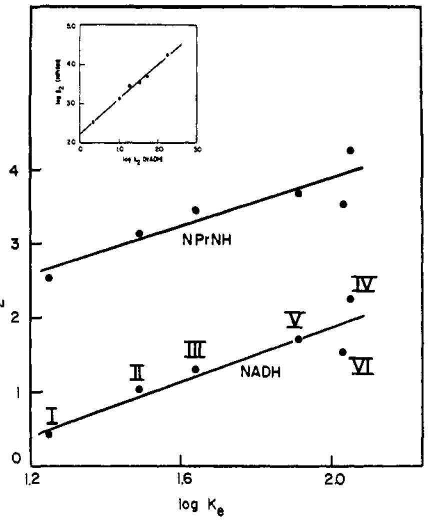
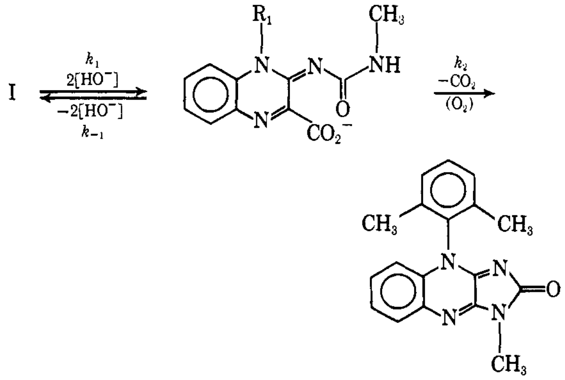


Figure 2. Linear free-energy correlations of rates of reduction of isoalloxazines I–VI by NPrNH and NADH with equilibrium constants for the formation of complexes of I–VI with tryptophan. The inset is a plot of log $k_{\text{rate}}$ for NPrNH *vs.* log $k_{\text{rate}}$ for NADH.

solution after the appropriate time interval. Compound VIII[8] does not yield I in acid. These results establish that the usual $HO^-$ attack at the 10a position is effectively blocked in I and redirected to the 4 position.[9]



VIII

(2)

The rates of reaction of compounds I–VI (dark, anaerobic, solvent water containing 5 vol % DMF) with four reagents have been determined: (a) sulfite[10] (pH 7.10, 29.9°); (b) 1,4-butanedithiol[11] (pH 8.98, 29.9°); (c) NADH[12] (pH 7.65, 29.9°); and (d) *N*-propyl-1,4-dihydronicotinamide[13] (NPrNH) (pH 7.71, 29.75°). Plots (Figure 1) of log $k_{\text{rate}}$ *vs.* the polarographic half-wave potentials ($E_{1/2}$) determined for I–VI (pH 8.97, 30°, reference, saturated calomel electrode) reveal a linear free-energy relationship for both sulfite and 1,4-butanedithiol. Since steric hindrance at the 10a position does not bring about negative rate deviations we are assured that *nucleophilic addition does not occur at the 10a position.*[14,15]

For NADH and NPrNH, plots of the log of the second-order rate constants *vs.* $E_{1/2}$ exhibit increasing negative deviation in the order III < II < I (plot not shown). If the best straight line is drawn through the points for IV, V, and VI, the rate constant for I exhibits a negative deviation of *ca.* 150-fold. These results suggest that either reduction of the isoalloxazine is initiated at the hindered 10a position or that face-to-face complexing is important. Plots of log $k_{\text{rate}}$ for both NADH and NPrNH *vs.* log of the complexing constants $K_e$ (determined by fluorescence quenching[16]) of I–VI (pH 7.85; solvent $H_2O$-5 vol % DMF) for tryptophan (Figure 2) and β-resorcylic acid were found to be linear. From this result it is clear that kinetically important preequilibrium *complex formation takes place between flavins and the dihydronicotinamide ring system.* A plot of log $k_{\text{rate}}^{\text{NADH}}$ *vs.* log $k_{\text{rate}}^{\text{NPrNH}}$ (insert to Figure 2) is of slope 0.9 and intercept 2.23 indicating that NADH and NPrNH possess essentially equal sensitivity to the electronic and steric alterations in going from I to VI but that the rate constants for NPrNH exceed those for NADH about 100-fold. That the second-order rate constant ($K_ek_r$ of eq 3) is less for

$$\text{flavin} + \text{dihydronicotinamide} \overset{K_e}{\rightleftarrows} \text{complex} \xrightarrow{k_r} \text{product} \quad (3)$$

NADH than for NPrNH may find partial explanation in the decreased availability of flavin for complexing with the dihydronicotinamide ring of NADH owing to competitive (but nonproductive) complexing by the adenine moiety. Relatively strong intermolecular[16] and intramolecular[17] complexing of adenine with flavins is known.

