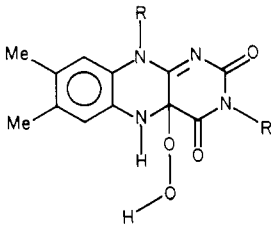
The reactivity of 1 toward 2,3-dimethyl-2-butene[10] compares well with that of 2-hydroperoxyhexafluoro-2-propanol[5] and appears to be greater than that of α-peroxy esters and nitriles.[6] The reactivity of 2-hydroperoxyhexafluoro-2-propanol can be rationalized[5] by structural similarities with peracids as well as the presence of electron-withdrawing substitutents. For α-peroxy esters, ketones, amides, and nitriles,[6] intramolecular hydrogen bonding similar to that in peracids[11] appears to account for the epoxidation reaction. Similarly, 1 can also be considered a peracid analogue. Intramolecular hydrogen bonding of the peroxy hydrogen in 1 to the ring nitrogen as well as the slightly electron-withdrawing substituents could then be the major factors for the increased reactivity of 1 as compared to that of alkyl hydroperoxides.

There are structural similarities between 1 and flavin 4a-hydroperoxides (3). Flavin 4a-hydroperoxides are



3

believed to be important intermediates in external flavoprotein monooxygenase activity[12] including bacteria bioluminescence.[13] Hamilton suggested[12a] that flavin 4a-peroxides undergo rearrangement to a carbonyl oxide intermediate (oxenoid[12a] intermediate) that would then be the oxygen-transfer agent in several monooxygenase reactions. A number of oxygen-transfer reactions have been suggested[6b,14] as model systems for these biochemical systems. The model system results[14c] of Bruice[15] have shown that flavin hydroperoxides are capable of oxidation of amines and sulfides. Preliminary results from 1 show that it will also readily oxidize amines and sulfides. It appears that 1 may mimic many of the reactions of flavin 4a-hydroperoxides. The reaction[16] of 1 with *N,N*-dimethylaniline or diphenyl sulfide produced 2 (50% isolated yield in both cases) and the corresponding amine oxide or sulfoxide in good yield. The amine oxide (isolated by crystallization) and the sulfoxide (isolated by preparative GC) were characterized by comparison of spectra with those of authentic samples. The reaction of 1 (0.1 M in $CDCl_3$) with diphenyl sulfide (5-fold excess) was complete within 10 min while the reaction of 1 and *N,N*-dimethylaniline, under similar conditions, was complete after 1 h.

Our data indicate that a hydroperoxide can be sufficiently reactive to effect oxygen-transfer chemistry without added catalysts to generate more reactive species. The reactions of 1 and similar peroxides[4-6] parallel those shown by flavin 4a-hydroperoxides[14,15] and suggest the continued study of these compounds as models for in vivo enzymatic monooxygenase activity.

We are continuing to investigate the oxygen-transfer properties of 1 to further evaluate 1 as a model for flavin systems.

**Acknowledgment** is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research and to NIH (Grant RR 09201).

**Registry No.** 1, 76847-41-1; 2, 76847-42-2; 2,3-dimethyl-2-butene, 563-79-1; tetramethylethylene oxide, 5076-20-0.

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(10) Dialkyl olefins did not undergo epoxidation upon treatment with 1 (underwent normal thermal decomposition[9]). Enol ethers underwent reaction with 1 to produce 2 and a variety of epoxide rearrangement products.

(11) (a) Reference 1, pp 750–1. (b) Reference 2, p 472–5.

(12) (a) Hamilton, G. A. *Prog. Bioorg. Chem.* **1971**, *1*, 83–157. (b) Massey, V. Hemmerich, P. *Enzymes* **1976**, *12*, 191–252. (c) Bruice, T. C. *Prog. Bioorg. Chem.* **1976**, *4*, 1–87.

(13) Hasting, J. W. *CRC Crit. Rev. Biochem.* **1978**, 163.

(14) (a) Reference 5. (b) Keay, R. E.; Hamilton, G. A. *J. Am. Chem. Soc.* **1975**, *97*, 6876. (c) Ball, S.; Bruice, T. C. *Ibid.* **1980**, *102*, 6498 and references therein.

