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Equilibrium Acidities and Homolytic Bond Dissociation Energies of Acidic C−H Bonds in α-Arylacetophenones and Related Compounds

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The equilibrium acidities (pK_{AH}s) and the oxidation potentials of the congugate anions {$E_{ox}(A^-)$s} were determined in dimethyl sulfoxide (DMSO) for eight ketones of the structure $GCOCH_3$ and 20 of the structure $RCOCH_2G$, (where R = alkyl, phenyl and G = alkyl, aryl). The homolytic bond dissociation energies (BDEs) for the acidic C−H bonds of the ketones were estimated using the equation $BDE_{AH} = 1.37pK_{AH} + 23.1E_{ox}(A^-) + 73.3$. While the equilibrium acidities of $GCOCH_3$ were found to be dependent on the remote substituent G, the BDE values for the C−H bonds remained essentially invariant (93.5 ± 0.5 kcal/mol). A linear correlation between pK_{AH} values and {$E_{ox}(A^-)$s} was found for the ketones. For $RCOCH_2G$ ketones, both pK_{AH} and BDE values for the adjacent C−H bonds are sensitive to the nature of the substituent G. However, the steric bulk of the aryl group tends to exert a leveling effect on BDEs. The BDE of α-9-anthracenylacetophenone is *higher* than that of α-2-anthracenylacetophenone by 3 kcal/mol, reflecting significant steric inhibition of resonance in the 9-substituted system. A range of 80.7−84.4 kcal/mol is observed for $RCOCH_2G$ ketones. The results are discussed in terms of solvation, steric, and resonance effects. Ab initio density functional theory (DFT) calculations are employed to illustrate the effect of steric interactions on radical and anion geometries. The DFT results parallel the trends in the experimental BDEs of α-arylacetophenones.

Introduction

The measurement of pK_{AH}'s of large number of acids together with oxidation potentials for their conjugate anions, using the overlapping indicator method, has provided thermochemical data for large molecules that are not readily accessible to alternate BDE methods for measurement.[1,2a,5] Combination of the pK_{AH} values with the oxidation potentials of the corresponding conjugate anions {$E_{ox}(A^-)$}, measured by cyclic voltammetry, has given new bond strengths for weak C−H, N−H, O−H, and S−H acids as well bonds for organometallic hydrides, M−H (eq 9).[2,5b−d] Equation 9 was derived from the thermochemical cycle shown in eqs 1−8. The constants 1.37 and 23.1 in eq 9 are used to convert the pK_{AH} units and the redox potential units, in volts, into kcal/mol. Equation 8 represents the free energy BDE $_G$ values.

$$A{-}H(sol) \rightarrow A^-(sol) + H^+(sol) \quad 2.3RTpK_{AH} \qquad (1)$$

$$A^-(sol) \rightarrow A^\bullet(sol) + e^- \quad E_{ox}(A^-) \qquad (2)$$

$$H^+(sol) \rightarrow H^+(aq) \quad -\Delta G^\circ_{tr}(H^+) \qquad (3)$$

$$H^+(aq) + e^- \rightarrow {}^1/_2H_2(g) \quad \Delta G^\circ = 0 \qquad (4)$$

$${}^1/_2H_2(g) \rightarrow H^\bullet(g) \quad \Delta G^\circ_f(H^\bullet)g \qquad (5)$$

$$H^\bullet(g) \rightarrow H^\bullet(sol) \quad \Delta G^\circ_{sol}(H^\bullet) \qquad (6)$$

$$A{-}H \rightarrow A^\bullet + H^\bullet \quad BDE_{AH} \qquad (7)$$

$$BDE_{AH(G)} = 2.3RTpK_{AH} + E_{ox}(A^-) - \Delta G^\circ_{tr}(H^+) + \Delta G^\circ_f(H^\bullet)g + \Delta G^\circ_{sol}(H^\bullet) \qquad (8)$$

$$BDE_{AH} = 1.37pK_{AH} + 23.1E_{ox}(A^-) + C \qquad (9)$$

The term $\Delta G^\circ_{tr}(H^+)$ is the free energy of transfer of the proton from water to DMSO (−4.8 kcal/mol, an average of two values, −4.5[6a] and −5.0[6b] kcal/mol), $\Delta G^\circ_f(H^\bullet)_g$ is the free energy of formation of the hydrogen atom taken as 48.6 kcal/mol,[6c] and $\Delta G^\circ_{sol}(H^\bullet)$ is the free energy of solvation of the hydrogen atom (−5.7 kcal/mol[6d]), assumed to be the same as that of the hydrogen molecule. $\Delta G^\circ_{sol}(AH)$ and $\Delta G^\circ_{sol}(A^\bullet)$ in the equilibrium, $AH \rightleftarrows A^\bullet +$

