(dd, $J_{3a,4}$ = 10.3 Hz, $J_{4,5}$ = 5.5 Hz, H-4α), 5.53 (dd, $J_{6,7}$ = 9.7 Hz, $J_{6,7a}$ = 1.4 Hz, H-6), 5.65 (ddd, $J_{6,7}$ = 9.7 Hz, $J_{7,7a}$ = 4.9 Hz, $J_{5,7}$ = 1.4 Hz, H-7), 7.37 (d, J = 8.1 Hz, Ar H), 7.78 (d, J = 8.1 Hz, Ar H); IR (CCl_4) 3050, 2980, 2940, 2890, 1595, 1545, 1300, 1150, 1090 cm^{-1}; MS(EI), *m/e* (relative intensity) 179 (3, $M^+ - C_7H_7SO_2H$), 157 (100), 133 (73), 132 (96, $C_{10}H_{12}^+$); calcd for $C_{10}H_{13}NO_2$ ($M^+ - C_7H_7SO_2H$) 179.0946, found 179.0934].

A recrystallized sample of **25c** was subjected to single-crystal X-ray diffraction analysis. Compound **25c** crystallizes from hexane/ethyl acetate in the monoclinic space group $P2_1/c$. The crystal data at 140 K are as follows: a = 5.321 (2) Å, b = 14.057 (10) Å, c = 21.484 (9) Å, β = 91.65 (4)°; ρ(calcd) = 1.39 g cm^{-3} for $Z = 4$; 2θ(max) = 50°; 1129 reflections with $F > 6\sigma$ (|F|) used, Mo K_α (graphite) (λ = 0.71069 Å), and ω scan, 3° min^{-1}; R = 0.066. SHELXTL programs were used on a DGC Eclipse S/230 computer.

(±)-5-Methyl-4-nitro-2,3,3aβ,4β,5α,7aα-hexahydro-1*H*-indene (19) and (±)-5-Methyl-4-nitro-2,3,3aα,4α,5α,7aα-hexahydro-1*H*-indene (20). (*Z*)-Nitro triene 4 (11 mg, 0.061 mmol) in chloroform-*d* (0.5 mL) was allowed to stand at room temperature, and the progress of the cycloaddition was followed by ^1H NMR. After 3.5 days, the reaction was judged to be complete. The solvent was then removed under reduced pressure and the crude product was purified by medium-pressure liquid chromatography (95:5 hexane/EtOAc), yielding an inseparable mixture of **19** and **20** (53:47) (8.2 mg, 0.045 mmol, 74%) [**19**, ^1H NMR (360 MHz, $CDCl_3$) δ 1.15 (d, J = 7.5 Hz, 3 H, CH_3), 1.78 (m, $J_{3a,4}$ = 2.2 Hz, 1 H, H-3aβ), 2.92 (dq, $J_{5,6}$ = 3.0 Hz, J_{5,CH_3} = 7.5 Hz, 1 H, H-5α), 4.71 (d, $J_{3a,4}$ = 2.2 Hz, 1 H, H-4β), 5.54 (ddd, $J_{6,7}$ = 10.0 Hz, $J_{5,6}$ = 3.0 Hz, $J_{6,7a}$ = 3.0 Hz, 1 H, H-6), 5.90 (d, $J_{6,7}$ = 10.0 Hz, 1 H, H-7); **20**, ^1H NMR (360 MHz, $CDCl_3$) δ 1.11 (d, J = 7.1 Hz, 3 H, CH_3), 2.68 (m, $J_{6,7a}$ = 3.0 Hz, $J_{7,7a}$ = 3.0 Hz, 1 H, H-7aα), 2.74 (m, $J_{3a,5}$ = 4.9 Hz, 1 H, H-3aα), 2.93 (ddq, $J_{5,6}$ = 3.0 Hz, $J_{5,7a}$ = 3.0 Hz, J_{5,CH_3} = 7.1 Hz, 1 H, H-5α), 4.88 (dd, $J_{4,5}$ = 4.9 Hz, $J_{3a,4}$ = 4.9 Hz, 1 H, H-4α), 5.51 (ddd, $J_{6,7}$ = 10.0 Hz, $J_{6,7a}$ = 3.0 Hz, $J_{5,6}$ = 3.0 Hz, 1 H, H-6), 5.66 (ddd, $J_{6,7}$ = 10.0 Hz, $J_{5,}$ = 3.0 Hz, $J_{7,7a}$ = 3.0 Hz, 1 H, H-7); IR (CCl_4) 3040, 2980, 2900, 1530, 1540, 1350 cm^{-1}; MS(E/I), *m/e* (relative intensity 181 (2, M^+), 135 (23, $M^+ - NO_2$); calcd for $C_{10}H_{15}NO_2$ 181.1103, found, 181.1092].

