX – HB) becomes less positive.

Values of k^H/k^D become more sensitive to change of base as the acidity of the substrate increases and more sensitive to change of substrate as the basicity of the base increases.

We have advocated several methods, based on kinetics, of probing into positions in the E2C–E2H spectrum and into the E2C- or E2H-like character of bases and substrates.[1,3,10,11] It is timely to compare the results of these probes.

Increasing E2H-like character in a set of eliminations can be detected in ways a–d. Examples are in Table III.

(a) For eliminations from two substrates which differ only in that one substrate has a β-acidifying substituents, R (*e.g.*, CN, Br, COR, SO_2R) and the other has R = H, the rate difference $\Delta_R \log k$ (R – H) between elimination from the two substrates will increase as the E2H-like character of the elimination increases.[11] Such an increase in E2H-like character can be produced by increasing the basicity of the attacking base.

(b) For elimination from two substrates, which differ only in that one has tosylate and the other has bromide as leaving group, the rate difference $\Delta_X \log k$ (OTs – Br) between dehydrotosylation and dehydrobromination will decrease as the E2H-like character of the elimination increases.[1,20] An increase in E2H-like character can be produced by increasing the basicity of the base.

(c) For elimination from two substrates, differing only in that one has a β deuterium in place of β hydrogen, the rate difference k^H/k^D between elimination of HX and of DX will increase to a maximum and occasionally then decrease as the E2H-like character of the elimination increases. An increase in E2H-like character can be induced either by increasing the basicity of the base or by changing the substrate. Both are shown in Table III.

(d) For eliminations induced by chloride and acetate ion, the rate difference $\Delta_B \log k$ (OAc – Cl) will increase as the E2H-like character of the elimination increases.[1,11,21] An increase in E2H-like character, induced by changes of substrate, is illustrated in Table III.

The new kinetic isotope effects, as well as the new rate data for dehydrobromination of XI (Table II), thus correlate in a most satisfactory way with our earlier observations on the effects of changing base, leaving group, and substituents. All kinetic observations on bimolecular β-eliminations can be explained by a set of variable transition states between the E2C and E2H extremes. Whether the E2C transition state is as in I or as in II remains to be decided.

Experimental Section

Mass Spectra. The isotopic compositions of labeled precursors, substrates, and products of the elimination reactions were determined by mass spectrometry. Products were isolated by preparative vpc. Compositions of cyclohexyl tosylate were equated with those measured for the parent cyclohexanol.

Samples were introduced into the AEI MS9 spectrometer through the heated inlet system and peak intensities from three slow scans of the molecular ion region at low ionizing voltage were averaged. Spectra of the unlabeled compounds, except cyclohexanol, run under these conditions showed that peaks in the molecular ion region, other than the molecular ion peaks, were negligible. Relative peak intensities of molecular ions of a partly deuterated compound were therefore a direct measure of the relative amounts of undeuterated, monodeuterated, and dideuterated compounds, provided that allowance was made for ^{13}C abundance.

The M − H_2O peak from cyclohexanol was isolated and under the condition of low ionizing voltage arises principally from 1,3 and 1,4 eliminations. Thus isotopic compositions of partly deuterated cyclohexanol could be determined. The small amount of 1,2 elimination would cause the deuteration to be underestimated.

Kinetics. Fast reactions of *cis*-2-bromocyclohexyl cyanide were measured with a Durrum Stop Flow Reactor, using *p*-nitrophenol as an indicator of consumption of acetate or ethoxide ion. Rates of reaction of bromide ion with *cis*-2-bromocyclohexyl cyanide were measured by following the increase of bromide ion by dehydrobromination, using a potentiometric titration with silver nitrate, together with the decrease of *cis*-2-bromocyclohexyl cyanide, through dehydrobromination and substitution with inversion, by vpc. An excess of substrate was used and the reaction was followed for the first half-life. Rates of reaction of chloride ion were followed in the usual way.[1] No substitution was observed.