(15) (a) Iwata, M.; Bruice, T. C.; Carrell, H. L.; Glusker, J. P. *J. Am. Chem. Soc.* **1980**, *102*, 5036 and references therein. (b) Ball, S.; Bruice, T. C. *Ibid.* **1979**, *101*, 4017.

(16) Inclusion of small amounts of *cis*-3-hexene[10] in the reaction mixture increased the isolated yields of 2 dramatically. 2 shows increased stability in the presence of olefins.

## Photochemical Reaction of *N,N*-Dialkyl β,γ-Unsaturated Amides. Intramolecular Hydrogen-Transfer Reactions of Acyclic Olefins via Seven-Membered Cyclic Transition States

*Summary:* *N,N*-Dibenzyl and *N,N*-diallyl β,γ-unsaturated amides undergo cyclization on irradiation to give the corresponding pyrrolidin-2-ones via an unprecedented 1,6-hydrogen shift in acyclic olefins, while *N,N*-diethyl and *N,N*-diisopropyl β,γ-unsaturated amides are unreactive toward photolysis.

*Sir:* Photocyclization via intramolecular hydrogen transfer (e.g., type II cyclization) is one of the most important reactions in the photochemistry of ketones,[1] thioketones,[2] and olefins.[3] Recently, intramolecular hydrogen-transfer reactions of olefins have received considerable attention.[3,4] In the case of acyclic olefins these reactions are quite inefficient, and the inefficiency has been attributed to the presence of competitive processes such as cis–trans isomerization.[4] Thus, photocyclization of olefins via intramolecular hydrogen transfer has been limited to cyclic olefins. It is well-known that intramolecular hydrogen transfer through seven-membered cyclic transition states (1,6-hydrogen shift) is less favorable than that through six-membered ones (1,5-hydrogen shift) in acyclic systems.[5] Consequently, the photochemical 1,6-hydrogen shift of acyclic olefins has not yet been reported.[6]

(1) Wagner, P. J. *Acc. Chem. Res.* **1971**, *4*, 168.

(2) (a) Ho, K. W.; de Mayo, P. *J. Am. Chem. Soc.* **1979**, *101*, 5725. (b) Aoyama, H.; Suzuki, S.; Hasegawa, T.; Omote, Y. *J. Chem. Soc., Chem. Commun.* **1979**, 899.

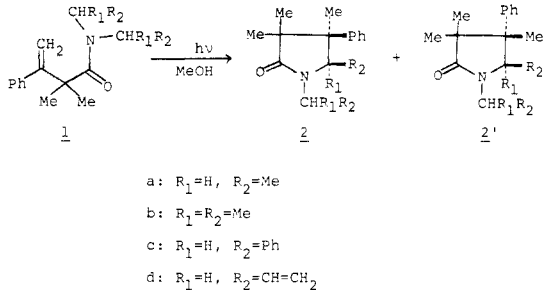
(3) Padwa, A.; Blacklock, T. J.; Chou, C. S.; Hatanaka, N. *J. Am. Chem. Soc.* **1979**, *101*, 5743 and references cited therein.

(4) Hornback, J. M.; Proehl, G. S. *J. Am. Chem. Soc.* **1979**, *101*, 7367 and references cited therein.

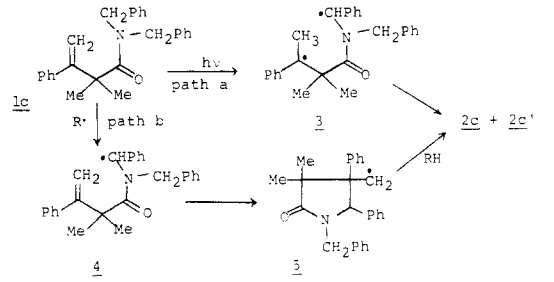
(5) Wagner, P. J.; Kelso, P. A.; Kemppainen, A. E.; Zepp, R. G. *J. Am. Chem. Soc.* **1972**, *94*, 7500.

