1-fluoroadamantane-4-one is higher than 95%.

Experimental Section

^1H NMR spectra were measured with Bruker WH-90 spectrometer at 90 MHz and with tetramethylsilane as internal standard. ^{19}F spectra were recorded with the same instrument at 84.67 MHz and were reported in parts per million upfield from $CFCl_3$ as internal standard (ϕ^*). Mass spectra were measured with a Du Pont 21-491B spectrometer.

General Procedure. Caution: Fluorine is, of course, a powerful oxidant, a strong poison, and very corrosive material. An appropriate vacuum line in a well-ventilated place should be constructed when working with fluorine. Such a vacuum line containing a 0.5-lb fluorine cylinder and double valve system in a commercial barricade can be obtained from Matheson Corporation. A detailed description of the working system can be obtained from Matheson report no. G-115B. The reaction itself can be carried out in glass vessels.

A mixture of about 1.5% fluorine in nitrogen was slowly bubbled through a cold solution (-75 °C) of about 1.5 g of an adamantane derivative. An efficient vibromixer (Chempec Inc., Hoboken, NJ) was used in order to ensure a good suspension of the gas bubbles in the solution. Dry ethanol-free chloroform and methylene chloride were obtained by refluxing and then distilling these solvents over P_2O_5. The same procedure was employed for $CFCl_3$ although it usually does not contain ethanol.

Shortly after the fluorine had been introduced a red-brown color (probably Br_2 or I_2—see text) was observed. The intensity of this color increased as the reaction progressed. The disappearance of the starting material and the appearance of the products as a function of the amount of fluorine passed through the reaction mixture were monitored by GC on a 3% SE-30 column. A trap of slightly acidic aqueous KI solution was usually placed after the rection mixture vessel so that the excess gas had to pass through it. At the beginning of the reaction no iodine was liberated from this KI solution, thus ensuring that all the fluorine had been consumed. The amount of the fluorine used during the reaction could easily be calculated from knowing its partial pressure with the aid of a gauge which is part of the system mentioned above and from the known volume of the F_2/N_2 mixture. Only when the substrate no longer reacts with fluorine or consumes it very slowly is excess of this element able to reach the KI solution: I_2 is liberated and titrated with thiosulfate. Since fluorine is practically insoluble in the solvents we worked with, it is easy to find out exactly how much fluorine reacts with the substrate and how much is leaving the reaction mixture unreacted.

After the reaction was complete (usually 1-3 h) it was poured into thiosulfate solution, washed with water, dried, and separated. Wherever a purification was required, it was achieved by chromatography on a silica open column or by a high-performance LC 10-μm silica column, using petroleum ether or cyclohexane as eluant. Usually the adamantane derivatives were eluted in the initial fractions. In the case of the known compounds their physical and spectral properties completely match the reported ones. A full characterization of the new compounds is presented in Table I.

Registry No. 1-AdBr, 768-90-1; 2-AdBr, 7314-85-4; 1-AdI, 768-93-4; 2-AdI, 18971-91-0; 1-AdF, 768-92-3; 2-AdF, 16668-83-0; 1-AdOEt, 6221-75-6; 1-AdCl, 935-56-8; 2-AdOEt, 29542-65-2; 2-AdCl, 7346-41-0; 3,5-dimethyl-1-AdBr, 941-37-7; 3,5-dimethyl-1-AdF, 30934-81-7; methyl (3-bromo-1-adamantyl)acetate, 14575-01-0; 5-bromo-2-adamantanone, 20098-20-8; methyl (3-fluoro-1-adamantyl)acetate, 75751-22-3; 5-fluoro-2-adamantanone, 41171-83-9; 5-chloro-2-adamantanone, 20098-17-3.

Light-Induced Free-Radical Reactions of 2-Methoxy-6-methyltetrahydropyran: Irreversible Ring Opening and Multisite Hydrogen Abstraction

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Acetophenone-initiated photodegradation of *cis*-2-methoxy-4-methyltetrahydropyran (**7**) in benzene solvent produced six products. The structures of the products, and studies using optically active **7**, showed that hydrogen abstraction occurs at both C-2 and C-6 of the tetrahydropyran ring. The products derived from the C-2 radical indicated two pathways for this radical: ring opening and loss of methyl, which is consistent with previous work on other similar systems. Results with optically active **7** showed that the ring-opening pathway is irreversible. Generation of an open-chain radical independently also showed that cyclization to a six-membered ring does not occur. The products from the photodegradation were *trans*-2-methoxy-6-methyltetrahydropyran (**8**), methyl hexanoate (**10**), 6-methyltetrahydropyran-2-one (**9**), methyl 5-phenylhexanoate (**11**), 1,7-dimethyl-7-phenyl-6,8-dioxobicyclo[3.2.1]octane (**13**), and 2-methoxy-2-(1-phenyl-1-hydroxyethyl)-6-methyltetrahydropyran (**12**). The yield of lactone **9** was found to be sensitive to the amount of residual oxygen present during the photolysis.

