Radical Stabilization Energies and Synergistic (Captodative) Effects

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Abstract: Radical stabilization energies (RSEs) have been estimated for 9-RR'N-fluorenyl radicals, relative to the fluorenyl radical, by combining their ΔpK_{HA} values with the oxidation potentials of their conjugate bases, $\Delta E_{ox}(A^-)$. The RSEs for 9-RNH-fluorenyl radicals, with R = H, Bu, or $PhCH_2$, and for the 9-azetidinylfluorenyl radical (13-15 kcal/mol) are all appreciably larger than those for the corresponding 9-$RNCH_3$-fluorenyl radicals (7-8 kcal/mol). The RSEs for α-amino, α-(dimethylamino)-, and α-piperidinylacetophenonyl radicals, relative to the acetophenonyl radical, are all ~21 kcal/mol; α-methoxy- and α-ethoxyacetophenonyl radicals have smaller RSEs (13 kcal/mol). α-Amino- and α-(dimethylamino)malononitrilyl radicals have RSEs, relative to the malononitrilyl radical, of 16 kcal/mol. Examination of these data indicates that N-alkylation has little or no effect on the stabilities of α-NH_2 carbon-centered radicals. The possible role played by synergistic (captodative) effects in determining the size of RSEs for radicals bearing two substituents is discussed in light of the presence of saturation effects.

There has been considerable interest and some controversy concerning the question of the degree of stabilization derived by the interactions of donor and acceptor groups in radicals of type **1**. Dewar first pointed out in a paper on MO theory that mutual

$$\underset{\mathbf{1a}}{H_2NCH^{\bullet}C{\equiv}N} \leftrightarrow \underset{\mathbf{1b}}{H_2N^{\bullet+}C^{-}HC{\equiv}N} \leftrightarrow \underset{\mathbf{1c}}{H_2N^{\bullet+}CH{=}C{=}N^{-}}$$

conjugation of donor and acceptor functions could occur when they are both attached to a radical center.[1] In 1971, Balaban suggested that "push-pull resonance" of the type shown for **1** stabilized a number of radicals,[2] and in 1974 Katritzky gave further examples of this phenomenon,[3] which he called "merostabilization".

Later, Viehe and co-workers, in two long papers, gave numerous applications and qualitative theoretical arguments supporting the existence of a powerful stabilizing effect operating between donor and captor groups in systems of this type.[4,5] They proposed that these "captodative" interactions provide greater stabilization than the sum of the stabilization effects in the singly substituted radicals.[5] Calculations by Schleyer in 1980 had indeed indicated that 3.4 and 12.3 kcal/mol of extra stabilization was present in $H_2N\dot{C}HCN$ and $H_2N\dot{C}HBH_2$ radicals, respectively.[6] On the other hand, later calculations by Katritzky, Zerner, and Karelson, referenced to the corresponding symmetrical radicals, gave quite different results.[7] They found no evidence of captodative stabilization in $MeO\dot{C}HCN$ or $H_2N\dot{C}HCN$ radicals in the gas phase, but large effects in a solvent of dielectric constant of 80. Recent calculations by Pasto indicate that substantial captodative stabilization is present in radicals of type G-$\dot{C}$H-BH_2, where G is F, HO, or NH_2, as well as in $HO\dot{C}HCHO$ and $H_2N\dot{C}HCHO$ radicals; the $H_2N\dot{C}HCN$ radical had only ~1 kcal/mol of extra stabilization, however.[8b]

On the experimental side, a study has shown that activation energies for rates of isomerization of *para*-substituted tetraphenylethylenes are lowered by 2 kcal/mol when MeO and CN groups are present.[9] A 2.9 (±2) kcal/mol lowering of the barrier to rotation of the π bond in the $CH_2{=}C\dot{C}(OMe)(CN)$ radical, relative to the singly substituted analogues has been ascribed to a captodative effect,[10a] but a comparison of the rotational barrier in the α-cyano-α-methoxybenzyl radical with the rotational barriers in the monosubstituted benzyl radicals failed to reveal a captodative effect.[10b] However, the rotational barriers about the C-N bonds in substituted aminoalkyl radicals were found to be substantially greater when an acceptor group is present, indicative of extensive π-electron delocalization.[11] Also, examination of thermolysis rates to form MeOCHCN radicals from $PhCH_2CH(OMe)CN$ has suggested an apparent 4 kcal/mol lowering of the activation barrier, relative to thermolysis of $PhCH_2CH_2Ph$.[12] But, thermolysis rates for the formation of $Ph\dot{C}(OMe)(CN)$ radicals from $[PhC(OMe)(CN)]_2$ gave no indication of an extra stabilization effect.[13] Finally, rates of dimerization of captodative-type radicals fail to show any diminution, relative to other types.[14]

Gas-phase measurements by various methods have provided bond dissociation energies (BDEs) for a number of substituted methanes, GCH_2-H.[15] The ΔBDEs, relative to CH_3-H (105 kcal/mol) can be used as a measure of the relative stabilities of the radicals, $GCH_2^{\bullet}$, formed by C-H bond scission. These results are compared in Table I with radical stabilization energies (RSEs) for $GCH_2^{\bullet}$ radicals calculated at the UHF 4-31G level.[8a]