0022-3263/81/1946-1965$01.25/0 

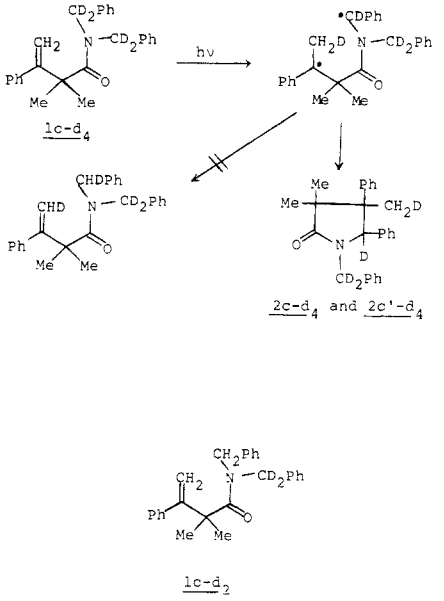
**Scheme I**



**Scheme II**



**Scheme III**



In relation to our previous studies on photocyclization of $\alpha,\beta$-unsaturated amides[7] and $\beta$-oxo amides,[8] we now report that of $\beta,\gamma$-unsaturated amides which involves an unprecedented 1,6-hydrogen transfer of olefins. This reaction also provides the first example of photocyclization of acyclic olefins via intramolecular hydrogen transfer.

*N,N*-Dialkyl $\beta,\gamma$-unsaturated amides (**1a–d**) were prepared by reaction of the corresponding $\beta$-oxo amides with methylmagnesium iodide followed by dehydration. Two methyl groups at the position $\alpha$ to the amides were introduced in order to avoid photochemical or thermal isomerization to $\alpha,\beta$-unsaturated amides. The *N,N*-diethyl amide (**1a**) and *N,N*-diisopropyl amide (**1b**) were unreactive toward photolysis, and prolonged irradiation of them resulted in the formation of intractable mixtures. On the other hand, when *N,N*-dibenzylamide (**1c**) in methanol was irradiated with a low-pressure mercury lamp, pyrrolidin-2-ones, **2c** (51%) and **2c′** (7%), were obtained. Photolysis of **1c** in acetonitrile gave a similar result. The structures of the products were determined on the basis of elemental analysis and spectral data.[9] The stereochemistry of **2c** and **2c′** was tentatively assigned as shown in Scheme I on the basis of the NMR spectra.[10] Photolysis of *N,N*-diallyl amide **1d** also gave the corresponding pyrrolidinones (**2d** and **2d′**; total 16%) which were not completely separated.

The formation of pyrrolidinone **2** is quite reasonably explained in terms of 1,6-hydrogen shift and subsequent cyclization of the resulting 1,5-biradical (**3**, Scheme II, path a). It may be conceivable that some radicals formed during irradiation[11] initiate the cyclization (path b). However, this mechanism is improbable because (a) addition of ethanethiol (a radical scavenger[12]) did not alter the efficiency of the reaction of **1c** and (b) isomerization of the radical (**4** to **5**) is energetically unfavorable and should be inefficient.

Furthermore, evidence in support of path a was obtained by the experiment using a deuterium-labeled amide (**1c**-$d_4$). Irradiation of **1c**-$d_4$ gave cyclization products, **2c**-$d_4$ and **2c′**-$d_4$, in which one of benzylic deuterium atoms of **1c**-$d_4$ was completely incorporated into the $C_4$-methyl group. These results lead to the conclusion that the cyclization of **1c** or **1d** proceeds through an unprecedented 1,6-hydrogen shift in acyclic olefins.

The inertness of **1a** toward photolysis is explainable by the strength of the methylene C–H bonds because it is known that the rate of hydrogen transfer of olefins is sensitive to the strength of the C–H bonds being broken.[3] However, the reason for the nonreactivity of **1b** is not clear at present since reactivity of isopropyl methyne hydrogens toward abstraction by excited olefins[3] or ketones[1] is comparable to that of benzylic hydrogens.