**Acknowledgment.** This work was supported by a grant from the National Science Foundation.

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[8] VIII was isolated by neutralization of an anaerobic hydrolysis reaction followed by solvent extraction and chromatography on silica gel and alumina: nmr singlets at δ 1.97 (6 H) and 3.51 (3 H) as well as between 6.8 and 8.1 (7 H); mass spectrum, parent peak *m/e* 304; calcd 304. *Anal.* Calcd: C, 71.05; H, 5.26; N, 18.24. Found: C, 70.83; H, 5.05; N, 18.37.

[9] $HO^-$ attack at the 4a position would be hydrolytically nonproductive[1a] so these results should not be construed to indicate the 4 position to be more electrophilic than the 4a position.

[10] F. Muller and V. Massey, *J. Biol. Chem.*, 214, 4007 (1969).

[11] I. M. Gascoigne and G. K. Radda, *Biochim. Biophys. Acta*, 131, 498 (1967).

[12] J. L. Fox and G. Tollin, *Biochemistry*, 5, 3865 (1966).

[13] C. H. Suelter and D. E. Metzler, *Biochim. Biophys. Acta*, 44, 23 (1960).

[14] F. Muller and V. Massey[10] provide evidence for the final position of sulfite to be at N-5.

[15] Contrary to the suggestions of Gascoigne and Radda[11] thiol anion generated *via* specific base catalysis is the reactive species.

[16] G. R. Penzer and G. K. Radda, *Quart. Rev., Chem. Soc.*, 21, 43 (1967).

[17] D. B. McCormick, "Molecular Associations in Biology," Academic Press, New York, N. Y., 1968, p 377.

[18] Postdoctoral Fellows of the Department of Chemistry, University of California at Santa Barbara.

[19] A portion of this material to be submitted by S. Smith in fulfillment of the requirement for the Ph.D. in Chemistry, University of California, Santa Barbara.

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# Intramolecular Quenching of the Excited Singlets of Phenyl ω-Dialkylaminoalkyl Ketones. Singlet State Type II Photoelimination of α-Dimethylaminoacetophenone

*Sir:*

Phenyl ketones undergo intersystem crossing so rapidly[1,2] that it is generally assumed that they do so

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[1] R. M. Hochstrasser, *Accounts Chem. Res.*, 1, 266 (1968).

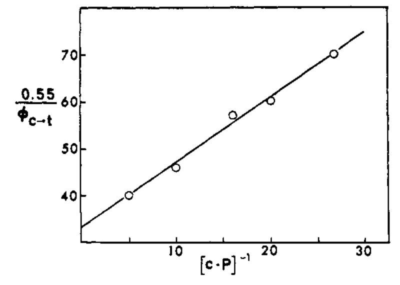

Figure 1. Efficiency with which α-dimethylaminoacetophenone sensitizes the cis–trans isomerization of 1,3-pentadiene (c-P) in methanol.

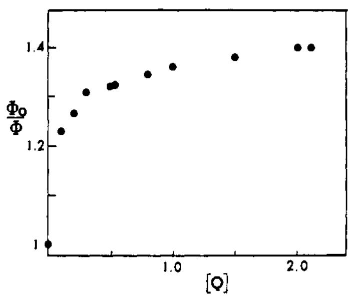

Figure 2. Stern–Volmer plot for 1,3-pentadiene quenching of acetophenone formation from α-dimethylaminoacetophenone in methanol.

with 100% efficiency. Recently, however, it has been shown that such is not the case for fluorenone[3,4] and *p*-aminobenzophenone.[5] We report here that in phenyl ω-dialkylaminoalkyl ketones the intersystem crossing yield decreases as the amino group moves closer to the carbonyl. Intersystem crossing is so inefficient in α-dimethylaminoacetophenone (α-DMAA) that the type II photoelimination reported for several α-amino ketones[6] arises probably exclusively from an excited singlet state.