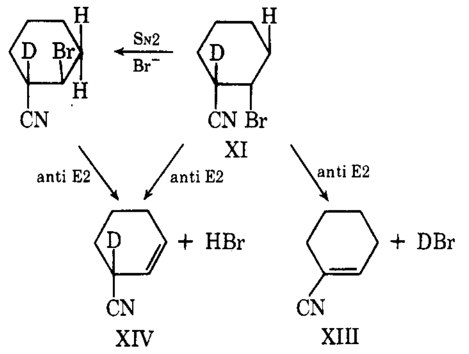
Intermolecular Competition Reactions of XI and XII with Various Bases. Equimolar proportions of base, *cis*-2-bromocyclohexyl cyanide $(XII)_0$ and its *1-d* analog $(XI)_0$ were mixed at 50° in acetone solution and allowed to react for time *t*, until all of the base was consumed. 2,6-Lutidine was used as an additive for the reactions with chloride and bromide ion to supress formation of the HCl_2^- and HBr_2^- species as elimination proceeded. Addition of lutidine to the reactions involving phenoxide and acetate ions was found to have no effect upon the kinetic results.

The unreacted *cis*-2-bromocyclohexyl cyanide $(XII)_t$ and its *1-d* analog $(XI)_t$ were recovered by pouring reaction mixtures into dilute nitric acid and extracting with pentane. Pentane extract were washed with water and dried over anhydrous $MgSO_4$. Solvent pentane was removed on the rotary evaporator and the resulting mixture was analyzed by mass spectrometry. The above extraction procedure had to be modified for reactions involving *p*-nitrothiophenoxide as the base, since *p*-nitrothiophenol formed as a reaction product could not be removed from the pentane extract by simply washing with H_2O. Its removal was effected by washing the pentane extract with dilute $AgNO_3$ solution, which precipitated the *p*-nitrothiophenol as the silver salt, subsequently removed by filtration. The isotopic *cis*-2-bromocyclohexyl cyanide substrates were shown to be stable to the extraction procedures used.

In the slower reactions with chloride ion, interference due to subsequent reaction of liberated bromide ion with unreacted substrate was found to be significant if the reaction was allowed to proceed until all the chloride ion was consumed. In the reactions with chloride ion, therefore, unreacted starting material was recovered and analyzed after no more than 50% reaction. All of the bases used in reactions with XI and XII were found to give 100% elimination with the exception of bromide ion, which also gave rise to 13 and 33% substitution with XII and XI, respectively (at 94°). Reactions of XI and XII with bromide ion were therefore analyzed during the first 25% of reaction to minimize the effects of subsequent reactions arising from the substituted products. The concurrent substitution reactions were taken into account, however, when determining the k^H/k^D value.

The rate of bromide-promoted dehydrobromination from XI (Table II) is only approximately ten times faster than the bromide-promoted elimination from cyclohexyl bromide.[1] This suggested that in XI elimination into the branch away from the cyanide substituent to give 3-cyanocyclohexene (XIV) might have been a significant reaction pathway in intramolecular competition with the expected pathway to give 1-cyanocyclohexene (XIII). Such intramolecular competition would be expected to decrease the observed k^H/k_D value compared to the "true" value.

It is to be noted that anti elimination from the substitution product from XI would also be expected to give XIV as the predominant product. However, product analysis by vpc for the reaction of XI with bromide ion, over the range of reaction used to determine k^H/k^D, showed XIII to be the only significant elimination product.



Values of k^H/k^D (*i.e.*, $k_H{}^H/k_D{}^D$) for the intermolecular competition experiments were evaluated from the expression

$$k_H{}^H/k_D{}^D = \log \frac{[XII]_0}{[XII]_t} \Big/ \log \frac{[XI]_0}{[XI]_t}$$

where the numerals refer to Figure 1. The original substrate concentrations, $[XIII]_0$ and $[XI]_0$, were determined by weighing and the ratio $[XII]_0/[XI]_0$ was checked by mass spectrometry. Account was taken of the incomplete deuteration of XI. The final substrate concentrations at time *t* were determined from the mass spectrometric ratio of $[XII]_t/[XI]_t$ and the amount of base consumed at time *t*. The expression has to be modified for the reactions with bromide ion to take into account the competitive substitution reactions, *i.e.*,

$$k_H{}^H/k_D{}^D = \frac{F^H}{F^D}\frac{\log\ [XII]_0/[XII]_t}{\log\ [XI]_0/[XI]_t}$$

where F^H and F^D are the fractions of the total reaction of substrates XII and XI, respectively, which are bimolecular elimination.

Intramolecular Competition Reactions of IV, V, and VI with a Variety of Bases. Substrates IV, V, and VI were individually treated with an excess of base at the temperatures shown in Table I and the product olefin mixtures were isolated by preparative vpc and analyzed by mass spectrometry in the vicinity of the molecular ion.

