Jeanette M. Erhardt, Edward R. Grover, James D. Wuest*

Department of Chemistry, Harvard University
Cambridge, Massachusetts 02138

Received December 26, 1979

Reactions with Olefins in Condensed Phases of O(³P) Atoms Produced by Microwave Discharge

Sir:

The reactions of ground-state oxygen atoms with olefins in the gas phase have been investigated extensively by Cvetanović,[1] Havel,[2] and their co-workers, but only limited knowledge exists on these reactions in the condensed phases.[1h] Recently, Sakurai et al.[3] and Sato et al.[4] reported on oxidations of olefins dissolved in liquid CO_2 and irradiated with γ rays, which was attributed to O(³P) atoms formed from CO_2.

We have found a simple and clean way to react O(³P) atoms with olefins in condensed phases, including neat liquids, solutions, suspensions, and solids, thus enabling utilization of oxygen atoms as reagents for preparative organic chemistry.

Ground-state oxygen atoms were generated by discharge of either O_2[1c,d,5] or a mixture of N_2 and N_2O.[6] In the first method, the O(³P) atoms formed are accompanied by O_2 molecules in their singlet and triplet states, and by O(¹D) atoms,[7] but the second method gives only almost pure O(³P) atoms.[6]

The reaction vessel consisted of a quartz U-tube of 15-mm diameter, containing 1–5 g of magnetically stirred substrate, and connected to a microwave generator (Kiva, MPG-2, operating at 2450 MHz with 100-W output) by a gas-discharge cavity (15-mm diameter) placed ca. 5 cm above the level of the substrate. A steady flow of a mixture of gases consisting of He and O_2 in a 7:1 ratio (total flow 0.7 L/min) or a He, N_2, and N_2O mixture in a 10:6:1 ratio (total flow 1 L/min), maintained by means of a high-vacuum pump operating at a constant pressure of 4 torr, was passed through the U-tube; the temperature and the duration of the reaction were variable.

Reaction of neat *cis*-stilbene (1) with O atoms produced by O_2 discharge resulted in a mixture of *cis*-stilbene oxide (3), *trans*-stilbene oxide (4), and benzyl phenyl ketone (5).[8] At 0 °C, all

(1) (a) Cvetanovic, R. J. *Adv. Photochem.* **1963**, *1*, 115–147. (b) Jarvie, J. M. S.; Cvetanovic, R. J. *Can. J. Chem.* **1959**, *37*, 529. (c) Sato, S.; Cvetanovic, R. J. *Ibid.* **1959**, *37*, 953. (d) Cvetanovic, R. J. *Ibid.* **1960**, *38*, 1678. (e) *J. Phys. Chem.* **1970**, *74*, 2730. (f) Cvetanovic, R. J.; Ring, D. F.; Doyle, L. C. *Ibid.* **1971**, *75*, 3056. (g) Atkinson, R.; Cvetanovic, R. J. *J. Chem. Phys.* **1971**, *55*, 659. (h) Hirokami, S.; Cvetanovic, R. J. *J. Am. Chem. Soc.* **1974**, *96*, 3738. (i) Singleton, D. L.; Cvetanovic, R. J. *Ibid.* **1976**, *98*, 6812.

(2) Havel, J. J. *J. Am. Chem. Soc.* **1974**, *96*, 530. Havel, J. J.; Chamberlain, W. T.; Krautter, P. M. *Ibid.* **1974**, *96*, 632. Havel, J. J.; Chan, K. H. *J. Org. Chem.* **1974**, *39*, 2439; *J. Am. Chem. Soc.* **1975**, *97*, 5800. Havel, J. J.; Hunt, C. J. *J. Phys. Chem.* **1976**, *80*, 779. Havel, J. J. *J. Org. Chem.* **1977**, *43*, 762.

(3) (a) Sakurai, H.; Akimoto, K.; Toki, S.; Takamuku, S. *Chem. Lett.* **1975**, 469. (b) Goto, S.; Hori, A.; Takamuku, S.; Sakurai, H. *Bull. Chem. Soc. Jpn* **1976**, *49*, 2956.

(4) Hirokami, S.; Wojnarovits, L.; Sato, S. *Bull. Chem. Soc. Jpn* **1979**, *52*, 299. Karasawa, H.; Sasmoto, T.; Yugeto, R.; Sato, S. *Bull. Chem. Soc. Jpn.* **1979**, *52*, 902.