The photodegradation of polysaccharides like cellulose is quite complex.[1-4] Consequently, studies on the photodegradation of carbohydrate models like 2-methoxytetrahydropyrans have evolved.[5-7] The models contain an acetal functional group which is a common linkage in polymeric carbohydrates and probably a site quite reactive toward photodegradation.[8] Hydrogen abstraction by a photoexcited ketone at the 2-position, resulting in the generation of radical **2**, appears to be the initial step in the

(1) G. O. Phillips and T. Richards, *J. Chem. Soc. B*, 455 (1969).
(2) G. O. Phillips, *Adv. Carbohydr. Chem.*, **18**, 9 (1963).
(3) R. L. Desai, *Pulp Pap. Mag. Can.*, **69**, T322 (1968).
(4) A. H. Reine and J. C. Arthur, Jr., *Text. Res. J.*, **40**, 90 (1970).
(5) T. Yamagisui, T. Yoshimoto, and K. Minami, *Tetrahedron Lett.*, 2795 (1971); R. D. McKelvey, *Carbohydr. Res.*, **42**, 187 (1975).
(6) K. Hayday and R. D. McKelvey, *J. Org. Chem.*, **41**, 2222 (1976).
(7) C. Bernasconi and G. Descotes, *C. R. Hebd. Seances Acad. Sci., Ser. C*, **280**, 469 (1975).
(8) V. Malatesta, R. D. McKelvey, B. W. Babcock, and K. U. Ingold, *J. Org. Chem.*, **44**, 1872 (1979).

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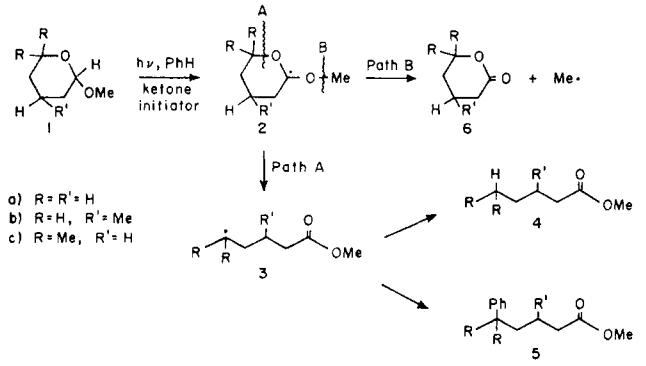
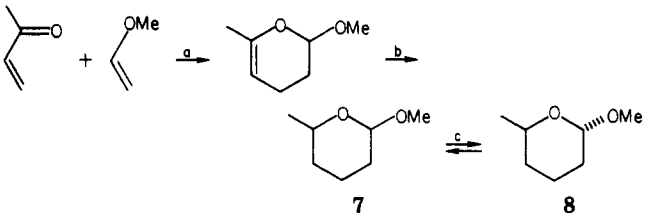
Scheme I. Ketone-Initiated Photochemical Degradation of 2-Methoxytetrahydropyrans



Scheme II. Preparation of Racemic 7 and 8[a]



[a] a, 180 °C, 5.5 h, autoclave; b, Raney nickel, Et_2O, autoclave, 1800 psig of H_2, 2 days; c, AcCl, MeOH, CCl_4, 2 days, spinning-band distillation.

reactions of these models (1). This radical has been proposed to decompose to a lactone (6) and open to acyclic radical 3 (Scheme I).[5-7] The acyclic radical appears to be the source of ester products 4 and 5, the first via hydrogen atom abstraction with other species in solution and the second via addition to the solvent (benzene).

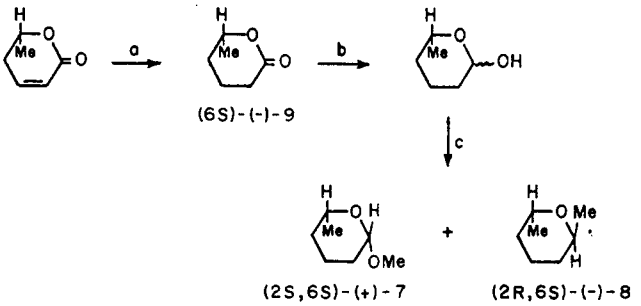
In comparing the three models shown in Scheme I, one might expect ring opening to be more prevalent in the photolysis of 1c since radical 3c (being tertiary) is more stable than radicals 3a and 3b (primary). However, the observed yield of lactone 6c (20%) is intermediate between the yields of 6a (14%) and 6b (29%).[5-7] One possible explanation of these results is that the ring-opening step, path A of Scheme I, is reversible, i.e., 2 ⇌ 3, and that this allows the apparently energetically less favorable but irreversible path B to compete with path A.[6]

The ketone-initiated photodegradation of 2-methoxy-6-methyltetrahydropyran (7) was chosen for this study because (a) it is more representative of the common saccharides than previous models and (b) photolysis of its optically active form should provide information on the reversibility of radical ring-opening reactions. Other aspects of this study included attempts to correlate the variability of lactone formation with different levels of oxygen in the system, to generate δ-lactones from open-chain radicals, and to determine sites of hydrogen abstraction.