Materials. Tetra-*n*-butylammonium salts were prepared as previously described.[22]

Deuterated cyclohexanol and cyclohexyl bromide were purified by distillation and had bp *ca.* 60° (20 mm). They were better than 99% pure, as determined by vapor phase chromatography. The cyclohexyl tosylates were prepared as previously described,[1,15] mp 44-46°.

Nmr spectra were determined using TMS internal standard.

The first mass spectrum recorded for each compound includes all peaks close to the molecular ion (M^+) region down to those of relative intensity 1 (1% of the base peak for the region recorded).

Cyclohexanol had mass spectrum (15 eV) *m/e* (relative intensity) 100 (7), 83 (7), 82 (100), 72 (13), 71 (20), 67 (21), 58 (9), 57 (72), and 56 (15).

Cyclohexyl bromide had detailed mass spectrum of the M^+ region (13 eV) *m/e* (rel intensity) 165 (6.5), 164 (100), 163 (7.5), 162 (100); normal mass spectrum (13 eV) *m/e* (rel intensity) 164 (8), 162 (8), 84 (7), 83 (100), and 82 (21).

Cyclohexenyl bromide had mass spectrum (12 eV) *m/e* (rel intensity) 163 (8), 162 (98), 161 (8), 160 (100), 82 (7), and 81 (73).

Cyclohexene had mass spectrum (12 eV) *m/e* (rel intensity) 83 (6.5) and 82 (100).

Cyclohexyl-*trans-2-d* bromide (0.8% d_2, 87.3% d_1, 11.9% d_0) was prepared by the addition of deuterium bromide to cyclohexene in the presence of inhibitors as previously described[23] and had detailed mass spectrum of the M^+ region (15 eV) *m/e* (rel intensity) 166 (7.3), 165 (98.3), 164 (20.7), 163 (100), 162 (13.3); normal mass spectrum (15 eV) 165 (2), 163 (2), 85 (9), 84 (100), 83 (18), 68 (7), 67 (6), 56 (40), and 55 (36).

Cyclohexanol-*trans-2-d* (1.2% d_2, 94.2% d_1, 4.6% d_0) was prepared as previously described[15] by reductive cleavage of cyclohexene oxide using lithium aluminum deuteride in refluxing ether. Finley and Saunders[15] found 4-5% of dideuterated product and other workers[24] have found 11%, which they suggest arises from hydride abstraction. In this work, however, a deficiency of lithium aluminum deuteride was used and this converted 2.2 mol of cyclohexene oxide, whereas in a previous experiment lithium aluminum hydride converted 2.6 mol of cyclohexene oxide. The product, obtained in 90% yield based on converted cyclohexene oxide, and with only 1.2% dideuteration, had mass spectrum (12 eV) *m/e* (rel intensity) 101 (10), 84 (7.9), 83 (100), and 82 (4.9).

cis-1,2-Dibromocyclohexane, mp 10–10.5° (lit.[25] mp 9.7–10.5°), prepared as previously described,[1] had mass spectrum in the M$^+$ region (12 eV) *m/e* (rel abundance) 245 (5), 244 (52.5), 243 (10), 242 (100), 241 (5), 240 (55); normal mass spectrum (12 eV) *m/e* (rel intensity) 244 (8), 242 (15), 240 (8), 163 (25), 161 (24), 82 (15), and 81 (100).

