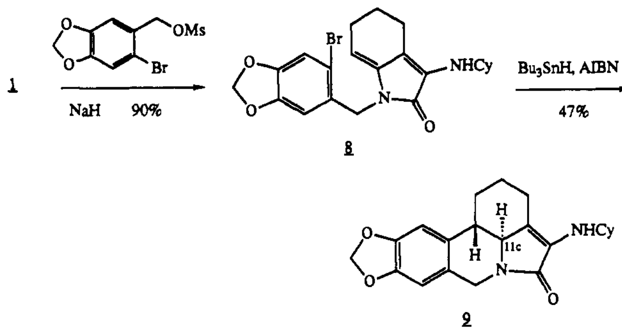
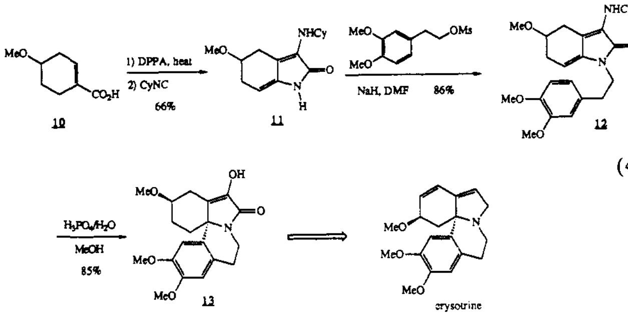


(3)

provided compound **8**[7] (mp 158–160 °C) in 90% yield. Radical-mediated cyclization[9] followed uneventfully to provide the tetracycle **9**[7] (mp 188–190 °C), as a single diastereomer. The exclusive formation of the requisite trans B–C ring fusion in this cyclization is particularly noteworthy since this stereochemical arrangement is often encountered in Amaryllidaceae alkaloids.[10]



(4)

A very concise, formal total synthesis of the *Erythrina* alkaloid, erysotrine, has also been achieved by employing the new methodology.[11] The normal [1 + 4] cycloaddition protocol conducted on 4-methoxy-1-cyclohexenecarboxylic acid (**10**)[12] gave hydroindole **11**[7] in 66% overall yield. Chemoselective N-alkylation at the enamide nitrogen followed by smooth acid-mediated cyclization (presumably via the corresponding *N*-acyliminium ion)[13] produced compound **13**[7] (mp 185–187 °C; lit.[14a] mp 187 °C) as a single diastereomer displaying a fully intact *Erythrina* carbon skeleton. This material has been carried on to erysotrine by Mondon and co-workers and as such constitutes a formal total synthesis of this natural product.[14b]

It is clear from the examples provided that this novel [1 + 4] cycloaddition chemistry is a versatile and powerful method for constructing a wide range of alkaloid systems, and additional applications to total synthesis are underway.

Acknowledgment. We thank the National Science Foundation (CHE-9021206) for their generous support of this work.

Supplementary Material Available: Typical experimental procedures and full characterizations of all new compounds including melting points, ^{1}H and ^{13}C NMR, IR, and mass spectral data, and HRMS and/or combustion analyses (8 pages). Ordering information is given on any current masthead page.

---

(9) Abeywickrema, A. N.; Beckwith, A. L. J.; Gerba, S. *J. Org. Chem.* **1987**, *52*, 4072.

(10) The proton at C_{11c} in compound **9** appeared as a doublet at δ 3.13 with $J = 11$ Hz. Typical trans J values for similar protons in naturally occurring alkaloids range between 10 and 12 Hz: (a) Torssell, K. *Tetrahedron Lett.* **1974**, 623. (b) Kotera, K.; Hamada, Y.; Tori, K.; Aono, K.; Kuriyama, K. *Ibid.* **1966**, 2009.

(11) For a recent review of the *Erythrina* alkaloids, see: Dyke, S. F.; Quessy, S. N. In *The Alkaloids*; Rodrigo, R. G. A., Ed.; Academic Press: New York, 1981; Vol. XVIII, p 1.

(12) Prepared from commercially available 4-methoxycyclohexanecarboxylic acid via a selenenylation–selenoxide elimination sequence: Reich, H. J.; Renga, J. M.; Reich, I. L. *J. Am. Chem. Soc.* **1975**, *97*, 5434.

(13) Tamura, Y.; Maeda, H.; Akai, S.; Ishibashi, H. *Tetrahedron Lett.* **1982**, *23*, 2209.

(14) (a) Mondon, A.; Hansen, K. F.; Boehme, K.; Faro, H. P.; Nestler, H. J.; Vilhuber, H. G.; Böttcher, K. *Chem. Ber.* **1970**, *103*, 615. (b) Mondon, A.; Nestler, H. J. *Angew. Chem., Int. Ed. Engl.* **1964**, *3*, 588.