(5) Huie, R. E.; Herron, J. T. *Int. J. Chem. Kinet.* **1972**, *4*, 521.

(6) Ung, A. Y.-M. *Chem. Phys. Lett.* **1975**, *32*, 351.

(7) Wayne, R. P. *Adv. Photochem.* **1969**, *7*, 330–332.

(8) Diphenylacetaldehyde, the product of phenyl migration, was detected only in trace amounts (<0.5%).

Table I. Reactions of O(³P) with *cis*-Stilbene 1

| conditions[a] °C	yield, %	conversion, %	product distribution, %		
			3	4	5
−40[b]	85	50	37	37	26
0[b]	75	100	31	40	29
0[c]	71	60	36	41	29
0[d]	90	65	31	36	33
25[b]	72	63	27	44	29
60[b]	e	e	13	51	36

[a] Performed on 1.5 g of substrate for 30 min, except in solution where reaction time was 2 h. [b] Neat liquid, O_2 discharge. [c] Neat liquid, N_2O/N_2 discharge. [d] 30% decane solution, O_2 discharge. [e] Not determined.

Table II. Product Distributions (%) in the Reaction of O(³P) with Styrene at −25 °C

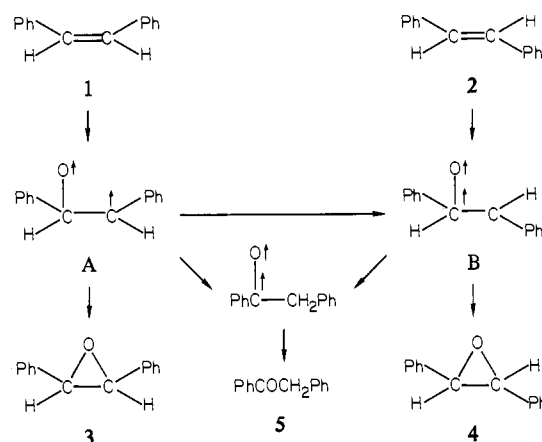| conditions	Ph—△O	PhCH₂-CHO	PhCOCH₃	PhCHO
O_2 (neat)[a]	44	25	12	19
O_2 (decane)[a]	57	27	9	7
N_2O/N_2 (neat)	62	31	2	5

[a] In addition, a small amount (<3%) of 1-phenylethanol and α-hydroxyacetophenone was isolated.

Scheme I
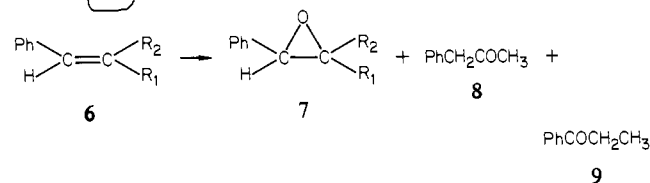
[a] **a**, $R_1 = CH_3$, $R_2 = H$; **b**, $R_1 = H$, $R_2 = CH_3$. **6a** → **7a** (58) + **7b** (8) + **8** (18) + **9** (12). **6b** → **7a** (36) + **7b** (16) + **8** (23) + **9** (12). Product distribution percentage in parentheses.

Scheme II

the starting material (1.5 g) was consumed within $^1/_2$ h; the total yield of characterized products was 75%, the rest consisting of an insoluble material (Table I). With shorter reaction times, the conversion was lower, but the relative yields were unchanged. As shown in Table I, similar product ratios were also obtained in a 30% *n*-decane solution, or when O atoms were produced by N_2/N_2O discharge. The product ratios were dependent on the reaction temperature: at higher temperatures, larger relative yields of both **4** and **5** were observed (Table I). In addition, we found a decrease in the reaction rate when the temperature was increased from 0 to 60 °C.[9]

(9) Negative temperature dependence of the reaction of O(³P) atoms with several olefins was observed previously; ref 1i and Atkinson, R.; Pitts, J. N., Jr. *J. Chem. Phys.* **1977**, *67*, 38.