cis-1,2-Dibromocyclohexane-*1-d* (2.3% d_2, 84.0% d_1, 13.7% d_0) was prepared from 1-bromocyclohexene-*2-d*, which could not be prepared straightforwardly from a 1-metallo-2-bromocyclohexene because of the instability of this type of intermediate; *e.g.*, 1-lithio-2-bromocyclohexene loses lithium bromide so rapidly that it cannot be carboxylated with CO$_2$ even at −120°.[26] Alternatively, 1,2-dibromocyclohexene (24 g, 0.1 mol) was treated with zinc (20 g, 0.3 mol, twice preequilibrated with D$_2$O) in a refluxing solution of D$_2$O (30 g, 1.5 mol) and acetic acid-d_1 sufficient to dissolve the 1,2-dibromocyclohexene (*ca.* 70 ml) for 24 hr to yield 1-bromocyclohexene-*2-d* (2.5% d_2, 83.8% d_1, 13.7% d_0), 8 g (50%). The purification was simplified by freezing out the relatively high-melting starting material. Identical results (including label) were obtained in the absence of D$_2$O, though the reaction may have been slower. The product had the following nmr spectrum (CCl$_4$), δ 1.5–2.5 (m, 8 H), 5.8 m, 0.12 H), consistent with the mass spectrum (12 eV) *m/e* (rel intensity) 164 (9.2), 163 (98.2), 162 (23.8), 161 (100), 160 (16), 83 (8), 82 (69), and 81 (13). The 1-bromocyclohexene-*2-d* was converted to *cis*-1,2-dibromocyclohexane-*1-d*, mp 10–10.5°, by photolytic addition of hydrogen bromide as for the undeuterated compound. The product had nmr spectrum (CCl$_4$) δ 1.2–2.4 (m, 8 H) and 4.28 (m, 1 H); detailed mass spectrum of the M$^+$ region (12 eV) *m/e* (rel intensity) 246 (6.5), 245 (49), 244 (16.5), 243 (100), 242 (20), 241 (51.8), 240 (7.5); normal mass spectrum (12 eV) *m/e* (rel intensity) 245 (15), 244 (5), 243 (31), 242 (7), 241 (15), 164 (42), 163 (16), 162 (43), 161 (14), 83 (29), 82 (100), and 81 (31).

cis-2-Bromocyclohexyl cyanide-*1-d* (0.5% d_2, 93.0% d_1, 6.5% d_0) was prepared from cyclohexenyl cyanide by addition of DBr, but differing from the method for cyclohexyl-*trans-2-d* bromide in that inhibitor concentrations were doubled, a time period of 2.5 hr was used, and the deuterium bromide was led directly from the generator through a cold trap (−40°) to the reaction vessel under a Dry Ice condenser. The acetyl bromide used to generate deuterium bromide was twice distilled from dimethylaniline. The product, obtained in 30% yield, had mp 26–27°; nmr spectrum (CCl$_4$) δ 1.73 (m, 5 H), 2.1 (m, 3 H) and 4.2 (5, 1.0 H, J = 8 Hz), and no peak at δ 3.18; detailed mass spectrum of the M$^+$ region (14 eV) *m/e* (rel intensity) 191 (8.8), 190 (97.9), 189 (15.2), 188 (100.0), 187 (7.2); normal mass spectrum (14 eV) *m/e* (rel intensity) 190 (8), 188 (7), 110 (7), 109 (100), and 108 (11).

cis-2-Bromocyclohexyl cyanide similarly prepared had mp 26–26.5°; nmr spectrum (CCl$_4$) δ 1.73 (m, 5 H), 2.1 (m, 3 H), 3.18 (q, 1.0 H), and 4.2 (m, 1.0 H) (*Anal.* Calcd for C$_7$H$_{10}$BrN: C, 44.70; H, 5.36; N, 7.45. Found: C, 44.49; H, 5.45; N, 7.56); detailed mass spectrum of the M$^+$ region (14 eV) *m/e* (rel abundance) 190 (8.5), 189 (95.5), 188 (8), 187 (100); normal mass spectrum (14 eV) *m/e* (rel intensity) 189 (8), 187 (8), 109 (8), 108 (100), and 107 (13).

It is interesting that the small, strongly electron-withdrawing cyano group does not strongly retard the rate of addition of HBr. This is consistent with a synchronous hydrogen bromide addition reaction mechanism, rather than a two-step protonation mechanism.

Registry No. IV, 1085-94-5; V, 49676-86-0; VI, 49676-87-1; XI, 49676-88-2; XII, 49676-89-3; C$_6$H$_{11}$OTs, 953-91-3; C$_6$H$_{11}$Br, 108-85-0; cyclohexanol-*trans-2-d*, 49676-90-6; *cis*-1,2-dibromocyclohexane, 19246-38-9; 1-bromocyclohexene-*2-d*, 49676-91-7; 1,2-dibromocyclohexene, 49676-92-8.