Results

Racemic acetals 7 and 8 were synthesized by the sequence of reactions shown in Scheme II.[9] Optically active 7, 8, and lactone 9 were synthesized from optically active parasorbic acid (Scheme III).[10,11] Since the chiral center at C-6 should not be disturbed in these transformations,

Scheme III. Preparation of Optically Active Materials[a]



[a] a, 10% Pd/C, Et_2O, H_2; b, $LiAlH_4$, Et_2O; c, MeOH, *p*-TsOH, 2 days, separate by preparative GC.

the optical purities of 7–9 should all be the same, presumedly,[12] 100%.

Three initiators (acetone, acetophenone, and benzophenone) and two solvents (benzene and *tert*-butyl alcohol) were evaluated for use in the photolysis of 7 and 8. Photolyses of dilute solutions of acetal 7 in benzene with acetophenone as the initiator provided the best yields of volatile photoproducts and was the principal system employed. The photolyses were not carried to completion in order to minimize degradation of products. The yields were relatively good for this kind of study.[5-7] The cis isomer of 5-methoxy-6-methyltetrahydropyran was approximately 10 times as reactive as the trans isomer. A similar preference for axial hydrogen abstraction has also been observed in reactions of *cis*- and *trans*-1b.[6] The cis isomer of 1b was 8 times as reactive as the trans isomer of 1b.[6]

The volatile photoproducts isolated from the photolysis of thoroughly degassed solutions of 7 are shown in Scheme IV; the yields were based on moles of consumed starting material 7, except for 14 which was based on the moles of acetophenone consumed. The products were isolated by preparative gas chromatography and characterized by spectral means. Authentic samples of 8–11 and 14 were purchased or synthesized for direct comparison. The assigned structures 12 and 13 should not be considered absolute since full characterization was precluded by the low amounts of sample available.

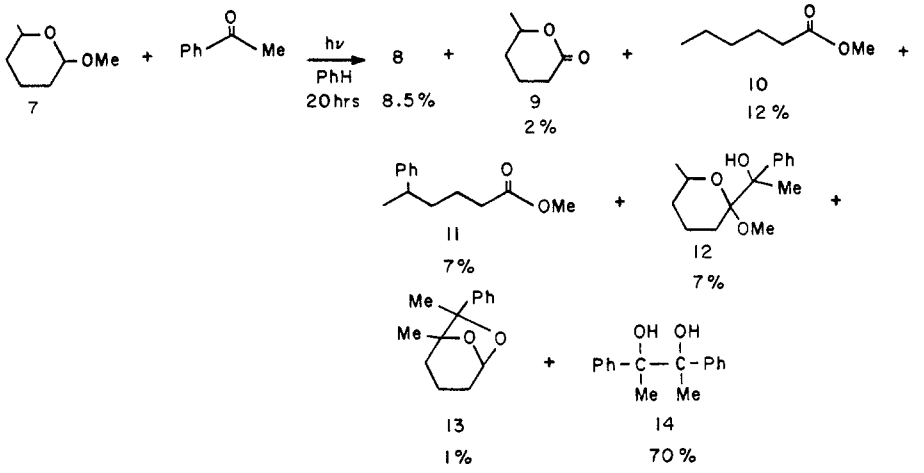
Compound 12, a mixture of three principal diastereomers, exhibited a molecular ion at 250 in its mass spectrum and a base peak at *m/e* 121, indicative of a PhC(OH)Me group. A ^1H NMR spectrum showed aryl signals, three singlet methoxy signals (δ 3.5), three singlet methyl signals (δ 1.4), several overlapping doublet signals (δ 0.8), assigned to the C-6 methyl groups, and the absence of an acetal proton signal. The spectral evidence strongly suggests that a PhC(OH)Me group is attached to the C-2 position of 7.

Structure 13, displaying a molecular ion at *m/e* 218, also appears to be an addition product of acetophenone and acetal 7, but with subsequent loss of methanol. A base peak of *m/e* 98 in the mass spectrum has been interpreted to correspond to a scission of the acetophenone two-carbon-bridge unit with retention of the charge on the pyran fragment. The appearance in the ^1H NMR of singlets at δ 0.78 (formerly the C-6 methyl) and 1.72 (formerly the acetophenone methyl), together with aryl (δ 7.3) and acetal proton (δ 5.73) signals but no methoxy methyl signal, was in accord with the proposed structure. A ^{13}C NMR spectrum also lent added support for structure 13.

Photolysis of acetal 8 gave the same products and in the same ratios as those obtained from acetal 7, only at a much

(9) R. M. Srivastava and R. K. Brown, *Can. J. Chem.*, 48, 2334 (1970).
(10) R. Kuhn and D. Jerchel, *Ber. Dtsch. Chem. Ges.* 76, 413 (1943).
(11) A. A. Frimer, P. D. Bartlett, A. F. Boschung, and J. G. Jewett, *J. Am. Chem. Soc.*, 99, 7977 (1977).
(12) R. Kuhn and K. Kum, *Ber. Dtsch. Chem. Ges.*, 95, 2009 (1962).

