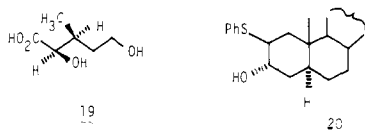the product can serve as an excellent precursor of verrucarinic acid **19**.[11]


This direct hydroxysulfenylation of olefins offers a very convenient and general approach to β-hydroxysulfides, particularly useful synthetic intermediates. In addition, this method provides a regio- and stereochemistry not available by alternative procedures. For example, whereas Δ^2-5α-cholestene gives **9** under our conditions, epoxidation and nucleophilic opening gives the isomeric **20**. This difference proved critical for the ring cleavage since **9** does cleave but **20** does not. The ring cleavage provides just one illustration of the utility of this methodology since the combined procedures allow the use of lead tetraacetate in effecting a net olefin cleavage[12] and also maintaining an intrinsic difference between the ends of the chain in the case of cyclic olefins. The question of the nature of the oxidizing agent remains one of the goals of future work.

References and Notes

(1) Sulfenic acids generally add to olefins to give sulfoxides rather than β-hydroxysulfides: E.g., Jones, D. N.; Hill, D. R.; Lewton, D. A.; Sheppard, C. *J. Chem. Soc., Perkin Trans. 1*, **1977**, 1574. Block, E.; O'Connor, J. *J. Am. Chem. Soc.* **1974**, *96*, 3929. 2,4-Dinitrobenzenesulfonyl acetate has been reported to add very slowly (16 days, 50 °C) to cyclohexene: Havlik, A. J.; Kharasch, N. *ibid.* **1956**, *78*, 1207. Putnam, R. E.; Sharkey, W. *ibid.* **1957**, *79*, 6526. The penicillin–cephalosporin interconversion involves such a reaction: Cooper, R. D. G.; Hatfield, L. D.; Spry, D. O. *Acc. Chem. Res.* **1973**, *6*, 32. For related work see the following. Szmant, H. H.; Najundiah, R. *J. Org. Chem.* **1978**, *43*, 1835. Uebel, J. J.; Milaszewski, R. F.; Arlt, R. E. *ibid.* **1977**, *42*, 585. Davis, F. A.; Friedman, A. J. *ibid.* **1976**, *41*, 897. Nederlof, P. J. R.; Moolenaas, M. J.; de Waard, E. R.; Huisman, H. O. *Tetrahedron Lett.* **1976**, 3175.
(2) For selenenic acids and carboxylates and their additions to olefins, see the following. Reich, H. J.; Wollowitz, S.; Trend, J. E.; Chow, F.; Wendelborn, D. F. *J. Org. Chem.* **1978**, *43*, 1697. Horio, T.; Sharpless, K. B. *ibid.* **1978**, *43*, 1689. Clive, D. J. *J. Chem. Soc., Chem. Commun.* **1974**, 100. Sharpless, K. B.; Lauer, R. F. *J. Org. Chem.* **1974**, *39*, 429. Reich, H. J. *ibid.* **1974**, *39*, 428.
(3) Trost, B. M. *Chem. Rev.* **1978**, *78*, 363. Trost, B. M. *Acc. Chem. Res.* in press.
(4) (a) Trost, B. M.; Hiroi, K. *J. Am. Chem. Soc.* **1975**, *97*, 6911. (b) Also see the following. Trost, B. M.; Hiroi, K. *ibid.* **1976**, *98*, 4313. Trost, B. M.; Tamaru, Y. *ibid.* **1977**, *99*, 3101. Trost, B. M.; Massiot, G. S. *ibid.* **1977**, *99*, 4405.
(5) Tamm, Ch. *Fortschr. Chem. Org. Naturst.*, **1974**, *31*, 63.
(6) Jones, S. R.; Meller, J. M. *J. Chem. Soc., Perkin Trans. 2*, **1977**, 511.
(7) Omission of the trifluoroacetic acid led to a 10% yield of β-acetoxysulfide after 60 h at reflux in acetonitrile.
(8) The regioisomer formed is normally evident from the NMR spectrum. Further confirmation arose by acetylation to shift the absorption for the methine proton adjacent to the hydroxyl group. For example, in the cyclohexadiene adduct, the pertinent protons appear at δ 3.13 (ddd, J = 9.2, 6.5, and 2.7 Hz) and 4.02 (d, J = 6.5 Hz). Acetylation shifts these absorptions to δ 3.3 and 5.21. The larger shift of the allylic methine proton assigns the hydroxyl group to the allylic carbon.
(9) Several intermediates appear reasonable (i-iii). Trifluoromethanesulfenyl
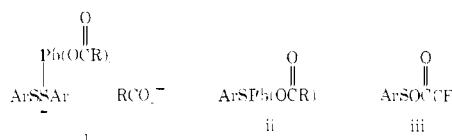
trifluoroacetate and relatives have been isolated: Haas, A.; Oh, D. Y. *Chem. Ber.* **1969**, *102*, 77. These reactions can be compared with the addition of sulfenyl halides to olefins. For a recent paper see Hopkins, P. B.; Fuchs, P. L. *J. Org. Chem.* **1978**, *43*, 1208.
(10) Nicolaou, K. C.; Lysenko, Z. *J. Chem. Soc., Chem. Commun.* **1977**, 293.
(11) The transformation of **16** to verrucarinic acid only requires adjustment of the oxidation level—i.e., reduction of the aldehyde to an alcohol and oxidation of the protected aldehyde to a carboxylic acid.
(12) Cf. Huber, F.; El-Meligy, M. S. A. *Chem. Ber.* **1969**, *102*, 872.