References and Notes

(1) Part V: P. Beltrame, G. Biale, D. J. Lloyd, A. J. Parker, M. Ruane, and S. Winstein, *J. Amer. Chem. Soc.*, **94**, 2240 (1972).
(2) G. Biale, A. J. Parker, I. D. R. Stevens, J. Takahashi, and S. Winstein, *ibid.*, **94**, 2234 (1072).
(3) D. N. Kevill and J. E. Dorsey, *J. Org. Chem.*, **34**, 1985 (1969).
(4) D. N. Kevill, G. H. Coppens, and N. H. Cromwell, *J. Amer. Chem. Soc.*, **86**, 1553 (1964).
(5) W. H. Saunders, Jr., *Surv. Progr. Chem.*, **3**, 109 (1966).
(6) A. Fry, *Chem. Soc. Rev.*, **1**, 163 (1972).
(7) W. H. Saunders, Jr., in "Investigation of Rates and Mechanisms of Reactions," Vol. 8, S. L. Friess, E. S. Lewis, and A. Weissberger, Ed., Interscience, New York, N. Y., 1961, p 389.
(8) J. F. Bunnett, *Angew. Chem.*, **74**, 731 (1962).
(9) D. Muir and A. J. Parker, unpublished work.
(10) A. J. Parker, M. Ruane, G. Biale, and S. Winstein, *Tetrahedron Lett.*, 2113 (1968).
(11) G. Biale, D. Cook, D. J. Lloyd, A. J. Parker, I. D. R. Stevens, J. Takahashi, and S. Winstein, *J. Amer. Chem. Soc.*, **93**, 4735 (1971); D. J. Lloyd and A. J. Parker, *Tetrahedron Lett.*, 5029 (1970).
(12) R. A. More O'Ferrall, *J. Chem. Soc. B*, 274, 785 (1970).
(13) F. H. Westheimer, *Chem. Rev.*, **61**, 265 (1961).
(14) A. F. Cockerill, *J. Chem. Soc. B*, 964 (1967); A. F. Cockerill and W. H. Saunders, Jr., *J. Amer. Chem. Soc.*, **89**, 4985 (1967).
(15) K. T. Finley and W. H. Saunders, Jr., *J. Amer. Chem. Soc.*, **89**, 898 (1967).
(16) D. Cook, M. R. J. Dack, R. E. J. Hutchinson, and A. J. Parker, unpublished work.
(17) C. G. Swain and C. B. Scott, *J. Amer. Chem. Soc.*, **75**, 141 (1953).
(18) R. P. Bell and D. M. Goodall, *Proc. Roy. Soc., Ser. A*, **294**, 273 (1966); R. P. Bell and B. G. Cox, *J. Chem. Soc. B*, 194 (1970).
(19) We have pK_a values for the bases HB in dimethylformamide, but not in acetone. We have noted, however, that pK_a values are linearly related in a variety of dipolar aprotic solvents and therefore assume $\Delta pK_a\ (HB - HBr)_{DMF} = \Delta pK_a\ (HB - HBr)_{acetone}$: B. W. Clare, D. Cook, E. C. F. Ko, Y. C. Mac, and A. J. Parker, *J. Amer. Chem. Soc.*, **88**, 1911 (1966); A. J. Parker, unpublished work.
(20) A. J. Parker and D. J. Lloyd, *Tetrahedron Lett.*, 5183 (1968).
(21) D. Cook, A. J. Parker, and M. Ruane, *Tetrahedron Lett.*, 5715 (1968).
(22) A. J. Parker, M. Ruane, D. A. Palmer, and S. Winstein, *J. Amer. Chem. Soc.*, **94**, 2228 (1972).
(23) G. S. Hammond and J. Warkentin, *J. Amer. Chem. Soc.*, **83**, 2554 (1961).
(24) R. Rickborn and J. Quartucci, *J. Org. Chem.*, **29**, 3185 (1964).
(25) H. L. Goering, P. I. Abell, and B. F. Aycock, *J. Amer. Chem. Soc.*, **74**, 3588 (1952).
(26) G. Wittig and W. Mayer, *Ber.*, **96**, 329 (1963).

Calculation of Bond Lengths and Angles of Hydrocarbons by the Iterative MOA Method

K. Kovačević and Z. B. Maksić*

Institute "Ruder Bošković," 41001 Zagreb, Croatia, Yugoslavia

Received July 26, 1973

The bond lengths and angles of some characteristic strained cyclic and polycyclic alkanes and alkenes were calculated by the iterative maximum overlap approximation (IMOA) procedure. The agreement with experimental bond lengths and angles is satisfactory indicating that IMOA method might be useful for a semiquantitative prediction of the geometry of hydrocarbons.

The experimental bond lengths and angles give some insight into the nature of chemical bonding in molecules. Unfortunately, there are available only a very few *ab initio* studies since the geometry variation is very time con-