Acknowledgment is made to The Committee on Research of The University of California, Davis and to the donors of The Petroleum Research Fund, administered by the American Chemical Society, for the support of this research. We gratefully acknowledge IBM Instruments for donation of an LC/9533 Ternary High–Pressure Liquid Chromatography System and E. G. Brown and C. B. Green for high-field ^1H NMR measurements.

Registry No. 1, 96575-21-2; (±)-**2**, 96556-47-7; (±)-**3**, 96556-48-8; **4**, 96556-49-9; (±)-**5**, 96575-22-3; **6**, 64275-80-5; **7**, 96556-50-2; (±)-**8**, 96556-51-3; (±)-**9**, 96556-52-4; (±)-**9** (benzyloxy triene), 96556-69-3; (±)-**10**, 96556-53-5; (±)-**11**, 96556-54-6; **12**, 96556-55-7; **13**, 50999-04-7; **13** (diene sulfone), 96556-70-6; (±)-**14**, 96556-56-8; (±)-**14** (triene sulfone), 96556-71-7; (±)-**15**, 96556-57-9; **16**, 96556-58-0; (±)-**17**, 96556-59-1; (±)-18, 96556-60-4; (±)-**19**, 96556-61-5; (±)-**20**, 96556-62-6; (±)-**21a**, 96556-63-7; (±)-**21b**, 96556-64-8; (±)-**22a**, 96556-65-9; (±)-**23b**, 96575-45-0; (±)-**24a**, 96556-66-0; (±)-**25c**, 96556-67-1; (±)-**25d**, 96556-68-2; $PhCH_2Br$, 100-39-0; p-$MeC_6H_4SO_2Na$, 657-84-1; $CH_2{=}CHCH_2Br$, 106-95-6; NO_2Me, 75-52-5.

Supplementary Material Available: Listings of atom and hydrogen atom coordinates, bond distances, bond angles, isotropic and anisotropic thermal parameters for **21b** and **25c** (10 pages). Ordering information is given on any current masthead page.

Hybridization of the Lone Pair Electrons in Carbanions

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Received November 13, 1984

The hybridization of the orbitals for the lone pair electrons of twelve acyclic, monocyclic, and polycyclic bridgehead carbanions has been calculated by the INDO-LMO method. Significant enhancement in s character has been found in methyl and all bridgehead carbanions. For other acyclic and cyclobutyl anions, rehybridization occurs in the opposite direction, presumably, due to the relief of B strain, while cyclopropyl anion retains the hybridization of its conjugate acid. The trend is discussed.

It is generally accepted that the percent s character contributed to the carbon–hydrogen bond by carbon adequately accounts for ranking of carbon acids in the absence of strongly acidifying substituents.[1] The intrinsic idea underlying this relationship is to assume that there is a negligible difference between the carbanion R^- and the carbon acid (RH) in (a) strain, (b) hybridization, and (c) solvation energy. It was, however, found that carbanions might, at most, be weakly solvated.[2] In 1956 Hammond suggested that the unshared pair of electrons in a carbanion should occupy an orbital having a considerable amount of s character.[3] If this were pure s orbital, the "natural" R–C–R bond angle in a carbanion would be 90°. B strain[4] would open this bond angle because of repulsion between the R groups and, thus, would increase the basicity of the anions. This view point has been tested by comparing the kinetic acidity of cubane with that of cyclopropane.[5] Despite the same formal C–H hybridization, cubane is 10^3 times as acidic as cyclopropane. Such an enhancement of acid strength for cubane was proposed to originate from the altered hybridization at the anionic carbon atom to an orbital with significantly enhanced s character.[5] Alternatively, one may argue that the steric environment for the lone pair in cubyl anion would be different from that in cyclopropyl anion.[1c] Ab initio molecular orbital calculations have been performed to show