We have used α-DMAA, γ-dimethylaminobutyrophenone (γ-DMAB), and δ-pyrrolidinovalerophenone (δ-PAV) to sensitize the cis–trans isomerization of 1,3-pentadiene[7] in various solvents. Intercepts of reciprocal quantum yield *vs.* reciprocal diene concentration plots such as in Figure 1 yield the $\phi_{isc}$ values listed in Table I.

Table I. Intersystem Crossing Yields of Various Phenyl ω-Dialkylamino Alkyl Ketones[a]

| | Solvent | | |
|---|---|---|---|
| Ketone (concn, *M*) | Benzene | $CH_3CN$ | $CH_3OH$ |
| δ-PAV (0.03) | 0.82 | 0.80 | 0.89 |
| γ-DMAB (0.10) | 0.58 | 0.51 | 0.72 |
| α-DMAA (0.10) | ≤0.01[b] | ∼0.01 | 0.03[c] |

[a] Reciprocal intercepts of plots such as in Figure 1. Irradiation at 313 nm. [b] Corrected for isomerization sensitized by acetophenone product. [c] Run at conversions <1% to avoid isomerization sensitized by acetophenone product.

Apparently intramolecular quenching of the n,π* singlet by the dialkylamino groups competes with intersystem crossing and grows faster the closer together the amino and carbonyl groups are, as might be expected.[8] This quenching is presumably of the charge-transfer type as observed for bimolecular quenching of ketone fluorescence[3,9] and shows the same interesting solvent effects which we first noted for the interactions of triplet ketones with trialkylamines.[10] If it can be assumed that the rate of intersystem crossing is the same for all three ketones (neither their absorption nor their emission spectra are significantly different from those of, say, propiophenone) and equals $10^{11}$ sec$^{-1}$,[1,2] we calculate rates of intramolecular singlet state quenching of $2.2 \times 10^{10}$, $7.1 \times 10^{10}$, and $10^{13}$ sec$^{-1}$ for δ-, γ-, and α-dialkylamino groups, respectively, in benzene.

There is no indication that this singlet state charge-transfer quenching produces any products in the γ- and δ-amino ketones, just as no products are observed from bimolecular quenching of singlets by amines.[3,9a] For example, a Stern–Volmer plot of the quenching of acetophenone formation from γ-DMAB in methanol is perfectly linear out to a $\Phi_0/\Phi$ value of 8.[11]

The behavior of α-DMAA is more confusing. It has been proposed that both n,π* and π,π* triplets of α-dialkylamino ketones undergo type II elimination with equal facility, since the reaction is not quenched by large concentration of dienes.[6] Since α-DMAA undergoes photoelimination in a quantum yield of 0.055 in benzene, hexane, and acetonitrile but forms triplets in at most 1% yield, the chemistry must arise primarily from the singlet state. In methanol, α-DMAA reacts with a total quantum yield of 0.085, of which one-third is readily quenchable, as Figure 2 shows. The total quenchable quantum yield very nearly equals $\Phi_{isc}$. We find that 2-butanone sensitizes the photoelimination of α-DMAA in high yield (0.47 in benzene) and conclude that triplet α-DMAA forms a 1,4-biradical very efficiently.

The data in Figures 1 and 2 indicate a $k_q\tau$ value ∼20 $M^{-1}$ and thus a $1/\tau$ value of $4 \times 10^8$ sec$^{-1}$ for triplet α-DMAA in methanol. This rate probably corresponds primarily to direct γ-hydrogen abstraction if the behavior of α-methoxyacetophenone[12] is any guide. Consequently, we conclude that charge-transfer quenching in triplet α-DMAA is inefficient and slower than in γ-[10] and δ-dialkylamino ketones,[11] in direct contrast to the behavior of the singlet states of the same ketones.