Yields of Excited Carbonyl Species from Alkoxyl and from Alkylperoxyl Radical Dismutations

G. David Mendenhall* and X. Christopher Sheng[1]

Department of Chemistry, Division of Chemical Sciences
Michigan Technological University
Houghton, Michigan 49931

Thérèse Wilson

The Biological Laboratories, Harvard University
Cambridge, Massachusetts 02138

Received June 4, 1990
Revised Manuscript Received September 17, 1991

Recently Niu and Mendenhall reported that the yields of singlet *molecular oxygen* from the self-reactions of simple alkylperoxyl radicals averaged about 0.1 and did not change much with changes in alkyl structure.[2] In this communication we show that the yields of excited *carbonyl* species, generated from reactions 1–3, are 10^3–10^4 less and vary by about 1 order of magnitude with changes in alkyl group.

$$t\text{-BuON=NO-}t\text{-Bu} \rightarrow 2\,t\text{-BuO}^\bullet + N_2 \qquad (1)$$

$$R_1R_2CHOOH + t\text{-BuO}^\bullet \rightarrow R_1R_2CHOO^\bullet + t\text{-BuOH} \qquad (2)$$

$$2R_1R_2CHOO^\bullet \rightarrow\rightarrow R_1R_2C{=}O(S_0,S_1,T_1) + R_1R_2CHOH + O_2(T_0,S_1) \qquad (3)$$

The yields of excited states were determined from the initial chemiluminescence emission from solutions 0.01–0.03 M in alkyl hydroperoxide[3] and *tert*-butyl hyponitrite initiator (BHN), by titration with 2-*tert*-butyl-9,10-dibromoanthracene (tDBA) (physical trap):

$$R_1R_2C{=}O(T_1) + tDBA(S_0) \rightarrow\rightarrow R_1R_2C{=}O(S_0) + tDBA(S_1) \qquad (4a)$$

$$\rightarrow R_1R_2C{=}O(S_0) + tDBA(T_1,S_0) \qquad (4b)$$

$$tDBA(S_1) \rightarrow tDBA(S_0) + h\nu \qquad (5)$$

Plots of 1/[tDBA] vs 1/(chemiluminescence intensity) were obtained, from which the product of the rate of energy transfer to fluorescer and the carbonyl excited-state lifetime, $k_{et}\tau$, and the relative yields of excited carbonyl species were calculated from the slope and intercept ($1/I_\infty$) by well-established procedures.[4]

For each carbonyl product, values of Φ_{TS}, defined as the ratio $k_{4a}/(k_{4a} + k_{4b})$, were independently obtained by analysis of the double-exponential decay curves of tDBA fluorescence, obtained by the single photon counting method following pulse excitation of degassed solutions of tDBA and the carbonyl compound.[5] The resulting values, along with current and corrected data from previous studies, appear in Table I. The lifetime of triplet benzaldehyde in t-BuPh was too short to obtain Φ_{TS}, and solutions of formaldehyde in organic solvents are too unstable to make reliable measurements.[6]

The values of $k_{et}\tau$ correspond to excited-state lifetimes on the order of 100 ns, consistent with triplet lifetimes in aerated solutions.

---

* Author to whom correspondence should be addressed. This work was presented at the symposium in honor of Frank Mayo, 198th Meeting of the American Chemical Society, Miami Beach, FL, Sept 1989.

(1) This work taken in part from the Masters Thesis of X. C. Sheng, Michigan Technological University, 1990.

(2) Niu, Q.; Mendenhall, G. D. *J. Am. Chem. Soc.* **1990**, *112*, 1656–7. Niu, Q.; Mendenhall, G. D. *J. Am. Chem. Soc.*, manuscript in press.

(3) Free-radical initiation with BHN in air-saturated ethylbenzene afforded PhCHMeOO$^\bullet$ radicals directly (Table I).

(4) Wilson, T.; Golan, D. E.; Harris, M. S.; Baumstark, A. L. *J. Am. Chem. Soc.* **1976**, *98*, 1086–91 and references therein.

(5) Catalani, L. H.; Wilson, T. *J. Am. Chem. Soc.* **1987**, *109*, 7458–62.

(6) Walker, J. F. *Formaldehyde*; 3rd ed.; Reinhold: New York, 1964; p 52.