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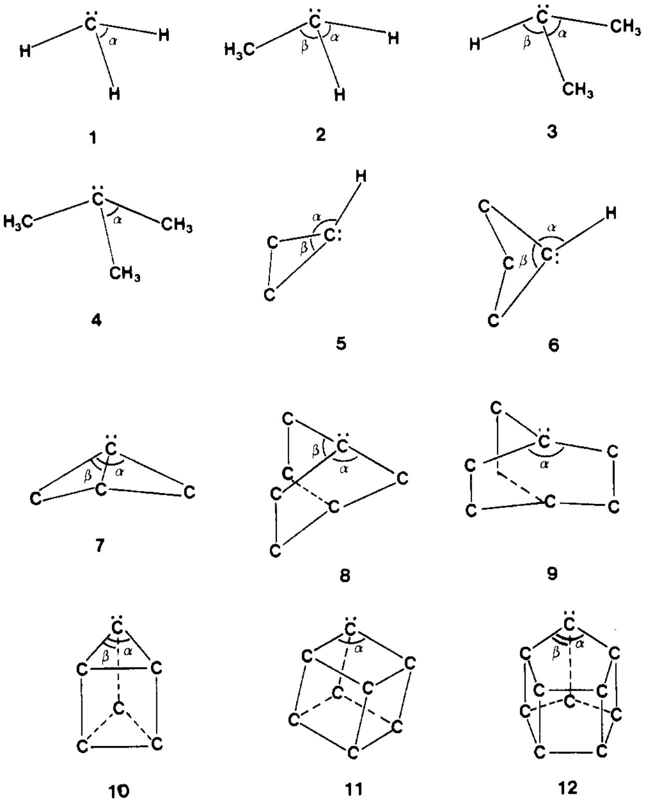

Figure 1. Optimized bond angles at the anionic carbon atoms of some carbanions. **1**, **4**, **9**, and **11** are found to have C_{3v} symmetry, and others C_s symmetry. **1**: $\alpha = 105.3°$. **2**: $\alpha = 110.0°$, $\beta = 118.4°$. **3**: $\alpha = 125.2°$, $\beta = 116.5°$. **4**: $\alpha = 119.6°$. **5**: $\alpha = 126.9°$, $\beta = 61.6°$. **6**: $\alpha = 129.0°$, $\beta = 95.7°$. **7**: $\alpha = 94.6°$, $\beta = 58.4°$. **8**: $\alpha = 96.7°$, $\beta = 103.7°$. **9**: $\alpha = 105.9°$. **10**: $\alpha = 59.6°$, $\beta = 85.5°$. **11**: $\alpha = 87.1°$. **12**: $\alpha = 105°$, $\beta = 88.4°$.

the effect of structural distortion of the acidity of methane[6,7] and ethane.[7,8] Indeed, as *one* bond angle of a tetravalent carbon is reduced, an exocyclic C–H bond gains s character and hence becomes more acidic.[6,8] We now wish to report a localized molecular oribtal (LMO) study on hybridization of the lone-pair orbital in carbanions of widely different geometries.

Calculations. The ground-state geometries of the simple aliphatic, monocyclic, and polycyclic bridgehead carbanions studied (Table I) were fully optimized by the force method (i.e, by the analytical calculation of energy gradients) at the INDO level by using a locally modified GEOMIN program.[9] The MO's obtained were transformed into localized orbitals, LMO's by the technique of Edmiston and Ruedenberg[10] by using the ORBLOC subroutine.[11a] The percent s character of the lone-pair orbital was then calculated from the atomic coefficients c's associated with the anionic carbon by the relation.[11b]