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X-ray Evidence for the Metal Ion Bridged Intra- and Intermolecular Stacking Interactions between Nucleotide Bases and Aromatic Heterocyclic Rings within the Ternary Complex [Cu(5'-AMP)(bpy)(H2O)]2·(NO3)2·6H2O

Sir:

The involvement of the charge-transfer interactions between nucleic acid bases and aromatic amino acid residues in biological systems is now widely recognized,[1] but such stacking adducts are usually weak unless they are additionally stabilized by polar interactions, e.g., proton or ionic bridges.[2] In a solution study[3] of the spectroscopic properties of the ternary complexes such as Cu(bpy[4])L (L = 5'-AMP, 5'-IMP, ATP, and ITP), which are known to be possible models for substrate–metal ion–enzyme complexes, it has been demonstrated that the metal ion bridge formation between the two constituents of the adducts can stabilize them in the following way: the metal ion is coordinated to the nitrogen donors of the bpy ligand and to the phosphate chain of the nucleotide, bridging and stabilizing the stacking between the aromatic amine and the purine moiety. In order to substantiate the formation of such a metal ion bridged stacking adduct and to elucidate its stereochemistry, we have undertaken a systematic X-ray crystallographic study[5] of the ternary complexes containing various metal ions, aromatic amines, and nucleotides. We report here the preparation and the structure of the ternary 5'-AMP-Cu[II]-bpy complex, which is the first example providing the direct evidence for the existence of such a metal ion bridged stacking adduct.[6]

The complex was prepared from 5'-AMP (3×10^{-4} M), Cu(NO$_3$)$_2$·2H$_2$O (9×10^{-4} M), and bpy (9×10^{-4} M), adjusting pH to ~4 with dilute NaOH solution, and the mixture was allowed to stand at room temperature. Blue columnar crystals formed after ~3 weeks. They were collected, washed with a little water, and air dried. Crystals of [Cu(5'-AMP)-(bpy)(H$_2$O)]$_2$·(NO$_3$)$_2$·6H$_2$O are triclinic, space group $P1$, with $a = 10.195$ (2), $b = 12.305$ (4), $c = 11.805$ (1) Å; $\alpha = 88.92$ (1), $\beta = 108.99$ (1), $\gamma = 104.41$ (1)°; $Z = 1$; $V = 1353.2$ Å^3; $D_m = 1.70$ and $D_c = 1.673$ g cm^{-3}. Intensity data were collected on a Rigaku automated diffractometer with Mo Kα radiation up to a 2θ limit of 45°. The structure was solved by Patterson and difference-Fourier methods and refined to present discrepancy indices R_F[7] and R_{wF} of 0.046 and 0.051, respectively, for 3567 reflections with $F_o \geq 3\sigma(F_o)$.[8]

