1583 cm^{-1}. **26** was hydrolyzed as usual giving the hydroxybenzylic polymer. From neutralized solution **27** (10.4 mg, 23.1%) was isolated by extraction with dichloromethane: mp 109–111 °C; IR (KBr) 3129, 2958, 1687, 1571, 1297, 1184, 1076 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.35 (dd, J = 8.5 Hz, J' = 6.7 Hz, 1 H), 7.05 (m, 2 H), 7.4 (s, 1 H), 7.65 (wide s, 2 H); ^{13}C NMR ($CDCl_3$) 100.6, 112.9, 120.5, 139.8, 144.1, 147.9, 163.7. Anal. Calcd for $C_7H_6N_2O_2$: C, 56.00; H, 4.00; N, 18.66. Found: C, 56.21; H, 4.16; N, 18.73.

Lifetime Determinations. In a series of experiments, suspensions of 6.5 mequiv of polymeric precursor (**9** or **12**) in Me_2SO at 170 °C were stirred in one of the PDR vessels. Trapping agent **17** (4.5 mequiv) was stirred in the other. A peristaltic pump was used to transfer the solvent carrying the intermediate from one vessel to the other. Previous peristaltic pump calibration allowed us to establish a relationship between flow rates and times the intermediate required to go from the precursor polymer to the trapping one. After each experiment (at a specific flow rate) was complete, the polymeric trapping agent was filtered, washed, and analyzed by hydrolysis and IR. The lifetime values are shown in Table I. The lifetimes for **1** and **2** were repeated under these conditions, and no changes were observed. For **5**, experimental conditions were as follows: 4.5 mequiv of **16**, 4.5 mequiv of **17**, and dioxane containing 3 mL of trifluoroacetic acid at room temperature.

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Molecular Orbital Estimation of the Activation Enthalpies for Intramolecular Hydrogen Transfer as Functions of Size of the Cyclic Transition State and C–H–C Angle

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The AM1 molecular orbital method was used to compute the activation enthalpies for H-transfer between carbons as a function of C–H–C angle and size of the cyclic transition state for intramolecular H-transfer. In the case of intramolecular H-transfer, reactions of a primary radical site with primary, secondary, and tertiary C–H's were considered for H-shifts to C_1 from C_3–C_8. The activation enthalpies are insensitive to C–H–C angle in the range 145–180°. Activation enthalpies are lowest for intramolecular H-transfers involving 1–5 and 1–6 H-shifts. The higher activation enthalpies for the other internal H-transfers are attributed to C–H–C strain for 1–3 and 1–4 H-transfers only, and conformational effects other than C–H–C angle in the transition states.

One expects the transition state for hydrogen atom transfer between carbons to prefer a linear arrangement of the carbons and the H-atom being transferred.[1] Molecular orbital calculations have confirmed this expectation.[2]

Recent developments in synthetic organic chemistry have generated new interest in the structure of the transition states for these reactions and the effects upon the activation energies of distortions from the ideal structures. In particular, the cyclization of the 1-hexenyl radical[3] has become a useful synthetic reaction.[4] Applications often occur with complete or high regio- and stereospecificity.[5] However, cyclizations of this type often have to compete with intramolecular abstraction reactions when appropriately situated hydrogens are in the starting material.[6] Clearly, the synthetic chemist needs to have a reasonable measure of when to expect an abstraction to compete with a cyclization.

In view of the interest in this problem, we have undertaken a molecular orbital study of the effects of C–H–C angle and ring size on intramolecular H-abstraction. We have chosen to study the effect of C–H–C angle by calculating the transition states for H-transfer between two methyl groups as a function of C–H–C angle. The effects of ring size on the transition states for intramolecular H-transfer were studied for transfer of a hydrogen atom from primary, secondary, and tertiary carbons to a primary radical center involving three to eight carbons in the cyclic part of the transition state (see Figure 1). Houk has recently reported the results of an ab initio study of the intermolecular abstraction of a terminal hydrogen by n-butoxyl radical (Barton reaction),[7] which is similar to the 1–5 shifts studied here except that abstraction is by oxygen. We are unaware of other theoretical work on this problem.