The behavior of 1,5-biradical **3** is worth noting. The photolysis of **1c**-$d_4$ was stopped at 67% conversion, and the recovered **1c**-$d_4$ was examined by NMR spectroscopy. The spectrum clearly showed that no deuterium scrambling took place between the benzylic deuterium atoms and olefinic hydrogen atoms (Scheme III). This fact indicates that the 1,5-biradical does not undergo reverse hydrogen transfer to give the original amide but cyclizes exclusively to yield the pyrrolidinones. This result is intriguing because 1,5-biradicals formed by $\delta$-hydrogen abstraction of phenyl ketones[5] or phenyl thioketones[2] undergo efficient reverse hydrogen transfer (more than 96% in the case of a phenyl ketone[5]).

Photoreaction of **1c** or **1d** took place by direct irradiation, as described above, and was not sensitized by 3-methoxyacetophenone ($E_T$ = 72 kcal), xanthone (74 kcal),

(6) Padwa reported photochemical intramolecular disproportionation of a 3-substituted cyclopropene which might involve a 1,6-hydrogen shift. However, the reaction is also explainable in terms of a 1,5-hydrogen shift.[3]

(7) (a) Aoyama, H.; Hasegawa, T.; Okazaki, M.; Omote, Y. *J. Chem. Soc., Perkin Trans. 1* **1979**, 263. (b) Hasegawa, T.; Watabe, M.; Aoyama, H.; Omote, Y. *Tetrahedron* **1977**, *33*, 485.

(8) (a) Hasegawa, T.; Aoyama, H.; Omote, Y. *J. Chem. Soc., Perkin Trans. 1* **1979**, 963. (b) Hasegawa, T.; Inoue, M.; Aoyama, H.; Omote, Y. *J. Org. Chem.* **1978**, *43*, 1005. Photocyclization of related oxoamides has been reported: (c) Aoyama, H.; Hasegawa, T.; Watabe, M.; Shiraishi, H.; Omote, Y. *Ibid.* **1978**, *43*, 419; (d) Aoyama, Hh.; Hasegawa, T.; Omote, Y. *J. Am. Chem. Soc.* **1979**, *101*, 5343.

(9) **2c**: mp 138.5–139.5 °C; IR ($CHCl_3$) 1670 $cm^{-1}$; NMR ($CDCl_3$) $\delta$ 1.06 (s, 3 H), 1.12 (s, 3 H), 1.35 (s, 3 H), 3.63 and 5.29 (AB q, 2 H), 4.21 (s, 1 H), 6.5–6.65 (m, 2 H), 6.85–7.35 (m, 13 H); **2c′**: mp 157–159 °C; IR ($CHCl_3$) 1675 $cm^{-1}$; NMR ($CDCl_3$) $\delta$ 0.60 (s, 3 H), 1.12 (s, 3 H), 1.21 (s, 3 H), 3.74 and 5.40 (AB q, 2 H), 5.01 (s, 1 H), 6.9–7.6 (m, 15 H).

(10) The NMR spectrum of the major product **2c** shows a signal of aromatic protons at an unusually high field.[9] This suggests that the phenyl groups at $C_4$ and $C_5$ are cis.

(11) Tertiary amides have been known to undergo type I reaction ($\alpha$-cleavage): Nicholls, C. H.; Leermakers, P. A. *J. Org. Chem.* **1970**, *35*, 2754.

(12) Koenig, T.; Fischer, H. *Free Radicals* **1973**, *2*, 163.

or acetone (79–82 kcal).[13] Moreover, the reaction was not quenched by 1,3-pentadiene (59 kcal; 0.1 M). These results indicate that the photoreaction occurs from the singlet state. This is quite unusual because, to our best knowledge, hydrogen abstraction of olefins from the singlet states has not been reported. The quantum yield of the reaction of **1c** was $0.04_9$ (consumption of **1c**) and was much higher than that of 1,5-hydrogen transfer reaction of an $\alpha$-alkylstyrene from the triplet state ($\Phi = 0.0005$).[4] The isotope effects were measured by using **1c**-$d_2$.[14] The value, $\Phi_H/\Phi_D = 2.0$, is considerably smaller than that of the triplet-state reaction of the alkylstyrene ($\Phi_H/\Phi_D \simeq 5$).[4] In view of these results, it is conceivable that the photocyclization of **1c** involves sequential electron–proton transfer[15] rather than one-step hydrogen atom transfer, although electron transfer from amides to excited olefins has not been reported. The scope and further mechanistic studies of the photocyclization are being studied.