Scheme IV. Photolysis of *cis*-2-Methoxy-6-methyltetrahydropyran (7)



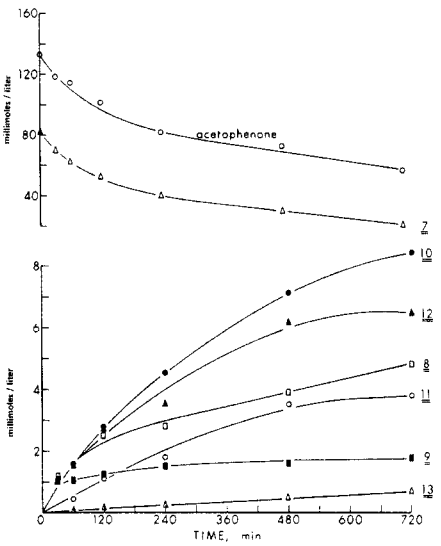


Figure 1. Reaction mixture composition, expressed as mmoles/liter, as a function of reaction time for the acetophenone-initiated photolysis of **7**.

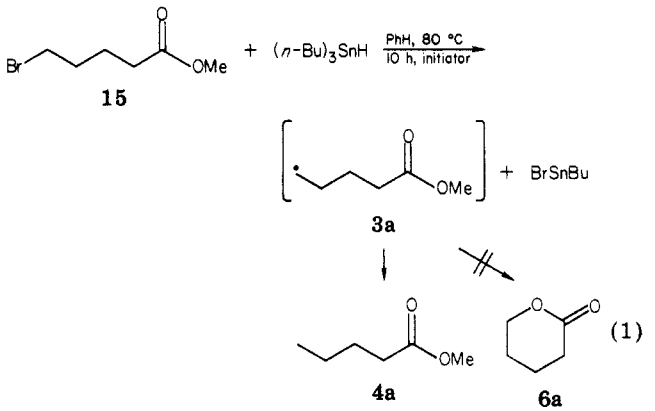
slower rate and in lower overall yields due to secondary degradation. It was not possible to determine if **8** isomerized to **7**, since the latter is much more photolabile than the former, and the two partially overlap under the conditions used in the gas chromatographic analysis.

The overall yield of volatile photoproducts and especially the yield of lactone **9** was greatly influenced by the presence of oxygen during photolysis. The yields reported in Scheme IV were obtained by degassing the mixture with a nitrogen purge stream before and during photolysis. Similar yields were obtained after four freeze–pump–thaw cycles and sealing under vacuum. Purging the reaction mixture with a stream of air during irradiation decreased the total yield of volatile products from 40% to 20% and increased the yield of lactone from 2% to 10%.

We followed the course of the photodegradation of acetal **7** by performing several identical reactions of differing durations. Analyses of the major photoproducts, together with disappearance of starting materials, are shown graphically in Figure 1. The steady, increased production of all the products, except lactone **9**, suggests that these are all primary photolysis products, i.e., derived from **7**. The initially rapid production of lactone followed by a leveling off suggests that (a) a steady state was reached, where its rate of production matched its rate of degradation, or (b) even under thorough degassing, some residual molecular oxygen was present, which led to the rapid initial production of **9**.

The optical rotation of lactone **9** ($[\alpha]_D$ −52°) isolated from the photolysis of (+)-**7** ($[\alpha]_D$ +106°) had the same value as the **9** that was used to prepare (+)-**7** (Scheme III). In other words, in the photoconversion of acetal **7** to lactone **9**, the geometry at C-6 does not change. The starting material recovered after partial photolysis of (+)-**7** had not lost any of its original optical rotation. The specific rotations of **8** produced in duplicate photolyses of (+)-**7** were +34° and +32°; these values are considerably different from that observed for **8** ($[\alpha]_D$ −144°) obtained via the reactions shown in Scheme III. Hence **8** obtained by photolysis of (2*S*,6*S*)-(+)-**7** must be a mixture of 62% 2*S*,6*R* and 38% 2*R*,6*S* configurations.

Two reactions of methyl 5-bromopentanoate (**15**) were investigated in an attempt to determine if acyclic radical **3a** would cyclize to **2a** and eventually **6a**. The first reaction involved heating the bromo ester with tri-*n*-butyltin hydride in benzene solvent in the presence of a radical initiator, azobis(isobutyronitrile) (eq 1). The only ester-