Methods

The AM1 approximation to molecular orbital theory[8] using the half-electron method[9] as implemented in the AMPAC computer

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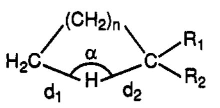

	R_1	R_2	n
a	H	H	1-6
b	H	$CH_3(CH_2)_{6-n}$	1-6
c	CH_3	$CH_3(CH_2)_{6-n}$	1-6

Figure 1. General structures of the transition states for the cyclic intramolecular primary (type a), secondary (type b), and tertiary (type c) H-transfer reactions. Complete structures are included in supplementary material.

Table I. AM1 Activation Enthalpies and Geometric Parameters for the Transition States of *n*-Alkyl Radical Primary H-Transfer Reactions[a]

H-shift	ΔH_{act} (kcal/mol)	d_1 (Å)	d_2 (Å)	α (deg)	charge
1-3	42.5	1.41	1.41	98.5	0.157
1-4	27.5	1.35	1.35	125.2	0.153
1-5	20.9	1.32	1.32	144.5	0.168
1-6	21.0	1.31	1.31	158.0	0.165
1-7	23.0	1.30	1.31	163.6	0.163
1-8	24.9	1.31	1.31	178.1	0.163

[a] Structures of type a in Figure 1.

Table II. AM1 Activation Enthalpies and Geometric Parameters for the Transition States of Internal Secondary H-transfers in *n*-Nonyl Radicals[a]

H-shift	ΔH_{act} (kcal/mol)	d_1 (Å)	d_2 (Å)	α (deg)	charge
1-3	41.1	1.42	1.40	98.9	0.158
1-4	26.0	1.37	1.34	125.6	0.156
1-5	19.6	1.34	1.31	145.8	0.171
1-6	19.5	1.33	1.29	162.3	0.166
1-7	21.9	1.33	1.30	162.3	0.166
1-8	23.3	1.34	1.30	174.8	0.166

[a] Structures of type b in Figure 1.

Table III. AM1 Activation Enthalpies and Geometric Parameters for the Transition States of Internal Tertiary H-Transfers in Methyl-Substituted 1-Nonyl Radicals[a]

H-shift	ΔH_{act} (kcal/mol)	d_1 (Å)	d_2 (Å)	α (deg)	charge
1-3	39.6	1.44	1.40	99.4	0.156
1-4	23.9	1.39	1.33	126.3	0.158
1-5	17.6	1.37	1.30	147.3	0.174
1-6	18.6	1.36	1.28	168.2	0.167
1-7	21.0	1.36	1.29	172.9	0.167
1-8	21.7	1.36	1.29	180.0	0.168

[a] Structures of type c in Figure 1.

Table IV. AM1 Activation Enthalpies and Geometric Parameters for H-Transfer between Methyl Radicals

α (deg)	ΔH_{act} (kcal/mol)	d_1 (Å)	charge
180.0	15.5	1.29	0.154
175.0	15.5	1.29	0.154
170.0	15.6	1.29	0.155
165.0	15.7	1.29	0.156
160.0	15.8	1.29	0.157
155.0	16.0	1.30	0.159
150.0	16.2	1.30	0.161
145.0	16.6	1.30	0.164
140.0	17.0	1.31	0.167
135.0	17.6	1.32	0.170
130.0	18.5	1.32	0.174
125.0	19.6	1.34	0.178
120.0	21.1	1.35	0.183
110.0	25.6	1.38	0.195
105.0	28.9	1.40	0.203
100.0	33.1	1.42	0.213

program was used for all calculations. This method has been previously shown to provide accurate results for H-transfer between carbons.[10] Calculations were performed on IBM RS/6000 and Ulysses Systems I386-based workstations.

Each of the transition states for the internal abstractions was optimized in all of their (up to 87) internal coordinates. Initial trial geometries were obtained using the PCMODEL program[11] and the MMX empirical force field.[12] Several conformations of the larger rings were calculated. In particular, the effects of exchanging the alkyl groups (R_1 and R_2 in Figure 1) and various ring conformations were considered. The transition-state conformations having the lowest energies are included in the tables. Force constants were calculated for each transition state to verify the structures. Only one negative force constant was calculated in each case.

The activation energies for H-transfer between methyl groups was calculated in an analogous manner except that the C–H–C angle was fixed at each 5° interval from 100 to 180° while all other internal coordinates were varied. Since (except for the structure with a 180° angle) these are not true saddle points on the potential surface, force constants were not calculated for these structures.