**Registry No.** **1a**, 76916-92-2; **1b**, 76916-93-3; **1c**, 76916-94-4; **1d**, 76916-95-5; **2c**, 76916-96-6; **2c'**, 76916-97-7; **2d**, 76916-98-8; **2d'**, 76916-99-9; *N,N*-diethyl-2,2-dimethyl-3-oxo-3-phenylpropionamide, 76917-00-5; *N,N*-diisopropyl-2,2-dimethyl-3-oxo-3-phenylpropionamide, 76917-01-6; *N,N*-dibenzyl-2,2-dimethyl-3-oxo-3-phenylpropionamide, 61845-93-0; *N,N*-diallyl-2,2-dimethyl-3-oxo-3-phenylpropionamide, 76917-02-7; methyl iodide, 74-88-4.

(13) Murov, S. L. "Handbook of Photochemistry"; Marcel Decker: New York, 1973.
(14) A similar measurement of isotope effects has been reported: Padwa, A.; Eisenhardt, W.; Gruber, R.; Pashayan, D. *J. Am. Chem. Soc.* **1971**, *93*, 6998.
(15) (a) Padwa, A.; Gruber, R. *J. Am. Chem. Soc.* **1970**, *92*, 107. (b) Wagner, P. J.; Kemppainen, A. E.; Jellinek, T. *Ibid.* **1972**, *94*, 7512; (c) Arnold, D. R.; Maloulis, A. *Ibid.* **1977**, *99*, 7355.

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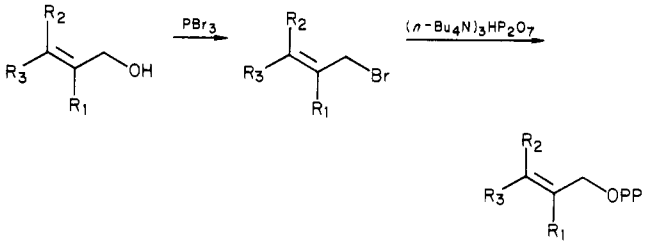
## Tris(tetra-*n*-butylammonium) Hydrogen Pyrophosphate. A New Reagent for the Preparation of Allylic Pyrophosphate Esters

*Summary:* Tris(tetra-*n*-butylammonium) hydrogen pyrophosphate was used to prepare dimethylallyl pyrophosphate (**1**-OPP), 7-methylocta-2,6-dien-1-yl pyrophosphate (**2**-OPP), geranyl pyrophosphate (**3**-OPP), 2-fluorogeranyl pyrophosphate (**4**-OPP), and farnesyl pyrophosphate (**5**-OPP) from the corresponding alcohols in moderate yields by a two-step sequence via the corresponding primary, allylic bromides.

*Sir:* Pyrophosphate esters of allylic alcohols are important intermediates in terpene metabolism.[1] Since the pyrophosphate group is introduced very early in the pathway,[2] most biological syntheses of the allylic substrates begin with acetate or mevalonate and lack flexibility for the preparation of analogues. Although terpene allylic pyrophosphates were discovered in the late 1950's[3,4] few chemical syntheses from the corresponding alcohols have been reported. The lack of success in this area is undoubtedly due to two reinforcing factors—the 3,3-dialkyl allylic moiety typically found in the substrates is highly reactive,[5] and phosphate and pyrophosphate residues are superb leaving groups when they bear little or no negative charge.[6] The only procedure routinely used to synthesize allylic pyrophosphates was first reported in 1959[7] and has not been significantly altered since then.[8,9] This one-pot sequence involves treating the alcohol with inorganic phosphate and trichloroacetonitrile. The desired product must then be isolated from a complex mixture of organic and inorganic mono-, di-, and triphosphates by ion-exchange chromatography. Yields are sometimes as high as 30% but are often less. In addition, the procedure is difficult to manage if more than ca. 50 mg of product is desired.