Figure 1 shows the molecular structure of the dimeric [Cu(5'-AMP)(bpy)(H$_2$O)]$_2^{2+}$ unit, where each AMP molecule exists as a monovalent anion with the N(1) of the adenine base being protonated,[9] and with the phosphate group doubly ionized.[10] The two independent [Cu(5'-AMP)(bpy)(H$_2$O)]$^+$ units are approximately related by a noncrystallographic center of inversion except the sugar parts. The most remarkable features in this structure are that the nucleotide is coordinated to the metal ion through the phosphate group only and not through the base moiety[11] and that the complex forms a metal ion bridged intramolecular stacking adduct, in which the imidazole part of the purine base is stacked on one of the pyridyl
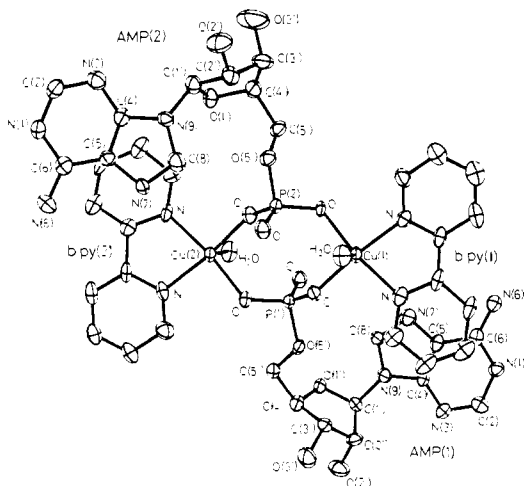

Figure 1. The molecular structure of the dimeric [Cu(5'-AMP)(bpy)-(H₂O)]₂²⁺ unit, showing the metal ion bridged intramolecular stacking between the adenine moieties and the bpy rings.

rings of the bpy ligand at average spacings of 3.4 Å (AMP(1)-bpy(1)) and 3.3 Å (AMP(2)-bpy(2)). The two planes of the aromatic rings are not quite parallel to each other: the tilt angles are 6° (AMP(1)-bpy(1)) and 8° (AMP(2)-bpy(2)), and this is in accordance with an earlier indication[3] from a solution study based on spectroscopic observations. The two independent AMP molecules adopt the energetically favored forms;[12] namely both molecules exhibit the usually observed C(3')-endo[13] (AMP(1)) and C(2')-endo (AMP(2)) sugar puckering modes with the bases anti[14] (χ_{CN}[15] = -2.8° (AMP(1)) and 52.8° (AMP(2)), and with the gauche-gauche[16] conformations about the C(4')-C(5') bond. This result also supports the finding[3] that such a type of adduct is the prominent species in solution for the ternary complex systems containing aromatic amines. Each copper ion is in a distorted (4 + 1) square-pyramidal environment, with the basal plane defined by the two phosphate oxygens of the different nucleotide molecules (Cu(1)-O_{av}, 1.915 Å, and Cu(2)-O_{av}, 1.942 Å) and by a bidentate bpy ligand (Cu(1)-N_{av}, 1.965 Å, and Cu(2)-N_{av}, 2.021 Å) and with the apical position occupied by a water molecule (Cu(1)-OH₂, 2.390 Å, and Cu(2)-OH₂, 2.360 Å).