0002-7863/91/1513-8976$02.50/0

Table I. Excitation Yields of Carbonyl Products from Peroxyls

reaction[a]	solvent, T, °C	[BHN],[b] M	$k_{et}\tau/10^3$	Φ_{ST}[c]	S_T[d]
$2Me_2CHOO^\bullet \rightarrow Me_2CO$	Ph-*t*-Bu, 27	0.016	4.1	0.10	3×10^{-5} $(5 \times 10^{-6}–5.5 \times 10^{-4})$[e]
	MeCN, 28	0.002	1.6	0.05	$(5 \pm 1) \times 10^{-4}$
$2EtOO^\bullet \rightarrow MeCHO$	Ph-*t*-Bu, 26	0.0015	1.2	0.20	$(2 \pm 1) \times 10^{-5}$
	MeCN, 31	0.0013	1.6	0.05	$(6 \pm 1) \times 10^{-4}$[f]
$2PhMeCHOO^\bullet \rightarrow PhCOMe$	PhEt, 27.6	0.01	0.45	0.07[g]	$(5 \pm 2) \times 10^{-4}$
$2PhCH_2OO^\bullet \rightarrow PhCHO$	MeCN, 26	0.0013–0.016	4.6	0.025	$(1 \pm 0.3) \times 10^{-4}$
$2TOO^\bullet \rightarrow$ 1-tetralone	Ph-*t*-Bu, 27	0.015	0.60	0.008	$(1 \pm 0.1) \times 10^{-4}$

[a] Reaction sequence 1–3 assumed. [b] Rates of decomposition of BHN in *t*-BuPh calculated from activation parameters in ref 12; in MeCN, we measured $k_d = 1.06 \times 10^{-6}$ s^{-1} at 25.5 °C and assumed E_a = 27 kcal/mol to calculate k_d at other temperatures. Cage effects from ref 12 or assumed 10%. [c] Fraction triplet carbonyl that gives excited singlet tDBA in the indicated solvent. [d] Fraction of reaction 3 giving triplet carbonyl products, relative to 3,3,4,4-tetramethyldioxetane (TMD) in the same solvent with S_T = 0.3 (ref 10). Average of two or more determinations. Values of k_d for TMD in *t*-BuPh calculated from activation parameters in ref 8. For acetonitrile k_d estimated as 8×10^{-7} s^{-1} at 24.7 °C (extrapolated value in CCl_4 from the following: Kopecky, K. R., et al. *Can. J. Chem.* **1975**, *53*, 1103). [e] Aliquot of TMD added to reaction mixture and S_T calculated from increases in luminescence. [f] Determined relative to S_T for $2Me_2CHOO^\bullet$. [g] Determined in *t*-BuPh at 44 °C.

We infer that triplets are the predominant excited state in all cases from reaction 3.[7]

Values of S_T, the fractional excited-state yield of triplets, in Table I are low, from 2×10^{-5} to 6×10^{-4}. The effect of alkyl structure is minor. Differences between S_T for a given peroxyl in the two solvents *t*-BuPh and acetonitrile are at most 1 order of magnitude and comparable to errors in extrapolating the various rate constants. In some cases (e.g., 2-PrOOH in *t*-BuPh), the reproducibility of the experiments was not good.

With the specific values of Φ_{TS} determined here, we can now refine some previously reported values of S_T for the related *alkoxyl* self-reactions:[8]

$$2R_1R_2CHO^\bullet \rightarrow R_1R_2CHOH + R_1R_2C{=}O(S_0,T_1) \quad (6)$$

The corrected yields of triplets based on *reacting*, caged alkoxyl pairs derived from hyponitrites[9] are as follows: for acetophenone, 1.5%; for acetaldehyde, 0.12%; for acetone, 1.8%; and for 1-tetralone, 8.3%. These values are quite high and comparable to triplet yields reported from thermolysis of many dioxetanes.[10]

We reported previously[8] that reaction 6 gave the lowest yields of excited states in *t*-BuPh when the carbonyl product was formaldehyde, benzaldehyde, or benzophenone. The triplet energies of these three compounds are 72 kcal or less.[11] Since a higher triplet state of DBA, located at 74.6 kcal, mediates the overall TS energy transfer,[5] eq 4a, it is not surprising that Φ_{TS} would be low for the two aldehydes and negligibly small in the case of benzophenone. In addition, *t*-BuPh was found to quench triplet benzaldehyde, whereas acetonitrile, used here, does not.