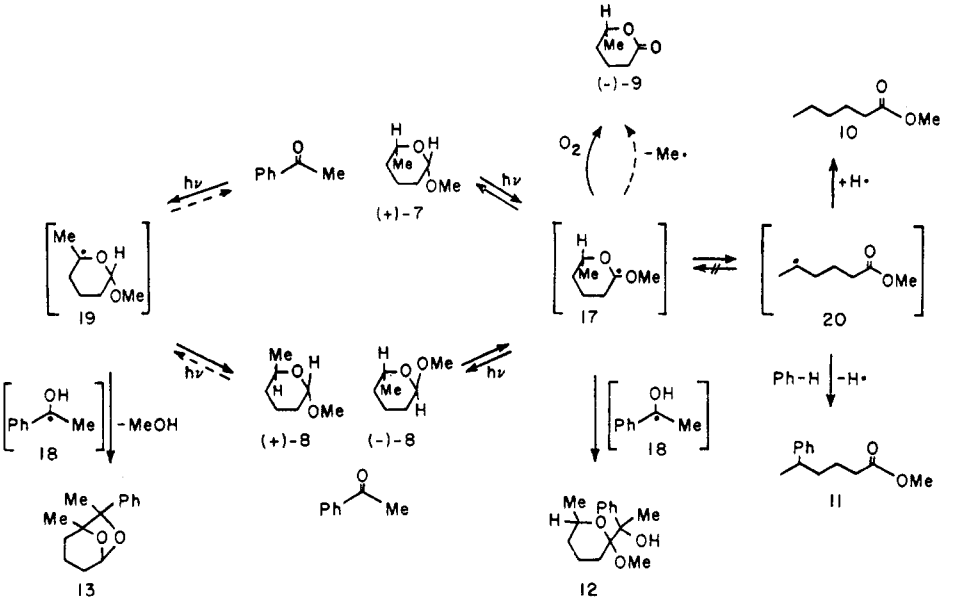


derived product was methyl pentanoate (**4a**), which was presumedly formed by a radical chain process[13] involving intermediate radical **3a**. No lactone was observed. The relative constituent amounts in the product mixture were 30% **4a**, 20% **15**, 6% Bu_3SnH, 36% Bu_3SnBr, 5% Bu_3Sn–$SnBu_3$, 1% Bu_4Sn, and 2% of an unknown tin derivative.

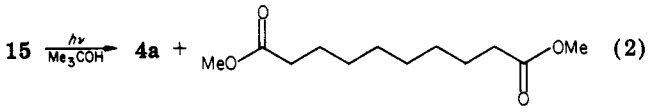
The second reaction, photolysis of methyl 5-bromopentanoate in *tert*-butyl alcohol, gave 41% methyl pen-

(13) H. G. Kuivila, *Synthesis*, 499 (1970); *Acc. Chem. Res.*, 1, 299 (1968).

Scheme V. Mechanism Consistent with the Photoproducts Derived from (+)-*cis*-2-Methoxyl-6-methyltetrahydropyran



tanoate (**4a**), 54% recovered bromo ester **15**, 2.5% of an ester dimer, of GC retention time identical with that of dimethyl decanedioate (**16**), and 3% of an unidentified component (eq 2). Again, no lactone was observed, even though the appearance of **4a** and the dimer strongly suggest that radical **2a** was generated.



(2)

16

Discussion

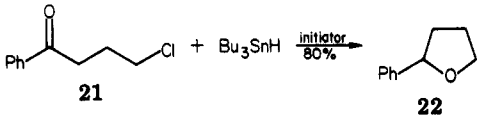
Scheme V provides a reasonable explanation of how photoproducts **8**–**13** arise; the proposed radical intermediates are shown in brackets. The majority of the isolated products appear to be derived from the C-2 radical intermediate **17**, either directly or after ring opening to radical **20**. The ratio of C-2 radical type products to C-6 radical (**19**) type products was about 7:1; of course, with approximately 60% unidentifiable products, this ratio may not be an accurate reflection of the relative amounts of these two radicals produced.

This study is the first to demonstrate a radical abstraction at a ring site other than the acetal carbon of a 2-methoxytetrahydropyran model. Abstraction at C-6 is evident by the predominant production of (+)-**8** from (+)-**7**. Although the mechanism for the formation of **13** was not studied, it seems reasonable that the C-6 radical must also be involved in its production.

Radical **17** has also been prepared by UV photolysis of cyclopropane solutions of acetals **7** and **8**, with di-*tert*-butyl peroxide as the initiator for hydrogen abstraction, and observed by EPR.[8] Interestingly, the C-6 radical **19** and the acyclic radical **20** were not observed under these conditions. Since products were not isolated, it is not possible to definitively conclude whether these radicals were absent, present in undetectable amounts, or just have relatively shorter lifetimes. Possibly, the production of radicals **19** and **20** requires activation energies that are not available in the low-temperature di-*tert*-butyl peroxide/cyclopropane photolysis.

The photodegradation of (+)-**7** also demonstrated that the ring opening of radical **17** to the acyclic radical **20** is not reversible. Recyclization of radical **20** should produce racemic **17**; products derived from radical **17** would then have reduced optical purities if recyclization occurs. Yet photolysis of (+)-**7** gave (−)-lactone **9** having only the *S* configuration, with no loss of optical purity. The (+)-*cis*-2-methoxy-6-methyltetrahydropyran (**7**) recovered after partial photolysis showed no loss of optical purity. It seems logical that if **8** is produced from radical **17**, so is **7**; actually, radical **17** should produce more acetal **7** than **8**, on consideration of microscopic reversibility and the relative reactivities of acetals of **7** and **8**.[14]