Results and Discussion

The intramolecular H-transfer reactions between primary carbon centers were modeled by calculating the transition states for transfer of a hydrogen to C_1 from the terminal carbon of the *n*-propyl, butyl, pentyl, hexyl, heptyl, and octyl radicals. The transfers of H-atoms from secondary to primary centers were modeled using the various transition states derived from transfers of H's from carbons C_{3-8} to C_1 in the *n*-nonyl radical. The analogous transfers of H's from tertiary positions were modeled using transition states derived from the methylnonyl radicals, where the methyl group is attached to the carbon from which the H is being transferred. The results are summarized in Tables I–III. All geometric parameters and drawings of the transition states are included as archive files in the supplementary material.

In all three cases, intramolecular transfer from either C_5 or C_6 to C_1 have the lowest ΔH_{act}'s, which are roughly equivalent. The 1-3 H-transfer is calculated to be particularly disfavored. The relative destabilizations for the 1-4, 1-7, and 1-8 H-transfers fall in the range of 2-5 kcal/mol, enough to kinetically disfavor their occurrences when 1-5 or 1-6 H-transfer is possible. Entropic factors should disfavor larger cyclic transition states as more rotations will be frozen. This effect should cause the 1-5 shift to be most favored at normal reaction temperatures.

The amount of distortion from the 180° ideal transition state decreases slightly upon changing from transfer of primary to secondary to tertiary hydrogens. The C–H distances become more unsymmetrical as the transition state becomes earlier, as expected.

The data obtained from the H-transfer between methyls as a function of C–H–C angle are presented in Table IV and Figure 2. The effect of distorting the angle up to 35° from linearity has less than a 1 kcal/mol effect upon ΔH_{act}. Examination of Tables I–III show that the C–H–C angle

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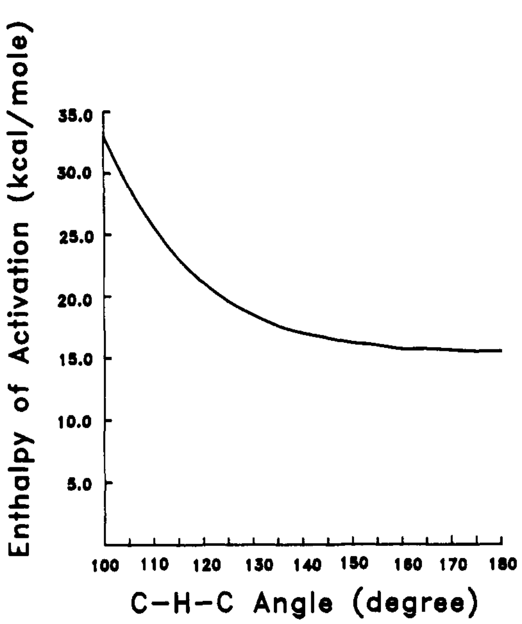

Figure 2. Variation of enthalpy of activation with C–H–C angle in the transition state for H-transfer from methane to methyl radical.

is never less than 145° for all cases with five or more ring carbons in the transition state.

For the 1–3 H-transfers the C–H–C angles vary from 98.5 to 99.4°, corresponding to an increased activation of about 19 kcal/mol based on Table IV. The calculated ΔH_{act}'s are 21.6, 21.5, and 22.0 kcal/mol above that for 1–5 H-transfer for the cases of primary, secondary, and tertiary H's, respectively. Thus, most of the additional activation can be attributed to strain in this angle.

For the 1–4 H-transfers the C–H–C angles vary from 125.2 to 126.3°. From the information in Table IV, we expect an increase in activation of about 5 kcal/mol for a transition state constrained to a C–H–C angle of 125°. The calculated ΔH_{act}'s are 6.6, 6.4, and 6.3 kcal/mol above that for 1–5 H-transfers from primary, secondary, and tertiary carbons, respectively. For the latter, the C–H–C angles vary from 144.5 to 147.3°, corresponding to an expected destabilization of about 1 kcal/mol. Roughly two-thirds of the additional barrier for 1–4 H-transfer is due to the C–H–C strain. The rest is apparently due to other conformational factors.

The differences in ΔH_{act}'s for the 1–6 and 1–5 H-transfers are 0.1, −0.1, and 1.0 kcal/mol for transfer from primary, secondary, and tertiary carbons. The C–H–C angle for 1–6 H-transfer varies from 158.0 to 168.2°, corresponding to no more than 0.3 kcal/mol additional activation due to C–H–C angle constraint. The results suggest that the 1–5 H-transfer has less ring strain than the 1–6 H-transfer (other than due to C–H–C angle). Furthermore, the difference increases from 0.2 to 1.4 kcal/mol as the transition state becomes increasingly early (changing from transfer of a primary to a tertiary hydrogen).