In our laboratory we have developed a method of estimating relative BDEs or RSEs in Me_2SO solution for acidic C-H bonds in weak acid families, HA, by combining pK_{HA} values with the oxidation potentials of their conjugate bases, $E_{ox}(A^-)$ (eq 1).[16]

$$\Delta BDE = RSE = 1.37\Delta pK_{HA} + 23.1\Delta E_{ox}(A^-) \quad (1)$$

This method is amenable to the estimation of the RSEs of radicals

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Table I. Relative Bond Dissociation Energies (ΔBDEs) of Methanes, GCH_2–H, Compared to Radical Stabilization Energies (RSE) Calculated for GCH_2• Radicals

G	BDE[a]	ΔBDE[b]	RSE[c]	G	BDE[a]	ΔBDE	RSE[c]
H	105	(0.0)		Ph	88	17	7.8 (C=C)
Me	98	7	3.3	MeC=O	92[g]	13	7.7 (HC=O)
HO	94	11	5.7	PhC=O	93[h]	12	7.7 (HC=O)
MeO	93	12	5.3	CN	93	12	5.3
H_2N	93	12	10.3[d]	F	100	5	1.6
MeNH	87	18	9.7[e]	F_2	105	0	0.56
Me_2N	84	21	8.9[f]	F_3	107	−2	−4.2

[a] In kcal/mol; ref 15 unless otherwise noted. [b] Equivalent to RSE. [c] From the calculations in ref 8a, unless otherwise noted. [d] References 6, 8a, and 17b. [e] References 8a and 17b. [f] Reference 17b. [g] Reference 18. [h] Reference 19.

of the type A–ĊH–D, where A is an electron acceptor and D is an electron donor. It is the purpose of this paper to examine RSEs for systems of this type.

Results and Discussion

Amino groups are the donors of choice since they are among the most powerful neutral donors available. There is some controversy concerning the effect of *N*-methyl substitution on the stability of NH_2CH_2• radicals, however. Whereas Griller and Lossing obtained the order NH_2CH_2• < $MeNHCH_2$• < Me_2NCH_2• from the measurement of appearance potentials and the heats of formation obtained therefrom (Table I),[17a] ab initio calculations by Goddard indicate a *reverse* order, i.e., 10.3, 9.7, and 8.9 kcal/mol, respectively, for H_2NCH_2•, $MeNHCH_2$•, and Me_2NCH_2• radicals.[17b] The stabilization energy calculated for the NH_2CH_2• radical by Goddard is essentially identical with the earlier value obtained by Crans, Clark, and Schleyer (10.2 kcal/mol),[6] and the recent value obtained by Pasto.[8a] The value of 21 kcal/mol for the stabilization energy of the Me_2NCH_2• radical is 9 kcal/mol higher than indicated by these calculations, but is in good agreement with the 18.5 kcal/mol effect of the Me_2N group in lowering the activation energy for the rearrangement of vinylcyclopropane to cyclopentene.[20] Further information on this question has now been obtained from RSE estimates made on the 9-aminofluorenyl radicals, 9-RR′NFl•, where R and R′ are alkyl or hydrogen.

RSEs of 9-Amino-, 9-(Alkylamino)-, and 9-(Dialkylamino)-fluorenyl Radicals. In an earlier paper we described the properties, including the ΔBDEs of the 9-C–H bonds in a number of 9-(dialkylamino)fluorenes, 9-R_2NFlH.[21a] (These ΔBDEs are believed to be equivalent to the RSEs of the corresponding 9-R_2NFl• radicals.) It was observed at that time that 9-(butylamino)-fluorene, 9-BuNHFlH, had a lower 9-C–H bond BDE than did most of the 9-R_2N-fluorenes. We have now extended the study to two other 9-RNH-fluorenes, to analogous 9-R(Me)N-fluorenes, and to 9-NH_2-fluorene. The data for these, along with the earlier data for 9-azetidinyl-, 9-pyrrolidinyl-, and 9-piperidinylfluorenes[21a] are shown in Table II.

Examination of Table II shows that the oxidation potentials of the 9-NH_2- and three 9-RNH-fluorenide ions are all more negative than those for the corresponding 9-(dialkylamino)-fluorenide ions by 0.215–0.375 V. In other words these carbanions are easier to oxidize than their 9-(dialkylamino)fluorenide ion counterparts by about 5–10 kcal/mol. The reason is that when *two* alkyl groups are present on nitrogen there is steric interference between these alkyl groups and the hydrogen atoms in the C-1 and C-8 positions on the fluorene ring that prevents effective orbital overlap between the lone pair on nitrogen and the odd electron in the fluorenyl radical being formed by the loss of an electron.[21a] Note that the maximum difference of 0.375 V is between the 9-H_2N- and 9-Me_2N-fluorenide ions.