From the corrected data corresponding to eq 6 and the data in Table I, we calculate carbonyl product excitation ratios for reaction 6/reaction 3 of 30 for R_1R_2 = 1-phenylethyl, 830 for 1-tetralyl, and about 600 for 2-propyl substituents. For the first two examples, these ratios are larger than those we reported, obtained by an indirect method.[12]

In some cases we have observed that competing luminescent reactions are present in our systems, and it may be prudent to regard our S_T values as upper limits for excitation according to reaction 3. For instance, a value of S_T for the sequence 1–3 could not be carried out with 1-tetralyl hydroperoxide in acetonitrile because, even in the absence of initiator, a relatively high luminescence was observed in this solvent that increased rapidly with time. Similarly, initiated solutions of 2-propyl hydroperoxide in *t*-BuPh containing small amounts of tDBA showed a linear, 5-fold increase in luminescence during 24-h observation. These observations afford potentially valuable insights into slow initiation processes and are under further study.

In summary, values of $S_{triplet}$ decrease in the order of precursor dioxetane > alkoxyl pair ≫ peroxyl pair. The differences in chemiluminescence emission intensities from reactions 6 and 3 with different alkyl groups are due in part to different photophysical pathways for decay of the first-formed triplets, which are generated with efficiencies spanning about a factor of 10 for reaction 3 and a factor of 10^2 for reaction 6. Solvent effects on triplet yields from peroxyl reaction 3 are small from the limited data in Table I. Correspondingly, for self-reaction of 2-propoxyl to give excited acetone in three solvents, the triplet yields differ only by a factor of about 20.[8]

Acknowledgment. This work was generously supported by grants from Himont USA, Inc., and 3M Company.

---

(7) For six other aliphatic ROOH (*t*-BuPh, 43 °C), we have measured values of $k_{et}\tau$ between 130 and 650.[1] These data are not included in Table I because we have not measured the values of Φ_{TS} for the carbonyl products.

(8) Quinga, E. M. Y.; Mendenhall, G. D. *J. Am. Chem. Soc.* **1986**, *108*, 474–8.

(9) In nonviscous solvents, reaction 6 is a minor pathway and most of the alkoxyls undergo diffusive escape from the solvent cage.

(10) Adam, W.; Beinhauer, A.; Hauer, H. In *Handbook of Organic Photochemistry*; Scaiano, J. C., Ed.; CRC Press: Boca Raton, FL, 1989; Vol. II, Chapter 12.

(11) (a) Benzophenone, E_T = 69 kcal;[11b] benzaldehyde E_T = 72 kcal;[11c] formaldehyde E_T = 72 kcal.[11d] (b) Carmichael, I.; Hug, G. L. In *Handbook of Organic Photochemistry*; Scaiano, J. C., Ed.; CRC Press: Boca Raton, FL, 1989; Vol. 1, Chapter 16. (c) Murov, S. L. *Handbook of Photochemistry*; Marcel Dekker: New York, 1973; Table 1-1. (d) Herzberg, G. *Electronic Spectra of Polyatomic Molecules*; Van Nostrand: Princeton, NJ, 1966; p 518.

(12) Lee, S.-H.; Mendenhall, G. D. *J. Am. Chem. Soc.* **1988**, *110*, 4318–23.

Directed Formation of Carbon–Bromine and Carbon–Sulfur Bonds by Tandem Radical Chain Reactions

David Wiedenfeld and Ronald Breslow*

Department of Chemistry, Columbia University
New York, New York 10027

Received July 29, 1991

We have described the remote chlorination of steroids and flexible chain molecules directed by attached template species.[1] In this process a chlorine atom becomes temporarily bound to the iodine of an iodophenyl template[2] or the nitrogen of a pyridine[3,4] or oxygen of a pyridine *N*-oxide,[5] which are attached as esters to a substrate hydroxyl group. The geometry of the template directs hydrogen abstraction by the complexed chlorine atom. In a second step, the resulting substrate radical then reacts with the

---

(1) For recent reviews, see: (a) Breslow, R. *Chemtracts Org. Chem.* **1988**, *1*, 333–348. (b) White, P.; Breslow, R. *J. Am. Chem. Soc.* **1990**, *112*, 6842–6847.

(2) Breslow, R.; Snider, B. B.; Corcoran, R. J. *J. Am. Chem. Soc.* **1974**, *96*, 6791–6793.

(3) Breslow, R.; Brandl, M.; Hunger, J.; Adams, A. D. *J. Am. Chem. Soc.* **1987**, *109*, 3799–3801.

(4) Breslow, R.; Brandl, M.; Hunger, J.; Turro, N. J.; Cassidy, K.; Krogh-Jespersen, K.; Westbrook, J. D. *J. Am. Chem. Soc.* **1987**, *109*, 7204–7206.

(5) Breslow, R.; Adams, A.; Brandl, M.; Guo, T.; Hunger, J. *Lectures Heterocycl. Chem.* **1987**, *9*, 43–50.

0002-7863/91/1513-8977$02.50/0