The 1–7 and 1–8 H-transfers are essentially without strain due to the C–H–C angle. Their differential ΔH's are entirely due to conformational strain in the rings.

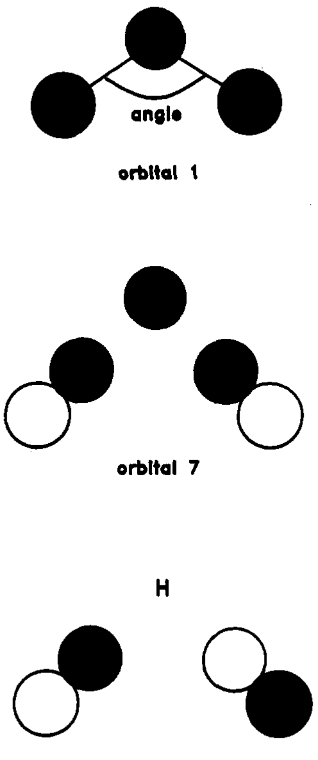

Figure 3. Orbitals 1, 7 (highest doubly occupied), and 8 (singly occupied) for the transition state for H-transfer from methane to methyl radical.

The data in Tables I–III indicate that the C–H partial bond length in the transition state and the charge on the migrating hydrogen both increase as the C–H–C angle increasingly deviates from 180°. These phenomena are due to the changes in the orbitals 1, 7, and 8 (see Figure 3). Orbital 1 involves interaction of the carbon 2s orbitals with the hydrogen orbital. This orbital becomes progressively more bonding (by 0.381 eV) as the angle changes from 180 to 100°. The enhanced bonding is due to the increase in direct interaction between the carbon 2s orbitals (the interaction between the hydrogen orbital and the carbon orbitals decreases). Orbital 7 is primarily comprised of two carbon 2p orbitals and the hydrogen orbital. It becomes less bonding (by 0.601 eV) as the angle changes from 180 to 100°. This effect is likely due to a decrease in σ-overlap that is not compensated for by an increase in π-overlap between the carbon 2p orbitals. Orbital 8 (the SOMO) is comprised of the antibonding combination of carbon 2p orbitals with a node passing through the migrating hydrogen. It becomes less bonding by 0.727 eV as the angle changes from 180 to 100°. Orbital 7 has the largest effect, as it contains two electrons compared to the one in orbital 8.

The enthalpies of activation for the reactions studied are not known quantitatively except for the transfer of an H-atom between methyl radicals, whose ΔH_{act} (14.9 kcal/mol[13]) is in good agreement with the AM1 results previously reported along with other similar results.[2c] Tunneling is generally considered to be part of the preexponential factor in the Arrhenius equation or incorporated into the transmission coefficient in transition-state theory.[14] As such, it should have no effect upon the experimental enthalpies of activation that are (necessarily) measured over a range of temperatures.

Conclusion

We conclude from these calculations that H-atom transfer can easily occur with C–H–C angles moderately distorted from linearity, such as occurs in 1–5, 1–6, 1–7, and 1–8 transfers. For these cases, the differential ΔH_{act}'s

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[14] Schatz, G. C. *Chem. Rev.* **1987**, *87*, 81.

are primarily due to other differences in the conformational requirements of the various cyclic transition states. For the cases of 1–3 and 1–4 H-transfers the necessary distortions of the C–H–C angle are sufficient to provide the major impediment to the reaction.

Acknowledgment. This work was supported in part by a BHE-PSC grant.

Registry No. $^{\bullet}CH_2CH_2CH_3$, 2143-61-5; $^{\bullet}CH_2(CH_2)_2CH_3$, 2492-36-6; $^{\bullet}CH_2(CH_2)_3CH_3$, 2672-01-7; $^{\bullet}CH_2(CH_2)_4CH_3$, 2679-29-0; $^{\bullet}CH_2(CH_2)_5CH_3$, 3356-67-0; $^{\bullet}CH_2(CH_2(_6CH_3$, 4606-96-6; $^{\bullet}CH_2(CH_2)_7CH_3$, 32757-65-6; $^{\bullet}CH_2CH_2CH(CH_3)(CH_2)_5CH_3$, 134848-03-6; $^{\bullet}CH_2(CH_2)_2CH(CH_3)(CH_2)_4CH_3$, 134848-04-7; $^{\bullet}CH_2\rightleftarrows CH_2(CH_2)_3CH(CH_3)(CH_2)_3CH_3$, 65388-48-9; $^{\bullet}CH_2(CH_2)_4CH(CH_3)(CH_2)_2CH_3$, 134848-05-8; $^{\bullet}CH_2(CH_2)_5CH(CH_3)CH_2CH_3$, 134848-06-9; $^{\bullet}CH_2(CH_2)_6CH(CH_3)_2$, 134848-07-0.