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TABLE 1. Comparison of Bond Dissociation Energies (BDEs) Obtained Form Eq 11 with Literature Values for Various Systems

entry	compd	$\mathrm{p}K_{\mathrm{HA}}$[a]	$E_{\mathrm{ox}}(\mathrm{A}^-)$[b]	BDE[c] (kcal/mol)	BDE (lit.)[d] (kcal/mol)
1	acetone	26.5	−0.674	94	92[e]
2	diphenylamine	24.95	−0.865	87.5	87.3
3	hydrazoic acid	7.90	0.415	93.7	92
4	thiophenol	10.3	−0.360	79	78.5
5	fluorene	22.6	−1.069	79.6	80.1
6	2,3-benzofluorene	23.1	−1.164	78	78.8
7	1,3-cyclopentadiene	18.0	−0.778	80	81.2
8	diphenymethane	32.2	−1.540	81.8	81.4
9	9,10-dihydroanthracene	30.1	−1.575	78	76
10	9-methylanthracene	31.1	−1.489	81.5	81.8

[a] Acidity costants were measured in DMSO using the overlapping indicator titration method previously described.[2,5a−d,12] [b] Irreversible oxidation potentials[12a,b] were measured by cyclic voltammetry and referenced to the ferrocene-ferrocenium couple (Fc/Fc$^+$), $E_{1/2}$ is 0.875 V vs Ag/AgI in DMSO. [c] BDE values were estimated using eq 11. [d] BDE values were obtained from ref 2a unless otherwise indicated. [e] See ref 13.

H$^\bullet$ are assumed to be equal for large organic molecules. To compare the free energy ($\Delta G°$) BDE values (eq 8) with $\Delta H°$ BDE values, an entropy term for the formation of the hydrogen atom, $T\Delta S°$, must be included. It is assumed that the entropy for $(\mathrm{A{-}H})_\mathrm{g}$ is equal to that of $(\mathrm{A}^\bullet)_\mathrm{g}$ and that $\Delta S° \simeq S°(\mathrm{H}^\bullet)_\mathrm{g} = 27.4$ eu.[6c,e] The total $T\Delta S°$ contribution to BDE, therefore, is 8.2 kcal/mol. Combining the values of terms in eq 8 provides eq 10 with a value of *56* kcal/mol for constant (*C*) when the oxidation potentials of the conjugate anions $\{E_{\mathrm{ox}}(\mathrm{A}^-)\mathrm{s}\}$ are measured versus the standard hydrogen electrode (SHE).[4b]

$$\mathrm{BDE}_{\mathrm{AH}} = 1.37\mathrm{p}K_{\mathrm{AH}} + 23.1E_{\mathrm{ox}}(\mathrm{A}^-) + 56 \quad (10)$$

In 1989, Tilset and Parker obtained a similar value for *C* in different solvents by referencing the $\{E_{\mathrm{ox}}(\mathrm{A}^-)\mathrm{s}\}$ to the ferrocene−ferrocenium couple ($\mathrm{F_C/F_C}^+$).[2b] The simplicity and advantages of the method, prompted Bordwell et al.[2a] to modify eq 10 by obtaining the oxidation potentials of the anions in DMSO and using ($\mathrm{F_C/F_C}^+$) as the reference for their measurements. With this modification, a value of 17.3 is added to 56 providing a new constant *C* with a value of 73.3 (eq 11).[5b−d] It should be noted that the BDE values estimated by eq 11 are derived gas-phase values and not DMSO solution BDE values.

$$\mathrm{BDE}_{\mathrm{AH}} = 1.37\mathrm{p}K_{\mathrm{AH}} + 23.1E_{\mathrm{ox}}(\mathrm{A}^-) + 73.3 \quad (11)$$

The oxidation potentials of the anions measured in this and previous studies were obtained by conventional cyclic voltammetry and are typically irreversible. However, the BDE values estimated by using eq 11 have proven to be reproducible,[4,5b−c] indicating that the onset of the irreversible cyclic voltammetry wave is an excellent approximation to the reversible wave potential. Bordwell et al.[2a] have demonstrated the applicability of this method by providing BDEs of various weak acids that are in good agreement, within ±2 kcal/mol, with the best available gas-phase literature BDE values (Table 1).[2a] The agreement between the literature BDE values and the estimated BDEs of various acids using eq 11 is remarkable; considering the empirical nature of our estimation. The reliability and the efficacy of the electrochemical method employed in this study are well established.[5b−d,7] Furthermore, Bausch and Gostowski[4a] have also shown that the irreversible oxidation potentials of nitranions (scan rate 0.1 V/s) are in good agreement (10−30 mV) with oxidation potentials obtained by high-speed cyclic voltammetry (10 000 V/s). Bordwell et al.[7g] have demonstrated for a series of carbanions that peak potentials determined by conventional cyclic voltammetry agree remarkable well (50 mV, 1.2 kcal/mol) with peak potentials determined by fast-scan cyclic voltammetry. The small shifts in oxidation potentials for changing the scan rate from 0.01 to 0.50 V/s for a series of fluorenide ions exhibiting irreversible as well as reversible potentials are in the range of 8−59 mV (0.18−1.36 kca/mol),[14a] indicating that changing the scan rate has little effect on peak potentials. In addition, Saveant[7a,b] demonstrated