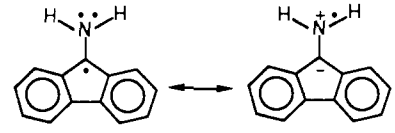
Table II. Acidities and Radical Stabilization Energies of 9-RR′N-Fluorenes and Oxidation Potentials of their Conjugate Bases

R	R′	pK_{HA}	$E_{ox}(A^-)$[b]	RSE[c]
fluorene		22.6	−0.194	(0.0)
H	H	22.1	−0.795	15
H	Me	22.5	−0.775	14
H	Bu[a]	21.5	−0.740	14.5
H	$PhCH_2$	21.3	−0.687	13.5
H	PhCH(Me)	21.1	−0.645	13
Me	Me[a]	22.5	−0.507	8
Me	Bu	22.1	−0.472	7.5
Me	$PhCH_2$	22.1	−0.446	7
		21.8	−0.700	13
		22.2	−0.625	11
		22.5	−0.485	7

[a] Reference 21. [b] Measured in Me_2SO by cyclic voltammetry versus a Ag/AgI electrode against a ferrocene couple standard (0.875 V). The potentials of 9-(dialkylamino)fluorenide ions were reversible, but the 9-amino- and 9-(monalkylamino)fluorenide ions were not. Both were recorded as E_p values. [c] Calculated by using eq 1.

When the steric effects of the 9-R_2N-fluorenide ions are decreased by joining the R groups in a ring the $E_{ox}(A^-)$ values become progressively more negative as the ring is reduced in size and becomes less sterically demanding, i.e., 6 (−0.485) < 5 (−0.625) < 4 (−0.700). 9-Azetidinylfluorenide ion has an oxidation potential in the same range as those for 9-H_2N- and 9-RNH-fluorenide ions, and the RSE calculated by eq 1 is also comparable. These results are consistent with the theoretical calculations of Goddard[17b] and Pasto,[8a] which indicate that N-alkylation does not increase stabilization of the H_2NCH_2• radical.

The observation of a *larger* radical-stabilizing effect for the 9-amino group on the fluorenyl radical (15 kcal/mol) than observed or calculated for the amino group in the aminomethyl radical (10–12 kcal/mol) is surprising. One would have expected the reverse to be true because the fluorenyl radical is stabilized by delocalization, and a saturation effect should ensue. The presence of a synergistic effect wherein the aromatic character of the fluorenide ion plays a role by virtue of contributor **2b** offers a possible explanation.



2a **2b**

Comparison of RSEs for 9-Substituted Fluorenyl and Substituted Methyl Radicals. In Table III we show a comparison of the effect of 9-substituents on the RSEs for 9-substituted fluorenyl radicals, 9-GFl•, with those calculated for the corresponding substituted methyl radicals, GCH_2•.[8a]

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Table III. Comparison of Radical Stabilization Energies (RSEs) of 9-Substituted Fluorenyl and Substituted Methyl Radicals

G	RSE(9-G-Fl•)[a]	RSE(GCH_2•)[e]
H	(0.0)	(0.0)
H_2N	15[b]	10.3[f]
MeNH	14[b]	9.7[g]
MeO	7	5.3
Ph	5.9 (9.7)[c]	7.8 (C=C)
Me	4.5	3.3
MeS	5.4	5.7 (HS)[h]
MeOCO	3.9	5.7 (CO_2H)
PhCO	2.5	7.7 (HCO)
H_2NCO	2.3	5.5
CN	5.7	5.3
$PhSO_2$	−2.1	−0.82
Me_3N^+	−5[d]	−4

[a] In kcal/mol; Bordwell, F. G.; Bausch, M. J. *J. Am. Chem. Soc.* **1986**, *108*, 1979–1985 unless otherwise noted (RSE = ΔAOP). [b] Present results calculated by using eq 1. [c] Fluoradene. [d] Reference 21. [e] In kcal/mol; Pasto, D. J.[8a] [f] Agrees with earlier calculations (ref 6 and 17b). [g] Agrees with an earlier value (ref 17b). [h] RSE of 2.3 kcal/mol without d orbitals.

Examination of Table III shows that, for the donor groups, H_2N, MeNH, MeO, and Me, the effects in stabilizing fluorenyl radicals are *greater* than those calculated for the stabilization of the corresponding methyl radicals. For G = Ph and MeS, the observed and calculated RSEs are of about comparable size. It would appear, then, that either most donors are exerting synergistic effects on fluorenyl radicals, or the RSE calculations are underestimating the size of the effects of these groups on methyl radicals. The effects of the carbonyl acceptor groups, MeOCO, PhCO, and H_2NCO, are all smaller for fluorenyl radicals than for methyl radicals, but this can be attributed to steric hindrance effects in the fluorenyl radicals. For the acceptor CN group the observed and calculated effects are of comparable size, which is not explicable in terms of the synergistic hypothesis since contributors of type **2b** should not be important here. Both the effects observed for the $PhSO_2$ and R_3N^+ groups on fluorenyl radicals and those calculated for methyl radicals are destabilizing.