The dimeric structure is further stabilized in the crystal lattice by hydrogen-bonded adenine-adenine base pairing (N(6)H- - -N(7), 2.98 and 2.89 Å), which is intercalated between the two bpy ligands and which in turn are stacked on one another at an average spacing of 3.4 Å (Figure 2). The stacking is then of the -B-B-A:A-B-B- type (B = bpy and A:A = adenine-adenine base pair), which is a reverse kind of nearest neighbor exclusion effect[17] first found in the complex[18] between 5'-AMP and (terpy)PtCl. However, in the latter complex there are no direct bonds between the metal atom and the nucleotide molecules. The interbase hydrogen bonding via two N(6)H- - -N(7) linkages has often been observed, for example, in double-helical poly(rA),[19] ApApA,[20] UpA,[21] and the A₉: A₂₃ pairing in yeast tRNA^{phe}[22] and in several adenine derivatives,[23] especially those in which the N(1) atom is protonated, probably because the protonation at the N(1) site prohibits the formation of the N(1)- - -HN(6) hydrogen bond. This adenine-adenine self-pairing is further stabilized by two N(6)-H- - -O—P- hydrogen bonds. This situation is common for all adenosine nucleotide structures[19-21] adopting this type of base-pairing scheme except for the A₉:A₂₃ pairing observed in tRNA^{phe}.[22]

The metal coordination geometry and the nature of forming a dimer in the present complex are notably similar to those in the other ternary complexes,[6] [Cu(5'-UMP)(dpa)(H₂O)]₂ and

[Cu(3'-GMP)(phen)(H₂O)]₂, and this confirms an earlier suggestion[6a] that the "phosphate only" type of coordination may be typical for the ternary complexes containing aromatic amines. A counter example exists in the mononuclear ternary complex,[5] [Cu(5'-1MP)(bpy)(H₂O)₂]⁺, where the metal ion binds to the nucleotide molecule through the base only and not through the phosphate group. Clearly, more crystallographic studies are necessary to understand the general binding modes for these ternary complexes.
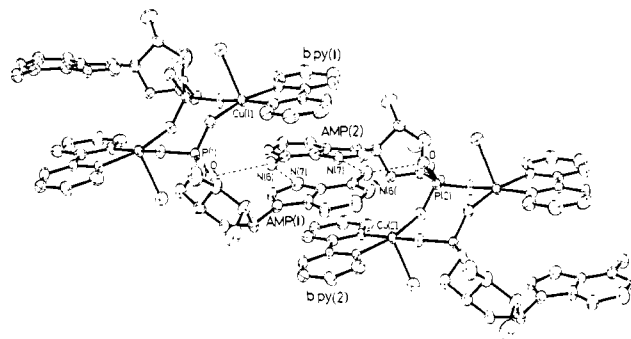
Figure 2. A view of two dimeric units, showing the intermolecular stacking and the adenine-adenine base pair (- - - -, hydrogen bond). Translation of this unit in the vertical direction produces additional head-to-tail stacking of the bpy ligands.