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(3) The irreversible oxidation potentials of the conjugate anions measured by the conventional cyclic voltammetry (scan rate is 0.1 V/s) were found to be within ±50 mV (1.16 kcal/mol) of the corresponding reversible oxidation potentials measured by the high-speed cyclic voltammetry (scan rate is 10 000 V/s).[4]

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in acetonitrile that the uncertainty caused by voltage sweep and substrate concentration is no more than 30 mV (0.7 kcal/mol) for a series of thiophenoxide ions. The reported oxidation potentials for the thiophenoxide ions were referenced to SCE.[7a] The results showed that peak potentials for the p-OMe, p-Me, H, Cl, and NO_2 derivatives are −0.035, 0.04, 0.1, 0.18, and 0.455 V, respectively.[7a] These values are slightly higher, 0.088 (±0.022 V), than the peak potentials obtained in DMSO (−0.143, −0.06, 0.005, 0.07, 0.39, respectively, when referenced to SCE).[7h] Clearly, the results are in excellent agreement. The small deviation is attributed to solvation effects of DMSO vs acetonitrile. Solvation or chelating effects have shown to affect the shift in peak potentials of anions.[8d]

In earlier papers, the BDE values of the acidic C−H bonds in acetophenone and acetone were estimated to be 93 and 94 kcal/mol, respectively.[5c,7c] Introduction of an acceptor group such as CN, SO_2Ph, or $^{+}NMe_3$ into the α-position of acetophenone significantly decreases the pK_{AH} values but has negligible effects on the bond strength of the acidic C−H bond.[7c−f] However, the introduction of SR, OR, and NR_2 as donor groups produced small effects on the pK_{AH} values, but greatly decreased the BDEs for the corresponding acids.[5b,c,8a,b] In the present paper, we extend the studies to include $GCOCH_3$ and $PhCOCH_2G$ structural categories of ketones, where G is alkyl, phenyl, or aryl. We also examine the effects of substituents G interacting as a remote ($GCOCH_2^{\bullet}$) or direct ($PhCOCH^{\bullet}G$) substituent at radical centers as well as the effects of ring strain and steric interaction on pK_{AH} and BDE values.

Results and Discussion

Equilibrium Acidities and Homolytic Bond Dissociation Energies of the Acidic C−H Bonds in $GCOCH_3$ Type Ketones. The pK_{AH} values of CH_3COCH_3, t-$BuCOCH_3$, $PhCOCH_3$, p-$CNC_6H_4COCH_3$, p-$MeOC_6H_4COCH_3$, 2,4,6-$Me_3C_6H_2COCH_3$, 1-$NaphCOCH_3$, and 9-$AnthCOCH_3$ together with the oxidation potentials of their conjugate anions were measured in DMSO and are summarized in Table 2. The BDE values of the acidic C−H bonds for the same ketones were estimated using eq 11 are also summarized in Table 2.

TABLE 2. Equilibrium Acidities and Homolytic Bond Dissociation Energies in DMSO for the Acidic C−H Bonds in $GCOCH_3$ Ketones.

entry	ketone	pK_{HA}[a]	$E_{ox}(A^-)$[b]	BDE[c]
1	CH_3COCH_3	26.5	−0.690	93.7
2	t-$BuCOCH_3$	27.7	−0.753	93.9
3	$PhCOCH_3$	24.7	−0.600	93.3
4	4-$CNPhCOCH_3$	22.0	−0.436	93.4
5	4-$MeOPhCOCH_3$	25.7	−0.658	93.3
6	$(CH_3)_3C_6H_2COCH_3$	24.8	−0.583	93.8
7	1-naphthyl-$COCH_3$	23.7	−0.505	94
8	9-anthracenyl-$COCH_3$	22.5	−0.435	94

[a,b] See footnotes a and b in Table 1. [c] BDE values were estimated using eq 11 and are relative to the BDE value of methane (105[5a]).

Entries 1 and 2 reveal that a decrease in acidity of 1.2 pK_{AH} units (1.6 kcal/mol) results from substitution of a methyl group in acetone with a *tert*-butyl group. This decrease was attributed to the increase of steric inhibition of solvation in the conjugated anion since the difference in inductive effect, σ_I, of *tert*-butyl and methyl is only −0.02,[8c] too small to account for the decrease in acidity between methyl-*tert*-butyl ketone and acetone. However, the increase in pK_{AH} by 1.8 units[9] (2.5 kcal/mol) of the C−H bond as the result of replacing of a methyl group with a phenyl (entry 3) is likely to be primarily due to the inductive effect of the phenyl group.[8c]