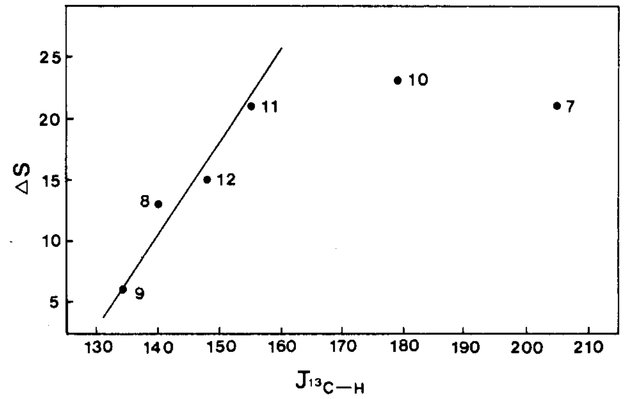

Figure 2. Relationship between the enhanced percent s character, Δs, of bridgehead carbanions and $J_{^{13}\mathrm{C-H}}$ of the corresponding conjugate carbon acids.

$$\%\mathrm{s} = \frac{c(2\mathrm{s})^2}{c(2\mathrm{s})^2 + c(2\mathrm{p}_x)^2 + c(2\mathrm{p}_y)^2 + c(2\mathrm{p}_z)^2} 100\%$$

Results and Discussion

The optimized bond angles at the anionic carbon atoms of the molecular species under investigation are summarized in Figure 1, while their fully optimized geometries are listed in Figure 3 as supplementary material. The calculated hybridizations of unshared pair of electrons for carbanions are compared with the $J_{^{13}\mathrm{C-H}}$ and the percent s character of their respective conjugate carbon acids in Table I. It is noted that methyl anion is definitely pyramidal and its bond angles are reduced from the normal tetrahedral angle to 105.3°. A similar reduction in bond angles at the anionic carbon atom is also found in bridgehead anions **7–12**. Such a reduction in bond angle will enhance the percent s character in the nonbonding orbital in carbanions, as is consistent with our results shown in Table I. In the other acyclic anions, the bond angles at the carbanion center, on the other hand, are larger than the normal tetrahedral angle due to relief of steric strain. Cyclobutyl anion behaves similarly. However, no significant change in geometry has been found for the cyclopropyl anion and this will be discussed later.

It is interesting to note from Table I that among the aliphatic series, the percent s character decreases with increasing number of methyl substituents at the α-carbon. These results are consistent with the Hammond's proposal that B strain may play some roles in the geometry and, thus, the hybridization of carbanions. In other words, such change in percent s character may arise from the steric effect which makes the carbanions more planar along the series with increasing number of methyl substituents (Figure 1). This may not directly imply the relative stability of these carbanions. It is generally believed that carbanions should be more stable the higher the 2s character of the orbital the lone-pair electrons occupy.[1,20]

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Table I. Percent s Character of Carbanions and Their Conjugate Acids

anion	%s(anion)	*J*, (Hz)	%s(C–H)[i]	Δs[j]
1	48	125[a]	25	+23
2	15	124.9[b]	25	−10
3	2	119.2[b]	24	−22
4	1	114.2[b]	23	−22
5	32	161.0[c]	32	0
6	7	134.0[c]	27	−20
7	62	205.0[d]	41	+21
8	41	140.1[e]	28	+13
9	33	134.3[e]	27	+6
10	59	179[f]	36	+23
11	52	155[g]	31	+21
12	45	148[h]	30	+15

[a] Reference 12a. [b] Reference 12b. [c] Reference 13. [d] Reference 14. [e] Reference 15. [f] Reference 16. [g] Reference 17. [h] Reference 18. [i] Calculated by using %s = $J_{^{13}C-H} \times 0.2$, cf., ref 19. [j] Δs = %s(anion) − %s(C–H).

Consequently, a compromise between the steric effect and the electronic configuration of the lone pair of electrons may be necessary to account for the stability of these simple carbanions. Recently, two groups independently reported the relative gas-phase acidities of simple alkanes.[21] They found that the trend of acidities in decreasing order in *t*-Bu–H > Me–H > *i*-Pr–H > Et–H. Such order can *not* simply be explained by the inductive effect. The fact that methane is more acidic than ethane is in agreement with theoretical prediction.[22] Our results are also compatible with this finding. Thus, due to change in percent s character in opposite directions in methyl and ethyl anions, one may predict that the former would be more stable than the latter. The steric strain relief in ethyl anion may not be able to compensate the energy loss due to a decrease in percent s character.