Cyclization products were not observed when a radical similar to **20** but presumedly more reactive was generated from the acyclic bromo ester **15** and tributyltin hydride. Methyl 5-phenylpentanoate (**5a**) was also not observed in this experiment, even though benzene was the solvent; possibly tri-*n*-butyltin hydride is too efficient a hydrogen atom donor to allow the primary radical **3a** to become involved in other reactions. However, ring closure to a five-membered ring has been observed in a somewhat similar system: the reaction of γ-chlorobutyrophenone (**21**) with tri-*n*-butyltin hydride in ether, and catalyzed by azobis(isobutyronitrile) (eq 3).[13]



(3)

21 **22**

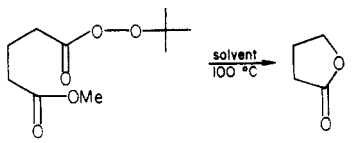
The photolysis of acetal **1a** has been done in both benzene and *tert*-butyl alcohol to give lactone **6a** in yields of better than 5% with no more than 1% yields of dimethyl decanedioate (**16**). Yet, the latter material was formed in approximately 3% yield from the photolysis of **15**, while lactone **6a** was not observed. The intermediate radical **3a** must have a lifetime long enough to allow it to find another radical in the dilute solution with which to couple. This occurs in preference to cyclization.

Interestingly, cyclization of open-chain radicals to five-membered-ring lactones has recently been observed

(14) Both **7** and **8** produce the same C-2 radical, albeit **8** produces it more slowly; the radical is not flat but has a cis geometry.[8]

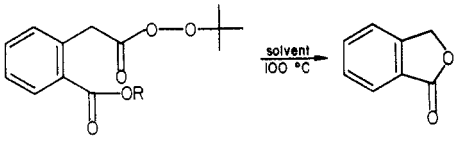
(15) L. W. Menapace and H. G. Kuivila, *J. Am. Chem. Soc.*, **86**, 3047 (1964).

(eq 4 and 5).[16] The yields of lactones **24** and **27** were



(4)

23 **24**



(5)

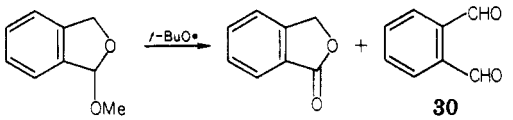
25, R = Me
26, R = CH_2Ph

27

approximately 4–6%; several other major products were isolated but are not shown in eq 4 and 5. These results raise the question as to a possible large rate difference between radical cyclization to five- vs. six-membered-ring lactones.

Since radical ring opening has been shown to be irreversible in the 2-methoxytetrahydropyran system, other explanations must be considered for the variability of lactone formaton from acetals **1a–c** and **7**. The production of lactone **9** from **7** has been shown to be quite dependent on the level of oxygen in the system. Scheme VI shows two ways that oxygen could contribute to lactone formation. The variability in procedures used, especially the degassing techniques, may account for the observed variable lactone yields from the photolyses of acetals **1a–c** and **7**.

Thorough degassing of reaction mixtures did not completely eliminate formation of lactone **9** in the photolysis of acetal **7**. This fact raises the possibility that some lactone is formed by direct loss of a methyl radical from cyclic radical **15**. Although degassing procedures were not described for the reactions outlined for eq 4–6, these are additional examples where a methyl or benzyl group appears to be lost in a radical process leading to a lactone product.[26]



(6)

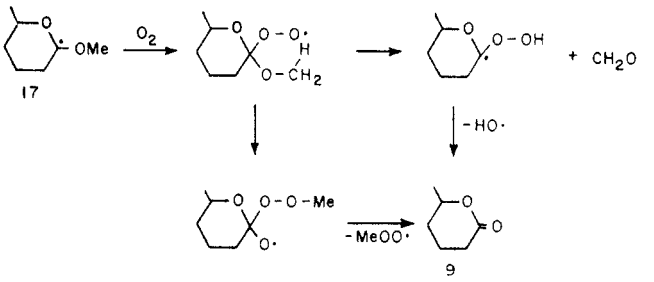
28 **29** **30**

Conclusions

The excited state of acetophenone can abstract a hydrogen atom from C-2 or C-6 in 2-alkoxytetrahydropyrans. The radicals undergo a variety of reactions, including ring opening, loss of alkyl radical, and coupling with the acetophenone ketyl radical. The ring-opening reaction is irreversible.

From the model studies conducted so far, it seems reasonable to assume that ketone-initiated photochemical degradations of carbohydrates will lead largely, but not exclusively, to acetal-type radicals, followed by fragmentation of glycosidic bonds. Competing to some extent with this process will be hydrogen abstraction reactions at carbons that carry one oxygen substituent. Since each of the ring carbons for most naturally occurring carbohydrates are secondary or tertiary and at least monooxygen substituted, it follows that hydrogen atom abstraction

Scheme VI. Possible Roles of Oxygen in Lactone Formation



reactions will be fairly random and may be directed by steric considerations.