Examination of Table 2 also shows that the replacement of one of the methyl groups in acetone by a naphthyl or an anthracenyl group (entries 7 and 8) increases the equilibrium acidity by 2.7 and 4.0 pK_{AH} units, respectively. The much larger acidifying effects for these aryl groups compared to that of the phenyl could not arise from the difference in inductive effects of the naphthyl and anthracenyl moieties. The σ_I of 1-naphthyl and 2-naphthyl groups were determined to be 0.14 and 0.13, respectively.[10,11a−c] The σ_I value of the phenyl group lies in the range of 0.10 to 0.15.[8c,11a,c] The strong steric interaction of the 9-anthracenyl system due to the *peri*-hydrogen atoms[11d,c] should decrease the acidities of the C−H bonds when compared with the phenyl analogue. However, the results in Table 2 indicate that the acidities are increased for the naphthyl and anthracenyl groups. Therefore, the increase in acidities is presumably caused by the stronger polarizability effects of both the naphthyl and anthracenyl rings compared to that of the phenyl ring. The polarizability effects must be large enough to overshadow the weakening of solvation and the steric inhibition introduced on the conjugate anions. Polarization effects introduced by various systems are known to have a remarkable influence on the equilibrium acidities,[12] but no or negligible effects on the homolytic bond dissociation energies.[12b,c]

The equilibrium acidities of $GCOCH_3$ ketones shown in Table 2 cover a range of 5.2 pK_{AH} units (7.1 kcal/mol) as a consequence of inductive and polarization effects. However, the BDE values of the acidic C−H bonds remain essentially constant, ranging between 93.3 and 94 kcal/mol. These results are in good agreement with a recently reported BDE value of 92 (±1.5 kcal/mol) for acetone.[13] Our results clearly show that remote electron donating and electron accepting groups in $GCOCH_3$ ketones influence acidity, but have no effect on BDE values of the corresponding C−H bonds. The changes in acidities of the ketones are offset in eq 11 by correspond-

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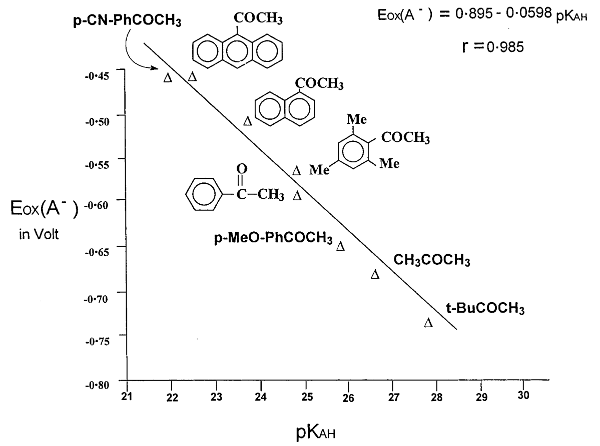

FIGURE 1. . Correlation of the oxidation potentials $\{E_{ox}(A^-)\}$ with the acidity (pK_{AH}) of C−H bonds in $GCOCH_3$ ketones.

TABLE 3. Equilibrium Acidities and Homolytic Bond Dissociation Energies in DMSO for the Acidic C−H Bonds of α-Substituted Acetones and Acetophenones

entry	ketone	pK_{HA}[a]	$E_{ox}(A^-)$[b]	BDE[c]	ΔBDE[d] (RSE)
1	CH_3COCH_3	26.5	−0.690	93.7[e]	(0.0)
2	$C_2H_5COCH_2CH_3$	27.1	−0.953	88.4	5.3[f]
3	CH_3COCH_2Ph	19.8	−0.753	83	10.7[f]
4	$CH_3COCHPh_2$	19.4	−0.770	82.2	11.5[f]
5	$PhCOCH_3$	24.7	−0.600	93.3[g]	(0.0)
6	$PhCOCH_2CH_3$	24.4	−0.815	88	5.3[h]
7	$PhCOCH_2Ph$	17.7	−0.645	82.7	10.6[h]
8	$PhCOCHPh_2$	18.7	−0.690	83	10.3[h]

[a−c] See footnotes a−c, respectively, in Table 2. [d] ΔBDEs are defined as radical stabilization energies (RSEs). [e] The RSE for acetone relative to that of methane is 11.3 kcal/mol (105−93.7). [f] Relative to that of CH_3COCH_3. [g] The RSE (ΔBDE) for acetophenone relative to that of methane is 11.7 kcal/mol (105−93.3). [h] Relative to that of $PhCOCH_3$.

ing shifts of $E_{ox}(A^-)$ values; resulting in no *net* change in BDE values. Furthermore, the equilibrium acidities were found to be linearly correlated with the oxidation potentials of the corresponding conjugated anions as shown in Figure 1.

Para-substituted acetophenones (entries 4−6 of Table 2) are also included in Figure 1 to demonstrate the generality of this correlation. Estimation of the pK_{AH} values of acids is a very laborious process. With this correlation, the pK_{AH} of the acidic C−H bonds in the ketone series presented above can now be easily estimated with accuracy; pending the availability of the more conveniently determined oxidation potentials of the conjugate anions. Plots with high correlation coefficients ($r \geq 0.98$) similar to that of Figure 1 have been observed in nine other studies where remote substituents causing the basicity changes have little or no stabilizing or destabilizing effects on the radicals being formed.[7c−f,12b,14]

Equilibrium Acidities and Homolytic Bond Dissociation Energies for the Acidic C−H Bonds in α-Substituted Acetones and Acetophenones. The pK_{AH} values of α-substituted acetones and acetophenones and the oxidation potentials of the conjugate anions together with the BDE values and the radical stabilization energies (RSEs) values are shown in Table 3.