The solvent independence of the singlet state type II quantum yield for α-DMAA probably means that the charge-transfer quenching process can be followed by proton transfer as originally proposed for the triplet.[6] Direct hydrogen atom abstraction seems less likely since its rate would have to be incredibly fast and show the same solvent dependence as the competing charge-transfer process.

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(2) (a) P. Rentzepis, *Science*, **69**, 239 (1970); (b) P. Rentzepis and C. J. Mitschele, *Anal. Chem.*, 42, 20A (1970).

(3) R. A. Caldwell, *Tetrahedron Lett.*, 2121 (1969).

(4) J. B. Guttenplan and S. G. Cohen, *ibid.*, 2125 (1969).

(5) S. G. Cohen, M. D. Saltzman, and J. B. Guttenplan, *ibid.*, 4321 (1969).

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(7) A. A. Lamola and G. S. Hammond, *J. Chem. Phys.*, **41**, 2129 (1965).

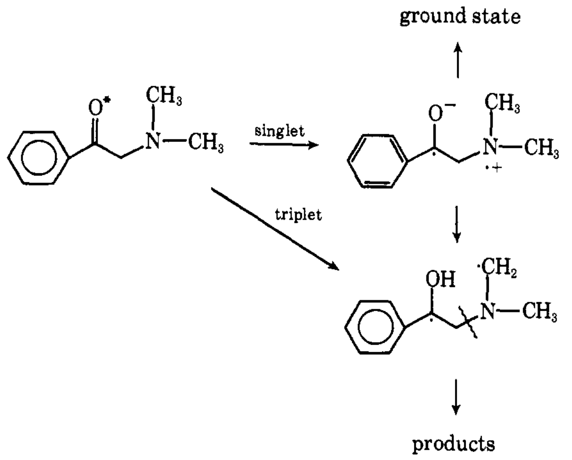
(8) D. O. Cowan and A. A. Baum, *J. Amer. Chem. Soc.*, **92**, 2153 (1970).

(9) (a) N. J. Turro and R. Engel, *Mol. Photochem.*, **1**, 143 (1969); (b) G. A. Davis, P. A. Carapellucci, K. Szoc, and J. D. Gresser, *J. Amer. Chem. Soc.*, **91**, 2264 (1969).

(10) P. J. Wagner and A. E. Kemppainen, *ibid.*, **91**, 3085 (1969).

(11) P. J. Wagner and T. Jellinek, paper in preparation.

(12) (a) P. J. Wagner and A. E. Kemppainen, *J. Amer. Chem. Soc.*, **90**, 5896 (1968); (b) N. J. Turro and F. D. Lewis, *ibid.*, **92**, 311 (1970).



Whatever the exact mechanism, type II photoelimination of $\alpha$-dialkylamino phenyl, biphenyl, and naphthyl ketones[6] is, for the present,[13] best interpreted as arising from their lowest n,$\pi^*$ singlets and not from comparably reactive n,$\pi^*$ or $\pi,\pi^*$ triplets.

**Acknowledgment.** This work was supported by grants from the National Science Foundation and from the Alfred P. Sloan Foundation. We thank Professor Padwa for a preprint and for several discussions.

(13) See P. de Mayo, *Accounts Chem. Res.*, 4, 41 (1971), footnote 10.
(14) Alfred P. Sloan Fellow, 1968–1972.

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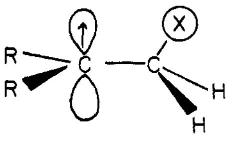
## Halogen Atom Additions to Olefins. An Electron Spin Resonance Study of the Intermediates

*Sir:*

Krusic and Kochi[1] have recently shown that radicals of type I, having $\beta$ substituents (X) such as $-SiR_3$, $-SnR_3$, and $-SR$, exist in a strongly preferred conformation in which the group X sits above the radical plane so that overlap between the $p_z$ orbital of the unpaired electron and the C–X $\sigma$ bond is a maximum. Independently we have made similar observations, including also $\beta$ groups $-PR_2$, $-PR_3^+$, $-AsR_2$, and $-AsR_3^+$, and in addition we have shown that there is a remarkably strong hyperfine interaction with the heavy atom (Sn, P, As) which shows that the unpaired electron is considerably delocalized onto group X.[2] Some pertinent results are included in Table I.