Experimental Section

Analytical gas chromatography (GC) was done on a Perkin-Elmer F-30 gas chromatograph with a column packing of OV-17 on Supelcoport in a $^1/_8$ in. × 6 ft stainless-steel column. Preparative GC was done on a Varian Aerograph 712 with OV-17 in a $^1/_4$ in. × 20 ft nickel column. Optical rotations, measured by using a Perkin-Elmer 141 polarimeter, were performed at room temperature in a 1.0-dm quartz microcell at 589 nm. Mass spectra were obtained on a Du Pont 21-491 mass spectrometer interfaced to a Varian Aerograph 1440-1 gas chromatograph via a jet separator. All NMR spectra were obtained on a JEOL FX-100 spectrometer; the chemical shift values are reported in parts per million and referenced to tetramethylsilane. The photochemical reactor was a Rayonet RPR-100 manufactured by the Southern New England Ultraviolet Co. This reactor was provided with a MGR-100 merry-go-round for the simultaneous irradiation of up to eight samples. The light source consisted of 16 RPR-3000A lamps (λ_{max} = 300 nm), and Pyrex glassware was used.

All benzene used was the "distilled in glass" grade as supplied by Burdick and Jackson. Acetophenone was supplied by Matheson Coleman and Bell and was distilled prior to use.

***cis*-2-Methoxy-6-methyltetrahydropyran (7).** A suspension of 3.0 g of Raney nickel (W-2)[17] and 30 g of 2-methoxy-6-methyl-2,3-dihydropyran[9] in 50 mL of ethyl ether was stirred in an autoclave under 1800 psig of hydrogen pressure for 48 h. A NMR spectrum of the crude product at this point indicated that no starting material remained. The mixture was filtered, concentrated and distilled to yield 28 g (93% yield) of **7**: bp 63 °C (46 mm), 36–37 °C (12 mm) [lit.[18] bp 35–36 °C (12 mm)]; ^{1}H NMR ($CDCl_3$) δ 4.28 (dd, J = 8, 2 Hz, 1 H, $HCOCH_3$), 3.5 (m, 1 H, $HCCH_3$), 3.46 (s, 3 H, OCH_3), 2.0–1.4 (m, 6 H, CH_2's), 1.21 (d, 3 H, J = 6 Hz, H_3CCH); ^{13}C NMR ($CDCl_3$) δ 103.0 (d, OCO), 71.8 (d, $OCCH_3$), 55.6 (q, OCH_3), 32.6, 30.8, 22.2 (t, CH_2's), 21.6 (q, CCH_3). The assignment of cis geometry is based on the C-2 proton's ^{1}H NMR signal.[18]

***trans*-2-Methoxy-6-methyltetrahydropyran (8).** A solution of 11 g of **7**, 1.0 mL of acetyl chloride, and 2.0 mL of methanol in 75 mL of CCl_4 was stirred at room temperature and analyzed periodically by gas chromatography. After 48 h, an equilibrium mixture of **7** and **8** had been reached. Spinning-band distillation gave a major fraction (5 g, 45% yield) of **8**: bp 53 °C (43 mm) [lit.[18] bp 35–36 °C (12 mm)]; ^{1}H NMR ($CDCl_3$) δ 4.69 (br s, 1 H, $HCOCH_3$), 3.8 (m, 1 H, $HCCH_3$), 3.35 (s, 3 H, OCH_3), 1.9–1.3 (m, 6 H, CH_2's), 1.14 (d, 3 H, J = 6 Hz, $HCCH_3$); ^{13}C NMR ($CDCl_3$) δ 98.1 (d, OCO), 63.8 (d, $OCCH_3$), 53.2 (q, OCH_3), 32.5, 31.8, 18.0 (t, CH_2's), 20.8 (q, CCH_3). The assignment of trans geometry is based on the C-2 proton's ^{1}H NMR signal.[18] A second fraction was collected containing 50% **7** and 50% **8**: 4 g, 36% yield; bp 60–63 °C (46 mm).

(2*R*,6*S*)- and (2*S*,6*S*)-2-Methoxy-6-methyltetrahydropyrans ((+)-7 and (−)-8). These were obtained by an adaptation of a published procedure.[11] The starting material, **9** ($[\alpha]_D$ −49°), was obtained by hydrogenation of optically active parasorbic acid

(16) C. M. Rynard, C. Thankachen, and T. T. Tidwell, *J. Am. Chem. Soc.*, **101**, 1196 (1979).

(17) R. Mozingo, "Organic Syntheses", Collect Vol. III, Wiley, New York, 1955, p 181.

(18) E. L. Eliel and C. A. Giza, *J. Org. Chem.*, **33**, 3754 (1968).

(from processing the berries of *Sorbus aucuparia*).[11] A solution of 13 g of **9** in dry ethyl ether (50 mL) was dried ($MgSO_4$) overnight, filtered, and placed in a round-bottomed flask. A 20% excess of reducing agent, 1.0 M $LiAlH_4$ in ethyl ether (35.0 mL), was added dropwise over 1 h to the stirred solution, cooled at −10 °C under a blanket of nitrogen. The reaction mixture was allowed to warm slowly (2 h) to room temperature, and 2.0 mL of water, 2.0 mL of 15% NaOH, and 5.0 mL of water were added dropwise in succession. Stirring was continued for 30 min. The gelatinous precipitate was removed by filtration over Celite, and the ether solution was dried ($MgSO_4$), filtered, and evaporated to yield 10 g of 2-hydroxy-6-methyltetrahydropyran as a clear oil.