References and Notes

(1) Dimicoli, J.-L; Helene, C. Biochemistry. 1974, 13, 714-723, and references cited therein.
(2) Naumann, C. F.; Prijs, B.; Sigel, H. Eur. J. Biochem. 1974, 41, 209-216.
(3) Naumann, C. F.; Sigel, H. J. Am. Chem. Soc. 1974, 96, 2750-2756.
(4) Abbreviations used in this paper are as follows: bpy for 2,2'-bipyridyl; dpa for 2,2'-dipyridylamine; terpy for 2,2',2''-terpyridine; phen for 1,10-phenanthroline; 5'-AMP, 5'-IMP, and 5'-UMP for the 5'-monophosphates of adenosine, inosine, and uridine, respectively; 3'-GMP for the guanosine 3'-monophosphate; ATP and ITP for the 5'-triphosphates of adenosine and inosine, respectively; UpA for the dinucleoside phosphate of uridyl-3',5'-adenosine; ApApA for the trinucleoside diphosphate adenylyl-3',5'-adenylyl-3',5'-adenosine; poly(rA) for the polyadenylic acid; and tRNA^{phe} for the phenylalanine transfer ribonucleic acid.
(5) Aoki, K. J. Chem. Soc., Chem. Commun. 1977, 600-602.
(6) Two other ternary complexes have appeared. (a) [Cu(5'-UMP)(dpa)-(H₂O)]₂·5H₂O: Fischer, B. E.; Bau, R. J. Chem. Soc., Chem. Commun. 1977, 272-273; Inorg. Chem. 1978, 17, 27-34. (b) [Cu(3'-GMP)(phen)(H₂O)]₂·7H₂O: Wei, C. Y.; Fischer, B. E.; Bau, R. manuscript in preparation. In these structures, the stacking interactions are indeed predominant, but they are of the intermolecular variety (base-base, dpa-dpa, or base-phen) instead of intramolecular.
(7) $R_f = \Sigma |F_o - |F_c|| / \Sigma F_o$ and $R_{wF} = (\Sigma w |F_o - |F_c||^2 / \Sigma wF_o^2)^{1/2}$.
(8) The major computer programs employed in this work have been mentioned elsewhere: Aoki, K; Yamamoto, Y. Inorg. Chem. 1976, 15, 48-52.
(9) The C(2)-N(1)-C(6) angles, 123.8° (AMP(1)) and 122.8° (AMP(2)), clearly show the N(1) protonation (in six-membered nitrogen heterocycles the angle around a nitrogen atom falls into the range 125 ± 3° if there is a proton on a nitrogen atom and in the range 116 ± 3° if there is no proton: Singh, C. Acta Crystallogr. 1965, 19, 861-864). Indeed, the hydrogen atom attached to the N(1) atom could be located in a difference-Fourier map.
(10) The lengths of the P-O bonds clearly show their double bond character: P(1)-O_c (coordinating oxygen), 1.500 and 1.520 Å, and P(1)-O_{nc} (noncoordinating oxygen), 1.480 Å, and P(2)-O_c, 1.514 and 1.524 Å, and P(2)-O_{nc}, 1.517 Å. Indeed, the final difference-Fourier map could reveal no hydrogen atom near the phosphate oxygens.
(11) There are a large number of the metal-nucleotide crystal structures containing metal-base or metal-base and -phosphate bonds. For example, see Gellert, R. W.; Bau, R. in "Metal Ions in Biological Systems"; Vol. 8; Sigel, H. Ed. Marcel Dekker: New York, 1978; in press. In contrast, so far there have been reported only three examples of complexes containing metal-phosphate bonds only: ref 6a and 6b, and [Co₂(5'-UMP)₂(H₂O)₄]_n by Cartwright, B. A.; Goodgame, D. M. L.; Jeeves, I.; Skapski, A. C. Biochim. Biophys. Acta. 1977, 477, 195-198.
(12) Sarma, R. H.; Lee, C.-H.; Evans, F. E.; Yathindra, N.; Sundaralingam, M. J. Am. Chem. Soc. 1974, 96, 7337-7348, and references cited therein.
(13) Jardetsky, C. D. J. Am. Chem. Soc. 1960, 82, 229-233.
(14) Donohue, J.; Trueblood, K. N. J. Mol. Biol. 1960, 2, 363-371.
(15) Sundaralingam, M. Biopolymers. 1969, 7, 821-860.
(16) Schefter, E.; Trueblood, K. N. Acta Crystallogr., 1965, 18, 1067-1077.
(17) Bond, P. J.; Langridge, R.; Jennette, K. W.; Lippard, S. J. Proc. Natl. Acad. Sci. U.S.A. 1975, 72, 4825-4829.
(18) Wong, Y.-H.; Lippard, S. J. J. Chem. Soc., Chem. Commun. 1977, 824-