It occurred to us that many of the problems presented by the highly reactive terpene system could be circumvented if the carbon–oxygen bond were introduced in a final step by utilizing a salt of inorganic pyrophosphate in a direct displacement. We now report a two-step procedure for synthesis of primary allylic pyrophosphate esters from the corresponding alcohols via the bromides as illustrated below. Moderate (i.e., 46–54%) yields were obtained for dimethylallyl alcohol (**1**-OH, $R_1 = H$; $R_2 = R_3 = CH_3$),[10] 7-methyl-2,6-octadien-1-ol (**2**-OH, $R_1 = R_2 = H$; $R_3 = C_6H_{11}$),[11] geraniol (**3**-OH, $R_1 = H$; $R_2 = CH_3$; $R_3 = C_6H_{11}$),[10] 2-fluorogeraniol (**4**-OH, $R_1 = F$; $R_2 = CH_3$; $R_3 = C_6H_{11}$),[12] and farnesol (**5**-OH, $R_1 = H$; $R_2 = CH_3$; $R_3 = C_{11}H_{19}$).[13]




Tris(tetra-*n*-butylammonium) hydrogen pyrophosphate is a white, hygroscopic solid which is soluble in acetonitrile and dimethyl sulfoxide. The material was prepared by passing a solution of disodium dihydrogen pyrophosphate (Stauffer) through a column of Dowex 50W-X8 ($H^+$ form) cation-exchange resin and titration of the acidic eluant to pH 7.0 with tetra-*n*-butylammonium hydroxide (Aldrich). Water was removed by lyophilization, and the powdery residue was stored over phosphorus pentoxide until used.

All of the primary allylic bromides used in the study were prepared from the corresponding alcohols by treatment with phosphorus tribromide.[15,16] Because of their

(1) Poulter, C. D.; Rilling, H. C. *Acc. Chem. Res.* **1978**, *11*, 307–313.
(2) Nes, W. R.; McKean, M. L. "Biochemistry of Steroids and Other Isoprenoids"; University Park Press: Baltimore, MD, 1977; pp 159–161.
(3) Lynen, F.; Eggerer, H.; Henning, U.; Kessel, I. *Agnew. Chem.* **1958**, *70*, 738–742.
(4) Lynen, F.; Agranoff, B. W.; Eggerer, H.; Henning, U.; Moslein, E. M. *Agnew. Chem.* **1959**, *71*, 657–662.
(5) Astin, K. B.; Whiting, M. C. *J. Chem. Soc., Perkin Trans. 2* **1976**, 1157–1160.
(6) Tidd, B. K. *J. Chem. Soc. B* **1971**, 1168–1176.
(7) Cramer, F.; Bohm, W. *Angew. Chem.* **1959**, *71*, 775.
(8) Cramer, W. D.; Weiman, G. *Chem. Ind. (London)* **1960**, 46.
(9) Cornforth, R. H.; Popjak, G. *Methods Enzymol.* **1969**, *15*, 359–390.
(10) Obtained from Aldrich.
(11) The synthesis of **2**-OH, including spectral data and combustion analyses for all new compounds, will be presented elsewhere.
(12) Poulter, C. D.; Argyle, J. C.; Mash, E. A. *J. Biol. Chem.* **1978**, *253*, 7227–7233.
(13) Prepared by reduction of methyl farnesate[14] with diisobutylaluminum hydride.
(14) Sum, F. W.; Weiler, L. *J. Am. Chem. Soc.* **1979**, *101*, 4401–4403.
(15) Coates, R. M.; Ley, D. A.; Cavender, P. L. *J. Org. Chem.* **1978**, *43*, 4915–4922.

0022-3263/81/1946-1967$01.25/0 