Scheme III
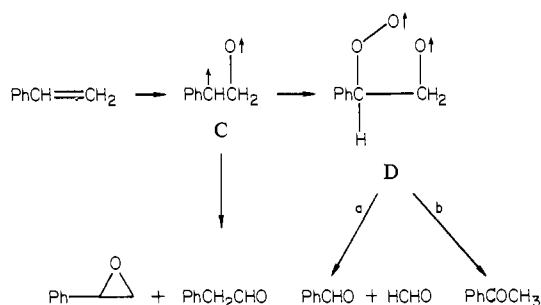
Since *trans*-stilbene (**2**) is a sparingly soluble solid, its oxidation was performed in the powder, resulting in a 15% yield of **4** and **5**, formed in a 2.5:1 ratio. When the oxidation was done in 15% diethylene glycol suspension, these two compounds were formed (25%) in a 1:1 ratio.[10] Triphenylethylene was also oxidized in the solid state, yielding triphenyl ethylene oxide and phenyl benzhydryl ketone in a 4:1 ratio (35% total yield).

Oxidation of *trans*- and *cis*-β-methylstyrene (**6a**) and (**6b**) with $O(^3P)$ atoms produced by O_2 discharge gave after 2 h at −25 °C two epoxides, **7a** and **7b**, and two ketones, **8** and **9**. The product of methyl migration, 2-phenylpropanal, was formed in minute amounts only (<1%). The product ratios (Scheme I) indicated a small preference for O attack on the β-C atom. However, when the source of the O atoms was N_2O/N_2 discharge, this preference was increased (2.5 vs. 1.5 for **6a**).

These differences in the regioselectivity were more distinct in oxidation of styrene. With N_2O/N_2 discharge, the major products were styrene oxide and phenylacetaldehyde while acetophenone and benzaldehyde were formed in small amounts (Table II). The relative abundance of the last two compounds increased when O_2 discharge was used, particularly in neat liquid, suggesting that O_2 also contributes to the formation of these products (Table II).

It is to be emphasized that in all the cases studied no products resulting from oxygen atom attack on the phenyl rings were detected.[11,12]

The suggested pathway for the reaction of $O(^3P)$ atoms with *cis*- and *trans*-stilbenes **1** and **2** involves the intermediacy of triplet diradicals A and B, respectively (Scheme II). The trans-diradical B possesses the geometrical requirements for both cyclization and H migration, giving *trans*-epoxide **4** and the ketone **5** (presumably as a triplet), respectively.[1e] The steric interactions of the phenyl groups in the cis-diradical A lead, in addition, to rotation about the C–C bond forming the *trans*-epoxide **4**.

When the temperature is lowered, the increased viscosity of the liquid slows down the rotation, resulting in a higher relative yield of *cis*-epoxide **3** and lower yields of *trans*-epoxide **4** and benzyl phenyl ketone **5**. It follows that in the solid state the relative yield of **3** will be the highest.

We assume that in the case of styrene, the molecular oxygen present in the O_2 discharge interferes by interaction with the primary diradical C to form peroxy diradical D (Scheme III). The latter undergoes either cleavage of the C–C bond to form benzaldehyde[13] and formaldehyde (path a), or rearranges by H migration with evolution of O_2 to give acetophenone (path b).

Investigations of $O(^3P)$ atom reactions in condensed phases with aromatic and other unsaturated systems are in progress.

Elazar Zadok, Dan Amar, Yehuda Mazur*

Department of Organic Chemistry
The Weizmann Institute of Science
Rehovot, Israel

Received March 28, 1980

Nonbleachable Rhodopsins Retaining the Full Natural Chromophore

Sir:

The visual pigments rhodopsins[1] consist of 11-*cis*-retinal (I)[2] bound to the ε-amino group of the apoprotein lysine moiety through a protonated Schiff base (II, SBH+).[3,4] The key event
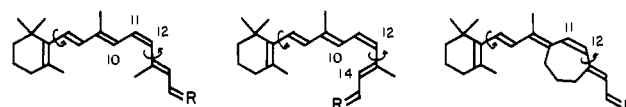
I R: O
II R: N+H-lys-OPSIN
III R: N+H-n·Bu

IV R: N+H-lys-OPSIN

V R: O (≡1)
VI R: N+H-lys-OPSIN

in the visual transduction is the photoisomerization of the 11-*cis*-ene to trans geometry,[2] which eventually yields *all-trans*-retinal and opsin ("bleaching"). In this communication, we report the preparation and properties of rhodopsins, e.g., VI, in which this key step is blocked.

We had previously reported that 11,12-dihydrorhodopsin[5] formed from retinal lacking the crucial 11-ene gave a "nonbleachable" pigment.[6] The data on this pigment and other hydrorhodopsins led to the external point-charge model[7] to account for the variance in λ_{max} of visual pigments. In contrast to hydrorhodopsins,[7b] the present pigments retain the full retinal chromophore.