Introduction of a phenyl group into the α-position of acetone and acetophenone increases the equilibrium acidities by 6.7 and 7.0 pK_{AH} units and lowers the BDE values by 10.7 and 10.6 kcal/mol, respectively (entries: 1, 3, 5, and 7). The C−H bond stabilization by the α-phenyl group of α-phenylacetophenone systems is comparable in magnitude to that of arylmethyl radicals[15a] and is attributed to the delocalization of the unpaired electron of the radical into the aromatic ring. Interestingly, Table 3 shows that lowering the BDE values of the acidic C−H bonds in α-phenylacetone and α-phenylacetophenone was largely due to the increase in acidities rather than the changes in the oxidation potentials of the anions.[15b] The introduction of the second phenyl group into the α-position of phenylacetone or phenylacetophenone (entries 4 and 8) produced no change in BDE values, primarily due to the saturation (leveling) and steric effects.[15a] The smaller stabilizing effects of the second phenyl are associated with the prevention of the delocalization of radicals and carbanions into the twisted phenyl ring.

TABLE 4. Equilibrium Acidities and Homolytic Bond Dissociation Energies in DMSO for the Acidic C−H Bonds in α-Arylacetophenones and Related Compounds

entry	ketone	pK_{HA}[a]	$E_{ox}(A^-)$[b]	BDE[c]	ΔBDE[d] (RSE)
1	$PhCOCH_3$	24.7	−0.600	93.3[e]	(0.0)
2	$PhCOCH_2Ph$	17.7	−0.645	82.6	10.7
3	$PhCOCH_2Anth(2)$	16.4	−0.614	81.6	11.7
4	$PhCOCH_2Py(1)$	15.7	−0.610	80.7	12.6
5	$PhCOCH_2Phen(2)$	17.0	−0.580	83.2	10.1
6	$PhCOCH_2Phen(3)$	17.1	−0.582	83.3	10
7	$PhCOCH_2Phen(9)$	17.7	−0.590	83.9	9.4
8	$PhCOCH_2C_5H_4N$	14.6	−0.330	85.7	7.6
9	$PhCOCH_2Ph[Cr(CO)_3]$	13.9	−0.377	83.6	9.7
10	$PhCOCH_2Anth(9)$	18.9	−0.640	84.4	8.9
11	$PhCOCH_2Naphth(1)$	17.6	−0.626	83	10.3
12	$PhCOCH_2Naphth(2)$	17.1	−0.607	82.7	10.6
13	1-acenaphthenone	17.0	−0.620	82.3	11
14	2-aceanthrenone	17.1	−0.721	80	13.3
15	1-aceanthrenone	17.9	−0.665	82.5	10.8

[a−c] See footnotes a−c, respectively, in Table 3. [d] ΔBDEs are defined as radical stabilization energies (RSE), relative to that of $PhCOCH_3$. [e] The RSE (ΔBDE) for acetophenone relative to that of methane is 11.7 kcal/mol (105−93.3).

Equilibrium Acidities and Homolytic Bond Dissociation Energies for the Acidic C−H Bonds in $RCOH_2G$ and Related Compounds. The conjugated anions derived from $RCOCH_2G$ are stable in color, indicating that these ketones are good indicators for our pK_{AH} measurements. Therefore, the equilibrium acidities (pK_{AH}'s) were usually determined using standard acids. The (pK_{AH}'s) of $RCOCH_2G$ ketones together with the oxidation potentials of their conjugate anions are summarized in Table 4. The BDE values estimated by using eq 11 and the radical stabilization energies (RSEs) are also included.

Examination of the entries 2−4 in Table 4 shows that the pK_{AH} values of $PhCOCH_2Ar$ are progressively decreased (17.7, 16.4, and 15.78, respectively). The change in the corresponding BDE values are as follows: 82.7, 81.6, and 80.7 kcal/mol, respectively. The progressive increase in the acidity and the slight decrease in BDE values are indicative of the delocalization of the anions

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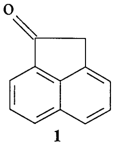
(15) (a) Herndon, W. C. *J. Org. Chem.* **1981**, *46*, 2119. (b) Bordwell, F. G.; Zhang, X.-M.; Filler, R. J. *J. Org. Chem.* **1993**, *58*, 6067.

and radicals into phenyl, 2-anthracenyl, and 1-pyrenyl rings. Herndon[15a] predicted similar trends for the resonance energy relationship using the empirical valence-bond method. The phenanthrene series in entries 5−7 shows that the pK_{AH} value for the acidic C−H bond in α-(9-phenanthrenyl)acetophenone is higher than those of the 2- and 3-phenanthrenyl analogues. The BDE values for the three systems remain within the experimental error, however.