825.
(19) Rich. A.; Davies, D. R.; Crick, F. H. C.; Watson, J. D. *J. Mol. Biol.* **1961**, *3*, 71–86.
(20) Suck, D.; Manor, P. C.; Germain, G.; Schwalbe, C. H.; Weimann, G.; Saenger, W. *Nature, New Biol.* **1973**, *246*, 161–165.
(21) Rubin, J.; Brennan, T.; Sundaralingam, M. *Biochemistry.* **1972**, *11*, 3112–3128. Sussman, J. L.; Seeman, N. C.; Kim, S.-H.; Berman, H. M. *J. Mol. Biol.*, **1972**, *66*, 403–421.
(22) Kim, S.-H.; Sussman, J. L.; Suddath, P. L.; Quigley, G. J.; McPherson, A.; Wang, A. H. J.; Seeman, N. C.; Rich, A. *Proc. Natl. Acad. Sci. U.S.A.* **1974**, *71*, 4970–4974; Jack, A.; Ladner, J. E.; Klug, A. *J. Mol. Biol.* **1976**, *108*, 619–649.
(23) Johnson, P. L.; Maier, C. A.; Paule, I. C. *J. Am. Chem. Soc.*, **1973**, *95*, 5370–5377, and references cited therein.

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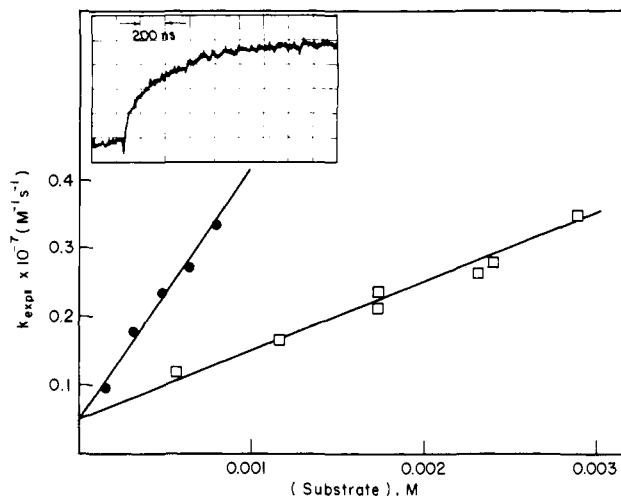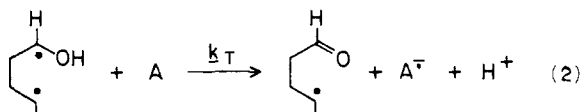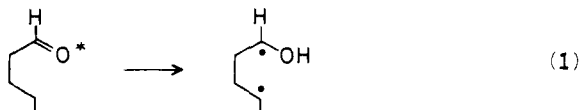
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Figure 1. Kinetic data for the trapping of biradicals by **1** (●) and **2** (□) in water–acetonitrile (1:9). Insert: typical time profile for paraquat 0.00064 M. The initial negative signal is due to fluorescence.

Formation, Trapping, and Lifetime of the Biradicals Generated in the Photochemistry of Valeraldehyde

Sir:

The biradicals produced in the Norrish type II reaction of alkyl aryl ketones have been the subject of a number of studies during the past few years.[1-3] Their formation, trapping, lifetimes, and spectral properties are now reasonably understood. The type II process also plays an important role in the photochemistry of aliphatic carbonyl compounds,[4] but the properties of the intermediate biradicals are largely unknown. The only examples of trapping are those reported by O'Neal for the 2-pentanone–hydrogen bromide system in the gas phase[5] and by Kusokawa and Anpo[6] for the interaction of oxygen with the biradicals from 2-pentanone adsorbed on Vycor glass. O'Neal et al.[5] estimated a biradical lifetime of ~10 μs from Stern–Volmer type of studies. No time-resolved experiments have been reported, and, while some of the techniques used for aromatic ketones[3] should be applicable to aliphatic carbonyl compounds, the wavelengths of the excitation sources usually employed (nitrogen laser, 337.1 nm, or frequency doubled ruby laser, 347.1 nm) are too long for aliphatic ketones. Aldehydes are slightly red shifted with respect to ketones;[7] this shift leads to a weak absorption at 337.1 nm, sufficient for adequate excitation.
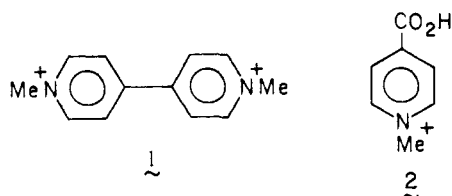
We have examined the photochemistry of valeraldehyde in the presence of the electron acceptors paraquat (1,1'-dimethyl-4,4'-bipyridylium) ions (**1**) and 4-carboxy-1-methylpyridynium (**2**)[8] which behave as efficient biradical traps according to reactions 1 and 2, where the asterisk denotes the triplet state, and A is an electron acceptor, **1** or **2**. The formation of A⁻· can be monitored in time-resolved laser flash

(1)

(2)

photolysis experiments;[3] the corresponding time profiles contain information on both, the rate of trapping k_T and the biradical lifetime τ_B. The buildup of A⁻· follows clean first-order kinetics and the experimental pseudo-first-order rate constants correspond to[10]

$$k_{exptl} = \tau_B^{-1} + k_T[A] \qquad (3)$$

Figure 1 shows plots of k_{exptl} vs. [A] for both electron acceptors. As expected, the slope changes, but the intercept is independent of the trapping agent and gives $\tau_B = 2$ μs in water–acetonitrile (1:9). The rates of trapping are 3.7×10^9 and 1×10^9 M⁻¹ s⁻¹ for **1** and **2**, respectively. Typical aldehyde concentrations were in the 0.35–1.10 M range. The kinetic parameters obtained were independent of this concentration as well as of the light intensity (laser pulses attenuated by a factor of 10).

The assumption and detailed analysis of this type of technique have been reported elsewhere.[3] However, it is important to emphasize that the reaction examined involves the biradical rather than the triplet state and that the lifetime of the latter is short compared with τ_B, a critical condition in this type of study. The triplet lifetime of valeraldehyde has been reported as 10 ns in hexane.[12,13] Further, if at constant paraquat ion concentration one adds a triplet quencher, e.g. *cis*-1,3-pentadiene, the plateau absorbances change, but the kinetics (as measured by k_{exptl}) do not. This is indicative of quenching the precursor of the species leading to A⁻·. In addition, a plot of A_∞^{-1} vs. [diene], where A_∞ is the plateau absorbance due to A⁻·, is linear and leads to $k_q\tau_T = 350$ M⁻¹ from which we estimate a triplet lifetime $\tau_T = 35$ ns,[14] which clearly shows that the condition $\tau_T \ll \tau_B$ is fulfilled. Similar experiments with 2-methylpropionaldehyde which has a comparable triplet lifetime but cannot give biradicals did not lead to the formation of A⁻·.

We have also examined samples of matched absorbance and constant paraquat-ion concentration containing valeraldehyde and γ-methylvalerophenone. Examination of the plateau absorbances and using the value of k_T and τ_B for both biradicals, we estimate that the quantum yield of biradical production (triplet derived) from valeraldehyde is $\phi_B = 0.32$ based on the assumption of $\phi_B = 1$ for γ-methylvalerophenone.[1,4] The value is expected to be lower than unity, reflecting that the quantum yield of intersystem crossing is also <1.[13] It is noteworthy that the signals due to A⁻· from both **1** and **2** are totally quenchable by dienes, indicating that the biradicals trapped arise exclusively from a triplet state reaction. No evidence for the trapping of singlet-derived biradicals was observed.