Examination of Table I supports the view that the calculated RSEs consistently underestimate the abilities of α substituents to stabilize methyl radicals. For most donors and acceptors the difference is of the order of 4–5 kcal/mol. For MeNH and Me_2N it is 8 and 12 kcal/mol, respectively, but only 2 kcal/mol for H_2N. The experimental BDE for H_2NCH_2–H of 93 appears to be too high for several reasons. First, because it indicates that the H_2N group is no better than MeO or HO (BDEs of 93 and 94, respectively) at stabilizing methyl radicals, whereas our $E_{ox}(A^-)$ data clearly demonstrate that H_2N is far superior to MeO in this regard. Thus, the $E_{ox}(A^-)$ value for 9-H_2NFl$^-$ ion (Table II) is 346 mV (8.0 kcal/mol) more negative than that for 9-MeOFl$^-$ ion,[16] and that for the α-aminoacetophenonide ion is ~475 mV (11 kcal/mol) more negative than that of the α-methoxyacetophenonide ion, as will be brought out shortly. Second, the $E_{ox}(A^-)$ value for 9-MeHNFl$^-$ is the same, within experimental error, as that of 9-H_2NFl$^-$ ion (Table II), indicating that N-methylation does *not* increase the stabilizing ability of H_2N in the H_2NFl• radical, in agreement with calculations on H_2NCH_2• and $MeHNCH_2$• radicals, but contrary to the 6 kcal/mol decrease reported for the BDE of $MeHNCH_2$–H, relative to that of H_2NCH_2–H (Table I).

α-Alkoxyl and α-Amino Effects in Radicals Derived from α-Substituted Acetophenones. Acidities of several α-substituted acetophenones, together with the oxidation potentials of their conjugate bases, are presented in Table IV.

Examination of Table IV shows that an α-MeO (or α-EtO) group increases the acidity of acetophenone by ~2 pK_{HA} units, whereas most dialkylamino groups have a somewhat smaller effect. The factors involved in determining the equilibrium acidity include (a) the field/inductive effects of the MeO and R_2N groups, (b) the repulsions between the carbanion lone pair and those on oxygen or nitrogen, and (c) steric effects, which in part control solvation, and the orientation of the functions one to the other. Note that 2,6-Me_2-c-$C_5H_8NCH_2COPh$ has the highest acidity of members of this group, presumably because in the presence of the 2- and 6-methyl groups twisting occurs that reduces lone-pair–lone-pair repulsions in the conjugate base, and the orientation for the C–N bond dipole is such as to maximize the field/induction effect.

Table IV. Acidities and Radical Stabilization Energies for Radicals Derived from α-Substituted Acetophenones, PhCOCHRR′

R	R′	pK_{HA}[a]	$E_{ox}(A^-)$[c]	RSE[d]
acetophenone		24.7	0.268	(0.0)
H	OMe	22.85	−0.175	13.1
H	OEt	22.9	−0.167	12.9
H	NH_2	~24[b]	−0.650	~22
H	NMe_2	23.55	−0.572	21
H	c-C_4H_8N	24.0	−0.610	21.6
H	c-$C_5H_{10}N$	23.5	−0.564	21
H	2,6-Me_2-c-C_5H_8N	22.8	−0.405	18.5

[a] In Me_2SO. [b] Estimated by analogy with ΔpK_{HA} values observed for analogous 9-RR′N-fluorenes. [c] In volts; measured in Me_2SO vs Ag/AgI by the method previously described.[16] [d] Calculated by using eq 1.

Table V. Stabilization Energies of Radicals Derived from Substituted Malononitriles, $GCH(CN)_2$, in Me_2SO at 25 °C

G	pK_{HA}[a]	$E_{ox}(A^-)$[b]	RSE[d]
H	11.0	0.938	(0.0)
H_2N	13.7	0.088	16
Me_2N	12.2	0.180[c]	16

[a] Measured in Me_2SO against two indicators. [b] E_p values in volts measured by cyclic voltammetry in Me_2SO under the conditions previously described[16] with a Ag/AgI electrode. [c] Reversible potential; E_p reported. [d] Calculated by using eq 1.

Introduction of an α-MeO or α-EtO group into acetophenone causes the oxidation potential of its conjugate base to become more negative by 0.435–0.443 V (10 kcal/mol). These effects are comparable in size to the large effects caused by the amino groups in relatively unhindered 9-aminofluorenide ions (Table II). They lead to RSEs of 13 kcal/mol (Table IV).

The introduction of α-NH_2 or α-R_2N substituents causes $E_{ox}(A^-)$ for the $PhCOCH_2^-$ ion to become more negative by ~0.6 V (14 kcal/mol). The $E_{ox}(A^-)$ value for the $PhCOC\bar{H}NH_2$ anion is ~0.10 V more negative than those of the $PhCOC\bar{H}NR_2$ anions, suggesting that NH_2 is slightly better than R_2N at stabilizing an adjacent carbon-centered radical. This is in agreement with Goddard's calculations,[17b] but contrary to the Griller and Lossing experimental results,[17a] which suggest that Me_2N is better than H_2N by 9 kcal/mol at stabilizing the methyl radical (Table I). The pK_{HA} for $PhCOCH_2NH_2$ is difficult to estimate because treatment of the $PhCOCH_2N^+H_3$ ion with base gives byproducts absorbing in the same spectral region as our indicators. The pK_{HA} should not differ greatly from the values observed for R_2NCH_2COPh, however, which would place the RSE in the same region as for the three relatively unhindered $PhCOCH_2NR_2$ compounds (21 kcal/mol). The 21 kcal/mol stabilizing effect of R_2N groups when substituted for one of the α-hydrogen atoms in the $PhCOCH_2$• radical is as large as that of the Me_2N group on the methyl radical. It is interesting to note in this connection that the stabilizing effect of the Me_2N group, as judged by ΔBDE values, is the largest of all the substituents shown in Table I, being slightly more effective than vinyl or phenyl groups at delocalizing an odd electron.