The introduction of pyridyl group (entry 8) at the α-position of acetophenone lowers the acidity by 3.1 units (entries 2 and 8). Since the solvation energy of the conjugate anions of the phenyl and pyridyl systems is expected to be similar, lowering the pK_{AH} of the α-pyridylacetophenone is attributed to the inductive effect of the pyridyl moieties (σ_I ranges from 0.21 to 0.40).[11a] On the other hand, the BDE value for the C−H bond is increased by 3 kcal/mol as the result of the presence of nitrogen atom. It should be noted that nitrogen substituents have been shown to have stabilizing as well as destabilizing effects on carbon-centered radicals.[5b−d,12b,c] The chromium tricarbonyl complexes strongly influence the pK_{AH}, but not the BDE of the adjacent C−H bonds (entry 9). The formation of Cr(CO$_3$) complex with the α-phenyl ring of α-phenylacetophenone causes an increase in the acidity of the adjacent C−H bond by 3.9 pK_{AH} units by virtue of the electron withdrawing ability of Cr(CO$_3$). This increase in acidity is offset by a shift of $E_{OX}(A^-)$ to a less negative potential, providing a bond strength similar to that of α-substituted phenylacetophenone. Similar observations were reported for a series of fluorene−transition metal complexes where the C−H bond in fluorene ligands were unaffected by π-coordination.[16]

Finally, the α-naphthyl and α-anthracenyl systems in acetophenone were examined to study the effect of steric interactions on the anion radical centers. Entry 10 of Table 4 shows that the anthracenyl moiety is destabilizing toward the corresponding anion as well as the neutral radical by virtue of decreasing the coplanarity of the radical with the aromatic ring. A similar interaction, but to a lesser extent, is expected for the 1-naphthyl substituent, and DFT calculations suggest very little deviation from planarity (vide infra). Indeed, experimental results show that the acidity and the BDE values of the C−H bond in α-phenylacetophenone are essentially the same as that of α-(1-naphthyl)acetophenone (entries 2 and 11).

The leveling effects on BDEs of the aryl substituents studies provide valuable indication of the importance of the steric hindrance. The distortion of the coplanarity prevents the delocalization of the incipient radical into the aromatic system. 1-Acenaphthenone (**1**) and 2-aceathrenone (**2**), entries 13 and 14 respectively) were used as model compounds to measure the strength of the corresponding benzylic C−H bonds in the absence of the steric inhibition.



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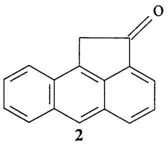

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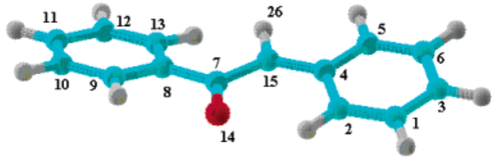

FIGURE 2. B3LYP/6-31G(d) structure of anion (shown) and radical (not shown) **1**. The anionic carbon, C15, deviates only slightly from planarity with the carbonyl and adjacent phenyl ring: The dihedral angles are: D(C5−C4−C15−H26) = −0.6°, D(C4−C15−C7−O14) = 5.0°, and D(O14−C7−C8−C9) = 16.7°. For the radical, the planarity of the radical center, C15, in relation to the adjacent phenyl ring and the carbonyl is essentially identical to the anion: D(C5−C4−C15−H26) = −1.4°, D(C4−C15−C7−O14) = 1.6°, and D(O14−C7−C8−C9) = 15.8°.

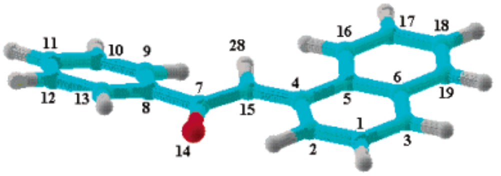

FIGURE 3. B3LYP/6-31G(d) structure of anion (shown) from α-1-naphthylacetophenone exhibits D(C5−C4−C15−H28) = −4.0°, D(C4−C15−C7−O14) = 1.6°, and D(C13−C8−C7−O14) = 17.9°. The radical (not shown) exhibits D(C5−C4−C15−H28) = −0.2°, D(C4−C15−C7−O14) = 6.5°, and D(C13−C8−C7−O14) =19.0°.

Entries 11, 13 and 10, 14 show that the BDE values for the C−H bonds in 1-acenaphenone and 2-aceanthrenone are lower than that of α-(1-naphthyl) acetophenone and α-(9-anthracenyl)acetophenone by 0.7 and 4.2 kcal/mol, respectively, as the result of better delocalization of the corresponding radicals into the aromatic rings.

For comparison with our experimetal results, ab initio density functional theory calculations[17] at the B3LYP/6-311+G(d,p)//B3LYP/6-31G(d) were carried out to obtain the strength of the C−H bonds of the α-arylacetophenones and related systems and to investigate the deviation from planarity of large aryl substituents. Both the radical and the anion formed from α-phenylacetophenone are essentially planar; resulting in spin density delocalized into the carbonyl and phenyl ring π-systems, Figure 2.