Our calculated results on the hybridization for the lone pair of electrons indicate a decrease in percent s character from Et^- to t-Bu^-. However, it was found that *t*-Bu–H is more acidic than *i*-Pr–H which, in turn is more acidic than Et–H.[21] Relief of steric interaction is apparently more important in carbanions having more substituents. Such effect would be particularly predominant in t-Bu^-, which makes its conjugate acid even more acidic than methane.[21] The importance of strain relief can also be reflected by a comparison of the relative acidity between *i*-Pr–H and Et–H. However, such relief of steric B strain would be at the expense of decreasing percent s character which would increase the energy content of the nonbonding orbital in the carbanion. Consequently, the acidity for CH_3–H which lies between those for *t*-Bu–H and *i*-Pr–H can be understood within this framework, namely, by balancing between steric and electronic factors.

The situation in the cyclobutane case may be similar. A decrease in percent s character (Δs = −20) may result in release of 1,3-nonbonding interactions. In the case of cyclopropane, there is no difference in percent s character in the exocyclic orbital between the anion and its conjugate acid. Shoud the nonbonding orbital in cyclopropyl anion rehybridize to more p character like cyclobutyl anion, the endocyclic bonding orbitals (which form carbon–carbon bonds) would be enriched in s character. This would lead to increase the strain energy of cyclopropyl anion. On the other hand, if the exocyclic orbital in the cyclopropyl anion would rehybridize to more s character, the α-hydrogen would move "backward" which would lead to an increase in strain energy due to increasing nonbonding interactions. It is also noted that the hybridization in an unshared electron pair for cubyl anion is greatly enhanced as shown in Table I. These results seem to be compatible with the early explanation on the acidity of cubane and cyclopropane.[5]

It is noteworthy that significant enhancement in percent s character is found in all bridgehead carbanions (Table I). A plot of Δs for the bridgehead carbanions against $J_{^{13}C-H}$ for the corresponding carbon acids is shown in Figure 2. It is interesting to note that four points for anions **8**, **9**, **11**, and **12** give a straight line ($r = 0.9571$). Such a linear relationship suggests that the hybridization for the nonbonding orbitals in carbanions **8**, **9**, **11**, and **12** is closely related to the hybridization of the exocyclic orbital of the corresponding bridgehead carbon acids. It is interesting to note from Figure 2 that more rehybridization in the bridgehead carbanion occurs for more strained hydrocarbon. Unlike the acyclic anions, it is not possible for bridgehead anions to significantly increase the endocyclic bond angles to release the strain energy. The carbon–carbon bonds in strained organic molecules are usually bent.[1c] Accordingly, rehybridization of the anionic center to an exocyclic orbital with enhanced s character may result in the exocyclic orbitals to acquire greater p character bringing the interorbital angles into better accord with the internuclear angle. However, one may expect that such enhancement may not exceed the value for methyl anion, Δs = 23 which may be the upper limit. Indeed, the Δs value for triprismane anion **10** is 23 and that for bicyclo[1.1.0]butyl anion **7** is 21. It is worth noting that Δs values for both species fall off the line in Figure 2. Moreover, both anions contain a three-membered ring moiety.

It has been suggested that semiempirical MO calculations may not be suitable for anionic species and, thus, the acidity of hydrocarbons.[8,23] Such a remark has been inferred largely from a CNDO/2 calculation on a few cycloalkanes[23a] which predicts the order of their relative potential energy differences to be the reverse of the experimental order of their acidities. However, the validity of this conclusion rests mainly on the ground that formation of carbanions causes negligible rehybridization, as is shown in this work to be questionable. In addition, within groups of closely related compounds, correlations have been found frequently with experimental reactivities.[24] We do not attempt here to set up a quantitative relationship between the acid strength of carbon acids and the hybridization of the corresponding carbanions. Yet we believe that the qualitative trend found is meaningful.

In summary, our results are compatible with Hammond's proposal,[3] and suggest that rehybridization will occur in carbanions in either directions depending on the nature of the substrate. We infer that the stability of carbanions depends on not only s character but also steric B strain. For the bridgehead systems, somewhat en-

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hancement of acid strength for the carbon acids may occur due to the altered hybridization at the anionic carbon atom to an orbital with significantly enhanced s character.