We have shown that of the two possible conformations for 11-*cis*-retinal, 12-*s-trans*-II and 12-*s-cis*-IV, both of which are nonplanar (indicated by curved arrows) due to the interaction between 10-H/13-Me and 10-H/14-H, the chromophore in rhodopsin adopts the transoid conformer II.[8] In order to mimic the nonplanar 12-*s-trans*-retinal, but more importantly to prepare an 11-cis-locked chromophore, we conceived the model retinal V

(10) Different products were reported to be formed in the γ radiolysis of *trans*-stilbene in liquid CO_2, ref 3a.

(11) It was claimed, however, that $O(^3P)$ atoms attack both the styrene ring and the styrene side chain: Sloane, T. M.; Brudzynski, R. J. *J. Am. Chem. Soc.* **1979**, *101*, 1495.

(12) $O(^3P)$ atom reactions with α-methylstyrene, 1,1-diphenylethylene, and 1-phenyl-2-butene resulted in an attack on the double bond only, giving the expected epoxides, ketones, and aldehydes.

(13) The formation of benzaldehyde by ozonolysis is less likely since only negligible amounts of ozone are produced in O_2 discharge: ref 1c and Herron, J. T.; Schiff, H. T. *Can. J. Chem.* **1958**, *36*, 1159. Moreover, we did not detect among the reaction products either styrene ozonide or benzoic acid.

(1) In view of the recent preparations of various artificial pigments from synthetic model retinals, we propose the use of the generic name "rhodopsin" prefixed by the specific modification carried out with the chromophore, e.g., 11,12-dihydro-9-*cis*-rhodopsin.

(2) Wald, G. *Nature* (*London*) **1968**, *219*, 800. Hubbard, R.; Kropf, A. *Proc. Natl. Acad. Sci. U.S.A.* **1958**, *44*, 130.

(3) The protonated Schiff base theory is the one generally accepted, especially on grounds of resonance laser Raman studies: Callender, R.; Honig, B. *Annu. Rev. Biophys. Bioeng.* **1977**, *6*, 33. Eyring, G.; Mathies, R. *Proc. Natl. Acad. Sci. U.S.A.* **1979**, *76*, 33.

(4) There are, however, still some controversial views regarding the protonated Schiff base theory; see: Favrot, J.; Leclercq, J. M.; Roberge, R.; Sandorfy, C.; Vocelle, D. *Photochem. Photobiol.* **1979**, *29*, 99.

(5) Gawinowicz, M. A.; Balogh-Nair, V.; Sabol, J. S.; Nakanishi, K. *J. Am. Chem. Soc.* **1977**, *99*, 7720, and references cited therein.

(6) The 11,12-dihydrorhodopsin, λ_{max} 315 nm, was not affected by room light, and hence was "nonbleachable" in the classical sense of the terminology. When irradiated with UV light, the pigment underwent irreversible photodecomposition of the chromophore rather than detachment of the chromophore from the opsin.

(7) (a) Nakanishi, K.; Balogh-Nair, V.; Gawinowicz, M. A.; Arnaboldi, M.; Motto, M. G.; Honig, B. *Photochem. Photobiol.* **1979**, *29*, 657. (b) Arnaboldi, M.; Tsujimoto, K.; Balogh-Nair, V.; Nakanishi, K. *J. Am. Chem. Soc.* **1979**, *101*, 7082. (c) Honig, B.; Dinur, V.; Nakanishi, K.; Balogh-Nair, V.; Gawinowicz, M. A.; Arnaboldi, M.; Motto, M. G. *Ibid.* **1979**, *101*, 7084. (d) Sheves, M.; Nakanishi, K.; Honig, B. *Ibid.* **1979**, *101*, 7086.

(8) (a) Chan, W. K.; Nakanishi, K.; Ebrey, T. G.; Honig, B. *J. Am. Chem. Soc.* **1974**, *96*, 3642. (b) Ebrey, T. G.; Govindjee, R.; Honig, B.; Pollock, E.; Chan, W. K.; Crouch, R.; Yudd, A.; Nakanishi, K. *Biochemistry* **1975**, *14*, 3933. (c) Callender, R. H.; Doukas, A.; Crouch, R.; Nakanishi, K. *Ibid.* **1976**, *15*, 1621.