The radical and anion formed from α-1-naphthylacetophenone depicted in Figure 3 show that both the radical and anion are very nearly planar, suggesting that charge and spin delocalization into the carbonyl and naphthyl π-systems are not significantly effected by steric interactions.

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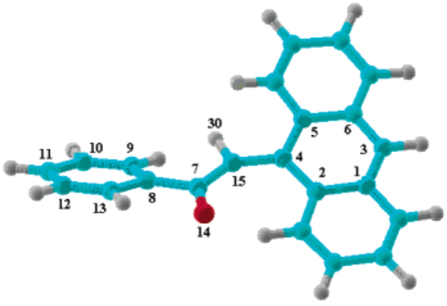


FIGURE 4. B3LYP/6-31G(d) structure of anion (shown) formed from α-9-anthracenylacetophenone. The dihedral angles are: D(C5−C4−C15−H30) = 19.4°, D(C4−C15−C7−O14) = 5.2°, and D(O14−C7−C8−C13) = 21.5°. The corresponding dihedral angles for the radical are: D(C5−C4−C15−H30) = 15.8°, D(C4−C15−C7−O14) = 8.2°, and D(O14−C7−C8−C13) = 21.3°.

TABLE 5. Bond Dissociation Energies from Isodesmic Calculations[a]

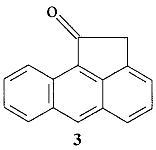
entry	ketone	BDE, expt (kcal/mol)	BDE, calcd (kcal/mol)
1	$PhCOCH_2Ph$	82.7	82.7
2	$PhCOCH_2$-1-Naph	83	81.5
3	$PhCOCH_2$-9-Anth	84.4	84.6
4	2-aceathrenone	80	82.0
5	1-aceathrenone	82.3	86.1

[a] Single-point B3LYP/6-311+G(d,p) calculations using B3LYP/6-31G(d) geometries are combined with thermal enthalpy corrections, using $PhCOCH_2Ph$ as the reference, 82.7 kcal/mol.

By contrast, the anion and radical formed from α-9-anthracenylacetophenone exhibit greater deviations from planarity than 1-naphthyl and phenyl analogues. Figure 4 depicts the structure of the anion.

Steric bulk introduced by the 9-anthracenyl group has been observed in a variety of studies.[11d,e] and is demonstrated in the present DFT calculations. Results of the net effects of steric interaction on radical stability of a series of the ketones studied are shown in Table 5. The DFT calculations parallel the experimental BDE values and show that steric effects are not extended in the 1-naphthyl case. However, a stronger C−H bond is observed in the case of 9-anthracenylacetophnone (entries 1−3).

The calculations predict a somewhat larger spread in BDE values for the more complex systems, 2-aceanthrenone (**2**) and 1-aceanthrenone (**3**), (enties 4 and 5), but reproduce the ordering of the increase.



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Conclusions

This work has shown that remote substituents in $GCOCH_3$ ketones have little or no influence on the strength of C−H bond dissociation energies (BDEs). However, solvation or inductive effect contributes significantly toward the pK_{AH} of the acids. The equilibrium acidities of $GCOCH_3$ ketones were found to correlate linearly with the oxidation potentials of the corresponding conjugate anions. Direct substituents in $PhCOCH_2G$ ketones have a major effect on both BDEs and acidity constants for C−H bonds, indicating delocalization of charge and spin density of the anions and radicals into G substituents. Other effects, such as polarization and steric effects enabled by large aromatic systems, must also be considered to understand the large variation in pK_{AH}'s and BDEs of the systems investigated. Furthermore, the significance of the presnt results is that, for systems with appreciable steric inhibition, the local steric effects may significatly attenuate resonance stabilization of radical centers. As a result of such attenuation, the cleavage of C−H and C−C bonds attached to large ploynuclear aromatic systems will not be enhanced over simple aromatic moieties. In such cases, the simple resonance theories will thus fail to describe the reactivity of alkyl aromatic systems in pyrolytic radical formation.

TABLE 6. Equilibrium Acidities of Ketones in DMSO Solution Determined by the Overlapping Indicator Method[a]