α-Amino and α-Dimethylamino Effects on Radicals Derived from Malononitriles. α-(Dimethylamino)malononitrile is known to be very easily oxidized, and the $Me_2N\dot{C}(CN)_2$ radical formed by loss of a proton from the resulting radical cation $Me_2N^{\bullet+}CH(CN)_2$, has been cited as an example of a radical made remarkably persistent by virtue of the presence of a captodative effect.[5] It was therefore of interest to include an examination of the RSEs of $H_2N\dot{C}(CN)_2$ and $Me_2N\dot{C}(CN)_2$ radicals in the present study (Table V).

Examination of Table V shows that both α-H_2N and α-Me_2N groups exert 16 kcal mol stabilizing effects when substituted for

the hydrogen atom in $(CN)_2CH^•$ radicals. Their effect in delocalizing the odd electron in $(CN)_2\dot{C}NH_2$ and $(CN)_2\dot{C}NMe_2$ radicals therefore rivals that of Ph in the $PhCH_2^•$ radical (RSE = 17 kcal/mol), but is slightly less than that of $CH_2{=}CH$ in the $CH_2{=}CHCH_2^•$ radical (19 kcal/mol).[15]

Note that once again there is no evidence to indicate that alkylation of H_2N groups increases their ability to stabilize adjacent radicals, contrary to the experimental findings reported in Table I.

The oxidation potential of the $(CN)_2C(NMe_2)^-$ anion is reversible, indicating that the $(CN)_2C(NMe_2)^•$ radical formed by loss of an electron has a sufficient lifetime on the electrode to be reduced back to the carbanion. On the other hand, the oxidation potential of the $(CN)_2(NH_2)^-$ anion is irreversible, showing that it is the steric effect introduced by replacing the hydrogen atoms of the H_2N group by methyl groups that leads to this persistence,[22] contrary to a previous assumption.[5]

Are Captodative Effects Operating in These Systems? To answer this question we must decide whether or not the RSEs in the donor-CH-acceptor radicals reported in Tables IV and V are greater than the sum of the individual donor-$CH_2^•$ and acceptor-$CH_2^•$ radical RSEs.[5] It is important before proceeding, however, to estimate the size of the experimental error in these RSEs. The ΔpK_{HA} values are estimated to be accurate to about ± 0.1 pK_{HA} unit (<0.5 kcal/mol), but the irreversibility of most of the cyclic voltammetric (CV) measurements makes them subject to larger errors. The difference in the E_p value and $E_{1/2}$ for the $E_{ox}(A^-)$ value of the $(CN)_2C(NMe_2)^-$ anion is ~50 mV (1.2 kcal/mol). A similar difference between reversible and irreversible potentials has been observed for 9-RR'NFl$^-$ ions,[21a] and this has proved to be general for fluorenyl radicals.[21b] From these observations we estimate an error of no more than 2–3 kcal/mol in our RSE values. Within a family the errors should be smaller.

Turning first to our $ROCH_2COPh$ system, we note that the RSEs estimated for the effects of the MeO and EtO groups in the $MeO\dot{C}HCOPh$ and $EtO\dot{C}HCOPh$ radicals are 12.9 ± 2 and 13.1 ± 2 kcal/mol, respectively, relative to the $PhCOCH_2^•$ radical. These effects are slightly larger than the effect of MeO in the $MeOCH_2^•$ radical (12 kcal/mol). We conclude, therefore, that the effects of MeO and PhCO in the $MeO\dot{C}HCOPh$ radical are approximately additive. There is no evidence for a captodative effect by this criterion. The RSEs for the R_2N groups in $R_2N\dot{C}HCOPh$, relative to the $PhCOCH_2^•$ radical, are large (21 kcal/mol), but no larger than expected, based on RSE for the $Me_2NCH_2^•$ radical. Again, we see no evidence for an effect greater than the sum of the individual effects, as the captodative theory requires.[5]