I

We have now extended these studies to include compounds in which X is Cl, Br, or I and find, again, a very large hyperfine interaction with the halogen nucleus. In all three cases exposure of the *tert*-butyl halide (chosen because of the absence of $\alpha$ protons) to $^{60}Co$ $\gamma$ rays at 77°K gave radicals of type I (X = hal), characterized by very large splittings between the components associated with hyperfine coupling to the halogen nuclei. A typical spectrum is given in Figure 1.

Table I. Esr Parameters for Radicals of Structure I at 77°K

| Group X | System irradiated | Isotropic hyperfine coupling to X, G | Coupling to $^1H$ $\alpha$ H | $\beta$ H |
|---|---|---|---|---|
| $SnEt_3$ | $SnEt_4 + \gamma$ | 409 ($^{117}Sn/^{119}Sn$) | ~20 | 13 |
| $AsEt_3^+$ | $AsEt_4I + \gamma$ | 127 ($^{75}As$) | 20 | 14 |
| $AsO_3H$ | $n$-$PrAsO_3H + \gamma$ | 232 ($^{75}As$) | 20 | 11 |
| Cl | $(CD_3)_3CCl + \gamma$ | 34 ($^{35}Cl$)[a,b] | ~2.8 ($^2H$)[c] | |
| Br | $Me_3CBr + \gamma$ | 280 ($^{81}Br$)[b] | ~12.5 | |
| Br | $CH_2{=}CH_2 + Br_2 + uv$ | 250 ($^{81}Br/^{79}Br$) | Not resolved | |
| I | $Me_3CI + \gamma$ | ~400 ($^{127}I$) | Not resolved | |
| I | $CH_2{=}CH_2 + I_2 + uv$ | ~400 ($^{127}I$) | Not resolved | |

[a] Strongly temperature dependent. [b] Considerable error because there are no well-defined || and ⊥ features. [c] Results for $(CH_3)_3CCl$ uncertain because the main features were hidden by those for $(CH_3)_3\dot{C}$ radicals.

Most of the other alkyl halides which we have used, with the notable exception of the methyl compounds, had esr spectra after irradiation, containing evidence for the formation of radicals of type I, although in many instances the lines were partially obscured by stray features from other radicals, such as $hal_2^-$ and $R_2\dot{C}$–hal.

Similar radicals have been prepared by exposing frozen solutions containing ethylene and bromine or iodine to ultraviolet light, as indicated in Table I. In addition to the large, almost isotropic, coupling to halogen, there was evidence on some or all of the main lines of proton hyperfine coupling, although in most cases this was too complex to allow complete analysis. However, as with the compounds of groups IV and V,[1,2] the smaller splitting always seemed to be close to 13 G, which strongly suggests structure I with the same preferred conformation. A $\beta$-proton coupling of this magnitude is diagnostic of such a conformation.[1,2]

The isotropic coupling can be used to estimate an approximate spin density in the valence s orbital of the halogen atoms (Table II). (We reject the idea that the outer vacant s orbital is involved to any major extent, because the spin density on halogen would then be near to unity, which is clearly not the case.[3]) The

Table II. Derived Atomic Populations for $\beta$ Substituents in Radicals of Type I

| Group X | Orbital populations, %[a] s | p[b] | p/s |
|---|---|---|---|
| $SnEt_3$ | 5.6 | | |
| $AsEt_3^+$ | 3.7 | ~13 | ~3.5 |
| $AsO_3H$ | 6.7 | ~14 | ~2.1 |
| Cl | 2.5 | ~8 | ~3.2 |
| Br | 3.4 | ~12 | ~3.5 |
| I | 5.5 | | |

[a] Calculated from atomic values based upon the best available wavefunctions [calculated from the data of C. Froese, *J. Chem. Phys.*, **45**, 1417 (1966)]. [b] Based on the maximum anisotropy; very approximate values.

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(1) P. J. Krusic and J. K. Kochi, *J. Amer. Chem. Soc.*, **93**, 846 (1971).
(2) A. R. Lyons and M. C. R. Symons, *Chem. Commun.*, in press.
(3) K. V. S. Rao and M. C. R. Symons, *ibid.*, 268 (1971).