Supplementary Material Available: Drawings and archive files for each of the 24 transition states optimized. They are organized in the following manner: drawing followed by archive files for each structure of type a (Figure 1) in order of increasing size; idem for type b and type c (36 pages). Ordering information is given on any current masthead page.

Calculated Double-Bond Stabilization by Bromine and Chlorine. Relevance to the k_{Br}/k_{Cl} Element Effect[†]

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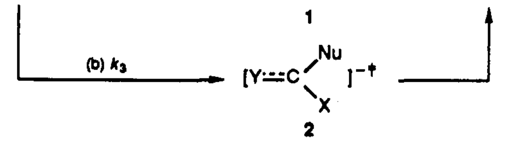
The relative stabilization of a carbon–carbon double bond by Cl and Br was obtained by ab initio MO calculations. The results at the MP2//RHF/CEP-21G* level corrected for differences in zero-point energy show that stabilization by Cl exceeds that by Br by ca. 1.3 kcal mol^{-1}. Consequences related to the use of k_{Br}/k_{Cl} ratios as mechanistic probes in vinylic substitution are discussed.

The halogen isotope effects $k(^{35}Cl)/k(^{37}Cl)$ or $k(^{79}Br)/k(^{81}Br)$ should serve as a powerful mechanistic tool for investigating the extent of cleavage of a bond to a leaving group in the transition state. In practice, however, the experimental difficulties associated with the accurate measurement of such small effects resulted in the application of the chlorine isotope effect in only a few cases.[1]

A substitute for a halogen isotope effect is the "element effect",[2] where the rate constants of two systems bearing different nucleofuges are compared. In order to be of mechanistic value, the nucleofuges compared in the element effect should resemble one another as much as possible. Hence, comparison between Cl and Br derivatives is frequently made. Heterolytic C–Br bond dissociation energies in alkyl bromides are several kcal mol^{-1} lower than the corresponding values for C–Cl,[3] and hence the k_{Br}/k_{Cl} ratios are expected to be >1 when the C–X bond is cleaved in the transition state of the rate-determining step.

Consequently, the element effect is a most valuable probe in an "all or nothing" situation, which occurs when the halogen is attached to an unsaturated center. As demonstrated in eq 1, the substitution of an aromatic, a vinyl, an acyl, or an imidoyl halogen (Y = C, O, NR) can proceed in a two-step mechanism via the negatively charged intermediate 1 (route a) where either k_1 or k_2 is rate limiting, or it can proceed via the concerted route b, where 2 is a transition state.



(1)

Bunnett introduced the use of the "element effect" in the study of nucleophilic aromatic substitution.[2] A comparative study of the reactivity of aryl chlorides and bromides resulted in k_{Br}/k_{Cl} ratios that were close to unity.[2,4] Based on the assumption that the electronic effects of Cl and Br are similar, this observation provides a strong evidence for the intermediacy of the anionic σ-Meisenheimer complexes (route a) with k_1 being rate determining in S_NAr reactions.

The k_{Br}/k_{Cl} element effect is also frequently used in nucleophilic vinylic substitution reactions where its value is around, or slightly higher than, unity for systems of largely different activation.[5] Again, this observation is considered to be the strongest evidence for the multistep nature of these reactions (i.e., eq 1, route a, Y = C).[6]

[†] Dedicated to Professor Joseph F. Bunnett on the occasion of his 70th birthday.

(1) E.g.: (a) Grout, A.; McLennan, D. J.; Spackman, I. H. *J. Chem. Soc., Chem. Commun.* 1976, 775. (b) *J. Chem. Soc., Perkin Trans. 2* 1977, 1758. (c) Koch, H. F.; McLennan, D. J.; Koch, J. G.; Tumas, W.; Dobson, B.; Koch, N. H. *J. Am. Chem. Soc.* 1983, *105*, 1930.

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