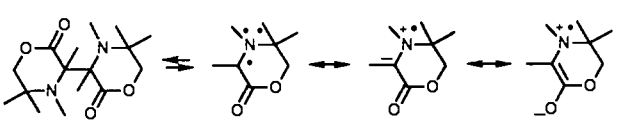
Saturation and Synergistic Effects. In a recent paper titled "A Quantitative Assessment of the Merostabilization Energy of Carbon-Centered Radicals" eq 2

$$\Delta E_M = E_{CHXY} - 0.5(E_{CHX_2} + E_{CHY_2}) \qquad (2)$$

was used to estimate the size of synergistic effects of donor and acceptor effects (ΔE_m) in $H\dot{C}XY$ radicals by theoretical calculations.[7] The second term in eq 2 is evidently included in an attempt to correct for saturation effects. The conclusion is drawn from these calculations that $H\dot{C}(Don)(Acc)$ radicals are significantly more stable than the corresponding symmetrical radicals, $H\dot{C}(Don)_2$ and $H\dot{C}(Acc)_2$, in a solvent of bulk dielectric constant of 80, but that 1–5 kcal/mol *destabilization* occurs in the gas phase. While it is difficult to take calculations seriously that suggest a greater than 20 kcal/mol stabilization by MeO in the $MeO\dot{C}HCN$ radical than by H_2N in the $H_2N\dot{C}HCN$ radical, the point that saturation effects need be considered is well taken. In Table VI evidence is presented to illustrate intrinsic (gas-phase) saturation effects on ΔBDEs for GCH_2–H bonds where G = Me, $CH_2{=}CH$, and Ph from gas-phase data. We see from Table VI that the effect of a second methyl substitution into methane is ~40% as large as the first, and that the substitution of a second vinyl group into methane is ~50% as large as the first. The effect of a second phenyl substitution into methane is only ~25% as large as the first, but here steric inhibition of delocalization in the radical also plays a role. Saturation effects of this type are not restricted to a series of successive substitutions. They are general. Another example (where steric effects are minimal) can be seen by comparing the RSEs of the 9-MeFl$^•$ and 9-CNFl$^•$ radicals, relative to the 9-HFl$^•$ radical, with those of $MeCH_2^•$ and $^•CH_2CN$ radicals, relative to the methyl radical. The larger RSEs for the latter radicals (7 and 12 kcal/mol, respectively, versus 4.5 and 5.7 kcal/mol for the former) can be attributed to the localized nature of the $CH_3^•$ radical, causing it to have a maximum sensitivity to the delocalization effects provided by the presence of a substituent. Substituent effects are much smaller on the delocalized fluorenyl radical, which is more stable by ~25 kcal/mol. In these examples, the RSE of Me in the 9-MeFl$^•$ radical is only ~64% of that of Me in the $MeCH_2^•$ radical, and the RSE of CN in the 9-CNFl$^•$ radical is only ~50% of that of CN in the $^•CH_2CN$ radical. From these examples the assumption of a 25% saturation effect for the substitution of an α-MeO or α-Me_2N group for an α-hydrogen atom in the $PhCOCH_2^•$ radical would appear to be a conservative estimate.[24] This would mean that a synergistic effect of at least 4 kcal/mol would be operative between the PhO and α-MeO groups; syn = [12 + 13 + (0.25 × 13)] − (12 + 12) = 4 kcal/mol. For $PhCO\dot{C}HNR_2$: syn = [12 + 21 + (0.25 × 21)] − (12 + 21) = 5 kcal/mol.

The data in Table I show that the ΔBDEs for $CNCH_2$–H and $PhCOCH_2$–H are each 12 kcal/mol. The BDEs for $(CN)_2CH$–H $(PhCO)_2CH$–H have been estimated to be 90 and 91 kcal/mol, respectively.[19] The effects of the second CN and PhCO substitutions are therefore ~75% smaller than that first. (Field/inductive and steric effects, as well as saturation effects, may contribute to the small size of these increases.) The RSE for substitution of an R_2N group for a hydrogen atom in the $(CN)_2\dot{C}H$ radical will be subject to further saturation. It is, therefore, surprising to note that the (doubly saturated) RSE observed for this substitution is only 23% smaller than for a comparable substitution into the $PhCOCH_2^•$ radical. It would appear, then, that a synergistic effect is also associated with this substitution.

Synergistic Effects and Solvent Effects. Olson and Koch have observed that formation of the persistent radical **4** from its dimer **3** at equilibrium is favored in the hydrogen-bonding solvent, EtOH,



3 **4a** **4a** **4c**

Table VI. Examples of Intrinsic Saturation Effects on ΔBDEs in GCH_2–H, G_2CH–H, and G_3C–H Compounds

compound	BDE[a]	ΔBDE	ΔΔBDE	ΔΔΔBDE
CH_3—H	105	(0.0)		
$MeCH_2$—H	98	7	(0.0)	
Me_2CH—H	95		3	(0.0)
Me_3C—H	93			2
CH_3—H	105	(0.0)		
$CH_2{=}CHCH_2$—H	86	19	(0.0)	
$(CH_2{=}CH)_2CH$—H	76		10	
CH_3—H	105	(0.0)		
$PhCH_2$—H	88	17		
Ph_2CH—H	84		4	
Ph_3C—H	82			2

[a] Reference 15.

(22) Since $t_{1/2}$ for the $(CN)_2\dot{C}Me_2$ radical has not been measured, it is uncertain as to whether it should be classified as a persistent or transient radical.[23]

(23) Griller, D.; Ingold, K. U. *Acc. Chem. Res.* **1976**, *9*, 13–19.