entry	ketone	pK_{HA}[b]	HIn[c]	pK_{HIn}[d]	avg SDV[e]
1	$(CH_3)_3C_6H_2COCH_3$	24.8	TP2H[f]	25.6	0.012
			TNT[g]	24.3	0.019
2	1-naphthyl-$COCH_3$	23.7	MFH[h]	22.35	0.027
3	9-anthracenyl-$COCH_3$	22.5	BBPS[i]	21.47	0.024
			DBS[j]	23.93	0.006
4	$PhCOCH_2Ph$	17.7	PFH[k]	17.9	0.014
5	$PhCOCH_2$Naphth(1)	17.6	FMY30[l]	18.1	0.032
			CANH[m]	18.9	0.017
6	$PhCOCH_2$Naphth(2)	17.1	PFH[k]	17.9	0.021
			FMY30[l]	18.1	0.009
7	$PhCOCH_2$Anth(2)	16.4	BSFH[n]	15.9	0.020
			PSFH[o]	15.4	0.042
8	$PhCOCH_2$Anth(9)	18.9	CBPS[p]	18.52	0.015
			PSC[q]	18.8	0.009
9	$PhCOCH_2$Py(1)	15.7	BSFH[n]	15.91	0.003
			PSFH[o]	15.4	0.028
10	$PhCOCH_2$Phen(2)	17.0	PFH[k]	17.9	0.026
			FMY30[l]	18.1	0.039
11	$PhCOCH_2$Phen(3)	17.1	PFH[k]	17.9	0.060
			FMY30[l]	18.1	0.002
12	$PhCOCH_2$Phen(9)	17.7	PFH[k]	17.9	0.030
			CNAH[m]	18.8	0.040
13	1-acenaphthenone	17.0	BSFH[n]	15.9	0.040
14	2-aceanthrenone	17.1	CBPS[p]	18.52	0.030
			Ph_2CHCN[r]	17.5	0.050
15	1-aceanthrenone	17.9	CBPS[p]	18.5	0.050
			Ph_2CHCN[r]	17.5	0.002
16	$PhCOCH_2C_5H_4N$	14.6	HZFP2[s]	12.95	0.016
			HZF[t]	14.95	0.012
17	$PhCOCH_2Ph[Cr(CO)_3]$	13.9	HZFO2[u]	12.95	0.015

[a] Acidity constants were measured in DMSO using the overlapping indicator titration method previously described.[2,5a−d] [b] The pK_{HA} values are an average of two or more runs. [c,d] Indicators and their pK_{Hin} values, respectively. [e] Average standard deviation. [f] 1,3,3-Triphenylpropene. [g] 1,1,3-Triphenyl-2-aza-1-propene. [h] 9-Methylfluorene. [i] 3-Bromobenzylphenyl sulfone. [j] Dibenzyl sulfone. [k] 9-Phenylfluorene. [l] 2-(Phenylsulfonyl)fluorene. [m] 4-Chloro-2-nitroaniline. [n] 9-*tert*-Butylthiofluorene. [o] 9-Phenylthiofluorene. [p] 4-Cyanobenzyl phenyl sulfone. [q] 1-Phenylthioacetone. [r] Diphenylacetonitrile. [s] 9-Fluorenone-4-chlorophenylhadrazone. [t] 9-Fluorenone phenylhydrazone. [u] 9-Fluorene-2-chlorophenylhydrazone.

Experimental Section

General Methods. The ketones and precursors were prepared and characterized according to the literature procedures.[16,18–25] The alcohols were oxidized to the corresponding ketones using pyridinium chlorochromate[22] or Dess–Martin[23] reagent with the latter being used with poly aromatic systems. Melting points were determined on an Electrothermal melting point apparatus and agreed with the reported values. The desired ketones were further identified using NMR spectroscopy and gas–liquid chromatography.

Equilibrium Acidities. The equilibrium acidities of the ketones were determined by the overlapping indicator method.[12] The results, together with the standard acids or indicator used are summarized in Table 6.

Oxidation Potentials. The oxidation potentials of the anions derived from these ketones were determined in dimethyl sulfoxide (DMSO) solution using the three-electrode Bioanalytical System Inc. (BAS) apparatus as described previously.[2a,14a] All experiments were conducted in glass cells. Sublimed tetraethylammonium tetrafluoroborate ($Et_4N^+BF_4^-$) was used as the supporting electrolyte. Anhydrous DMSO was used as the solvent. The purification of DMSO and the synthesis of potassium dimsylate was carried out as described previously.[12] The working electrode consisted of a 1.5 mm diameter platinum disk embedded in a cobalt glass seal. The electrode was polished with 0.05 μm Fisher polishing aluminum or cleaned with ultrasonic instrument, rinsed with ethanol, and dried before each run. The counter (auxiliary) electrode was a platinum wire, and a Ag/AgI electrode was used as the reference electrode. However, the oxidation potentials reported here were referenced to the ferrocene/ferrocenium couple.[2a,12]

In a typical run, about 5–7 mg of the desired acid was added to a glass cell fitted with three-way stopcock.[12d] The cell was evacuated and purged with argon. About 6–8 mL of DMSO (0.1 M in $Et_4N^+BF_4^-$) was then added to the cell via airtight syringe generating about 1–3 mM solution. The cell contents were syringed into the CV apparatus blanketed with argon. Dimsyl anion was then added dropwise to the solution via airtight syringe, providing a 1 mM solution of the desired anion, with continuous stirring and argon bubbling for maximum mixing.

Voltammograms were recorded at sweep rate of 0.1 V/s using a BAS CV 27 voltammeter. An $E_{1/2}$ of 0.875 V was observed for F_c/F_c^+ using Ag/AgI in DMSO as the reference electrode.

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Note Added after ASAP Posting. The Supporting Information paragraph was missing in the version posted November 16, 2002. The correct version was posted on December 6, 2002.

Supporting Information Available: Cartesian coordinates and energies for structures discussed in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

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