Registry No. 1, 15194-58-8; **2**, 25013-41-6; **3**, 25012-80-0; **4**, 65114-21-8; **5**, 1724-45-4; **6**, 60211-41-8; **7**, 96666-81-8; **8**, 89849-43-4; **9**, 89849-42-3; **10**, 96666-82-9; **11**, 96688-77-6; **12**, 96666-83-0.

Supplementary Material Available: Figure 3, showing the optimized geometries for all carbanions (5 pages). Ordering information is given on any current masthead page.

Theoretical Studies of the Regiospecificity of Diels–Alder Additions to Isoquinolinequinone

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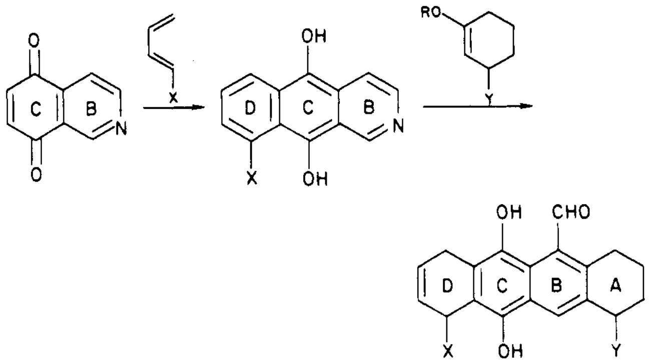
Received October 11, 1984

The MNDO approximation to molecular orbital theory is used to calculate the properties of isoquinolinequinone alone, as well as protonated or complexed with BF_3, at each oxygen or nitrogen. Frontier orbital theory is applied to the calculated species to illustrate how changes in regiospecificity of the Diels–Alder reaction might be anticipated as a function of the site of interaction and nature of the complexing acid. Another test of the regioselectivity was made by using the biradical model for the reaction mechanism. Radical localization energies were calculated by adding a hydrogen atom to each of the neutral and protonated species at each of the two reactive centers. Suggestions are made concerning experimental variables, particularly the choice of the diene and the acidity of the medium, that might be used to control regiospecificity in these reactions.

The Diels–Alder reaction is widely used in synthetic organic chemistry as a method of forming new rings. One of the most important reasons for its widespread use is the high regiospecificity that is often observed for these reactions. Control of this regiospecificity is a determining factor in designing successful synthetic procedure.

Several important theoretical studies of the Diels–Alder reaction have appeared in the literature[1-4]. The question of whether or not the reaction between ethylene and butadiene is synchronous or not has been studied by Dewar[2] and Salem[1] who reached different conclusions based upon potential surfaces calculated by using different MO methods. Theoretical studies of selectivity have more often been restricted to less expensive techniques, such as applications of perturbation theory to the MO's of the interacting molecules.[5,6,3] Frontier orbital theory,[7,8] one of the more sophisticated perturbation techniques, has been previously applied to several examples of the Diels–Alder reaction with success.[6,3,4]

Salts of isoquinolines have recently been shown to be useful synthetic intermediates because their heterocyclic rings serve as dienes in regiospecific Diels–Alder reactions that fuse new carbocyclic rings to the aromatic framework.[9-12] A synthetic plan could use the quinone portion of the subject isoquinolinequinone as a dienophile. Subsequently, the heterocyclic ring could be used as a diene. The outcome of these successive cycloadditions would be the fusion of the outermost A and D rings of naphthacene to the central B and C rings. It is important to control the regiospecificity of these reactions, if they are to be generally useful.



In this paper we present a theoretical study of the regiospecificity of the Diels–Alder reaction for the particular dienophile isoquinolinequinone, 1. This compound differs from 1,4-naphthoquinone only in the substitution of a nitrogen for a carbon at a position remote from the center of dienophilic activity. Compound 1 does not contain a plane of symmetry bisecting the dienophilic bond, but the effect of the nitrogen on this bond should be small. Thus, based purely on frontier orbital arguments, one would not expect a large Diels–Alder selectivity when 1 is used as a

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