(24) We have pointed out elsewhere that the gas-phase acidifying effect of the second CN group in the series CH_4, CH_3CN, $CH_2(CN)_2$ is subject to a 25% saturation effect.[25]

(25) Bordwell, F. G.; Algrim, D. J. *J. Am. Chem. Soc.* **1988**, *110*, 2964–2968.

relative to the nonpolar solvents $MeOCH_2CH_2OMe$ and C_6H_6 by 3.7 and 6.5 kcal/mol, respectively. They concluded on this basis that the dipolar nature of the captodative radical (note **4b** and **4c**) leads to strong solvation.[26] Also, the calculations of Katritzky, Zerner, and Karelson suggest that solvation effects are the sole cause of synergistic effects.[7] By contrast, Barbe, Beckhaus, and Rückardt failed to detect any significant solvent polarity effect on the thermodynamic and kinetic parameters for the formation of α-cyano-α-methoxyalkyl radicals from homolytic dissociation of their dimers.[13] Pasto discounted the importance of dipolar resonance contributors with appreciable charge separation, such as **4c**, in stabilizing radicals,[8b] and it seems doubtful to us that solvation will be a major factor in a non-hydrogen-bond donor solvent such as Me_2SO.

Summary and Conclusions. Comparison of the oxidation potentials of α-H_2N and α-R_2N carbanions derived from fluorene, acetophenone, and malononitrile show that N-alkylation has little or no effect on the stabilities of α-amino 9-fluorenyl, phenacyl, or malononitrilyl radicals, contrary to a previous report. We conclude, therefore, that the reported difference of a 9 kcal/mol smaller RSE for the $H_2NCH_2^\bullet$ radical than for the $Me_2NCH_2^\bullet$ radical is in error. The RSEs of GĊHCOPh radicals, where G = MeO and Me_2N, have been found to be 13 and 21 kcal/mol, respectively, relative to that of the $PhCOCH_2^\bullet$ radical. Since these values are the same, within experimental error, as those for the $MeOCH_2^\bullet$ and $Me_2NCH_2^\bullet$ radicals, respectively, there is no evidence that the PhCO group has contributed any extra stabilization. In other words, there is no captodative effect, as defined by Viehe, Janousek, Merênyi, and Stella.[5] The RSEs of the $H_2NĊH$ and $Me_2NĊ(CN)_2$ radicals, relative to the $(CN)_2ĊH$ radical are each 16 kcal/mol. This value is 5 kcal/mol less than that for the RSE of the $Me_2NCH_2^\bullet$ radical, indicating no captodative effect. Nevertheless, when saturation effects are taken into account, the presence of synergistic effects in the range of at least 4–5 kcal/mol are indicated to be present in ROĊHCOPh, $R_2NĊHCOPh$, and $R_2NĊ(CN)_2$ radicals. We conclude that the presence of strong donor and acceptor groups attached to a radical center does indeed introduce synergistic effects that contribute substantially to the stability of radicals, as postulated by many earlier investigators.[1-5]

Experimental Section

General Procedures. NMR spectra were recorded on a Varian EM-390 spectrometer. Mass spectra were measured by Dr. H. L. Hung on a HP 5985 GC/MS system. Melting points were determined on a Thomas Hoover capillary melting point apparatus. Elemental analyses were measured in the Micro-Tech Laboratories, Inc., Skokie, IL.

Materials. 9-(Dialkylamino)fluorenes and 9-(monoalkylamino)-fluorenes were prepared from the reactions of 9-bromofluorene with the appropriate amines and purified as described previously.[21a] 9-Aminofluorene was obtained by treating 9-aminofluorene hydrochloride (Aldrich Chemical Co.) with diisopropylamine and purified by chromatography on silica gel. α-(Dimethylamino)-, α-piperidinyl-, α-pyrrolidinyl-, and α-(2,6-dimethylpiperidinyl)acetophenones were prepared from the reaction of phenacyl bromide with the appropriate amine[27] and purified by vacuum distillation. α-Aminoacetophenone hydrochloride (Aldrich) was used directly for $E_{ox}(A^-)$ measurement by adding 2 equiv of CH_3SOCH_2K in Me_2SO solution. 2-Methoxyacetophenone (Aldrich) was purified by vacuum distillation. 2-Ethoxyacetophenone was prepared from the reaction of diazoacetophenone with ethanol in the presence of boron trifluoride etherate[28] and purified by vacuum distillation. Diazoacetophenone was obtained by treating benzoyl chloride with 1 equiv each of diazomethane and triethylamine.[29] The *p*-toluenesulfonate of aminomalononitrile was synthesized by the reduction of oximinomalononitrile by amalgamated aluminum followed by treatment with *p*-toluenesulfonic acid.[30] (*N,N*-Dimethylamino)malononitrile was synthesized by the method of Arnold and Svoboda[31] with a slight modification in which chloromethylenedimethylammonium chloride, $[Me_2N{=}CHCl]^+Cl^-$, was prepared from oxalyl chloride and *N,N*-dimethylformamide.[32] The purity and identity of unknown compounds was confirmed by NMR, MS, and microanalyses where appropriate.

9-(*N*,*n*-Butyl-*N*-methylamino)fluorene: Colorless oil; ^1H NMR ($CDCl_3$) δ 7.5–7.75 (m, 4 H), 7.2–7.4 (m, 4 H), 4.8 (s, 1 H), 2.6 (t, 2 H), 2.15 (s, 3 H), 1.3–1.6 (m, 4 H), 0.9 (s, 3 H); MS, *m/e* (relative intensity) 251 (11.1), 208 (34.9), 165 (100). Anal. Calcd for $C_{18}H_{21}N$: C, 86.01; H, 8.42; N, 5.57. Found: C, 85.83; H, 8.57; N, 5.41.

9-(*N*-Benzylamino)fluorene: mp 48.5–49.5 °C; ^1H NMR ($CDCl_3$) δ 7.5–7.75 (m, 4 H), 7.1–7.4 (m, 9 H), 4.9 (s, 1 H), 3.45 (s, 2 H), 1.85 (s, 1 H); MS, *m/e* (relative intensity) 271 (100), 270 (54.5), 180 (83.6), 165 (37.3).

9-(*N*-Methylamino)fluorene: mp 50.5–51.5 °C; ^1H NMR ($CDCl_3$) δ 7.5–7.8 (m, 4 H), 7.25–7.45 (m, 4 H), 4.85 (s, 1 H), 2.2 (s, 3 H), 1.8 (s, 1 H).

9-(*N*-Benzyl-*N*-methylamino)fluorene: mp 87–88 °C; ^1H NMR ($CDCl_3$) δ 7.65–7.8 (m, 4 H), 7.2–7.5 (m, 9 H), 4.95 (s, 1 H), 3.7 (s, 2 H), 2.25 (s, 3 H); MS *m/e* (relative intensity) 285 (76.3), 270 (3.8), 194 (85.6), 165 (100). Anal. Calcd for $C_{21}H_{19}N$: C, 88.38; H, 6.71; N, 4.91. Found: C, 88.64; H, 6.75; N, 4.84.

9-[*N*-(+)-(α-Methylbenzyl)amino]fluorene: mp 64–65 °C; ^1H NMR ($CDCl_3$) δ 7.2–7.8 (m, 13 H), 4.7 (s, 1 H), 4.3 (q, 1 H), 1.7 (s, 1 H), 1.35 (d, 3 H); MS, *m/e* (relative intensity) 285 (59), 270 (100), 180 (39), 165 (81). Anal. Calcd for $C_{21}H_{19}N$: C, 88.38; H, 6.71, N, 4.91. Found: C, 88.63; H, 6.75; N, 4.95.

α-Piperidinylacetophenone: bp 89–90 °C (0.11 mmHg) [lit.[27] bp 134–136 °C (1 mmHg)]; ^1H NMR ($CDCl_3$) δ 7.9–8.1 (m, 2 H), 7.3–7.6 (m, 3 H), 3.7 (s, 2 H), 2.4–2.55 (m, 4 H), 1.3–1.7 (m, 6 H).

α-Pyrrolidinylacetophenone: bp 88–89 °C (0.1 mmHg); ^1H NMR ($CDCl_3$) δ 7.9–8.1 (m, 2 H), 7.4–7.6 (m, 3 H), 3.9 (s, 2 H), 2.6 (m, 4 H), 1.8 (m, 4 H).

α-(*N*,*N*-Dimethylamino)acetophenone: bp 59–61 °C (0.15 mmHg) [lit.[27] bp 130–132 °C (20 mmHg)]; ^1H NMR ($CDCl_3$) δ 7.8–8.1 (m, 2 H), 7.35–7.6 (m, 3 H), 3.7 (s, 2 H), 2.35 (s, 6 H).

α-(2,6-Dimethylpiperidinyl)acetophenone: bp 100 °C (0.1 mmHg); ^1H NMR ($CDCl_3$) δ 7.8–8.0 (m, 2 H), 7.4–7.6 (m, 3 H), 4.2 (s, 2 H), 2.9–3.2 (m, 2 H), 1.2–1.8 (m, 6 H), 1.0 (d, 6 H); MS, *m/e* (relative intensity) 231 (1.3), 216 (1.1), 126 (100).

The acidities of 9-R′RN-FlH, $PhCOCH_2NR_2$, $PhCOCH_2OMe$, $PhCOCH_2OEt$, $H_2NCH(CN)_2$, and $(CH_3)_2NCH(CN)_2$ in dimethyl sulfoxide solution were determined by the overlapping indicator method described previously.[33] However, the pK_a of α-aminoacetophenone could not be measured because the solution of α-aminoacetophenone hydrochloride in dimethyl sulfoxide turned pink immediately after adding a small amount of CH_3SOCH_2K solution, presumably due to the formation of colored byproducts. Oxidation potentials of the conjugated bases of the compounds of interest were measured in dimethyl sulfoxide solution with 0.1 M of tetraethylammonium tetrafluoroborate electrolyte by cyclic voltammetry, as described previously.[16] The working and auxiliary electrodes were Pt and the reference electrode was Ag/AgI. The sweep rate was 100 mV/s with a reversible ferrocene–ferrocenium redox couple at $E_{1/2}$ = 0.875 V as a standard.

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