This oil was dissolved in methanol (200 mL), and *p*-toluenesulfonic acid (0.23 g) was added. After 48 h the mixture was shaken with sodium bicarbonate solution (50 mL) and extracted with ethyl ether (100 mL). The ether fraction was dried (Na_2SO_4), filtered, and evaporated to give 14 g of an oil containing methanol (30%), **7** (28%), and **8** (39%). Preparative gas chromatography was used to isolate samples of pure (+)-**7** and (−)-**8**. ^1H NMR spectra were in agreement with those for racemic **7** and **8**. Specific rotations were determined for both isomers: (+)-**7**, $[\alpha]_D$ +106° (absolute ethanol); (−)-**8**, $[\alpha]_D$ −144° (absolute ethanol).

Methyl 5-Phenylhexanoate (11). Esterification of 5-oxohexanoic acid[19] with acidic methanol–benzene, using a Dean–Stark trap, followed by distillation afforded 11 g (70%) of methyl 5-oxohexanoate: bp 135 °C (60 mm); ^1H NMR ($CDCl_3$) δ 3.65 (s, 3 H, OCH_3), 2.6–2.3 (m, 4 H, CH_2CO), 2.13 (s, 3 H, CH_3), 2.00–1.78 (m, 2 H, CH_2); ^{13}C NMR ($CDCl_3$) δ 207.0 (s, $H_3CC{=}O$), 173.0 (s, $COOCH_3$), 51.3 (q, OCH_3), 42.3, 32.9 (t, CH_2CO), 29.7 (q, CH_3), 19.0 (t, CH_2).

Anal. Calcd for $C_7O_3H_{12}$: C, 58.3; H, 8.38. Found: C, 57.9; H, 8.42.

Phenylmagnesium bromide (0.5 M in 200 mL of ethyl ether) was added dropwise to a vigorously stirred solution of methyl 5-oxohexanoate (11 g) in absolute ethyl ether (100 mL), forming a white precipitate. After the addition was complete, the mixture was left at room temperature for 30 min. Water (150 mL) was added to decompose the precipitate. After the mixture was shaken, an emulsion formed which was allowed to stand for 2 h. Careful addition of dilute sulfuric acid dissolved the magnesium salts while not allowing the pH to drop below 7. The mixture was extracted with ethyl ether five times, and the ether fractions were dried (Na_2SO_4). The ether was evaporated to give 18.7 g of crude product. The oil was distilled to yield a 9.0-g fraction, bp 160–163 °C (3 mm); ^1H NMR indicated that this fraction was methyl 5-phenyl-5-hydroxyhexanoate (20%) and 6-methyl-6-phenyltetrahydropyran-2-one (80%).

This oil was dissolved in methanol (50 mL), and 10% Pd/C (0.2 g) was added. The mixture was subjected to hydrogenation until hydrogen uptake ceased; the catalyst was filtered off, and the methanol was evaporated. At this time ^1H NMR indicated a mixture of 5-phenylhexanoic acid (80%) and methyl 5-phenylhexanoate (20%). This oil was esterified by using methanol–benzene and a Dean–Stark trap. Distillation gave a fraction containing 3 g (14% yield) of **11**: bp 147–152 °C (12 mm); ^1H NMR ($CDCl_3$) δ 7.5–7.0 (m, 5 H, phenyl), 3.56 (s, 3 H, OCH_3), 2.8–2.4 (m, 1 H, $HCCH_3$), 2.21 (t, 2 H, J = 6 Hz, $CH_2C{=}O$), 1.65–1.30 (m, 4 H, CH_2's), 1.21 (d, 3 H, J = 7 Hz, H_3CCH); ^{13}C NMR ($CDCl_3$) δ 173.3 (s, C=O), 146.7 (s, weak), 128.0 (d, strong), 125.7 (d, moderate, phenyl), 51.1 (q, OCH_3), 39.6 (d, $HCCH_3$), 37.6, 33.8, 23.0 (t, CH_2's), 22.2 (q, H_3CC).

Anal. Calcd for $C_{13}O_2H_{18}$: C, 75.7; H, 8.80. Found: C, 75.4; H, 8.94.

Preparative Photochemical Reaction. Acetophenone (0.168 g) and **7** (0.120 g) were dissolved in benzene (12.0 mL) and placed in a Pyrex ampule provided with a ground joint. The ampule was fitted with a condenser, degassed with a stream of nitrogen, and irradiated in a Rayonet reactor for 20 h. Preparative gas chromatography was used to collect eight components from the product mixture. The components were the following (retention time and temperature on the analytical GC column, NMR, major mass spectral peaks, other pertinent data).

***trans*-2-Methoxy-6-methyltetrahydropyran (8)**: 1.25 min, 60 °C; retention time and ^1H NMR spectra identical with those for authentic material.

Methyl hexanoate (10): 2.5 min, 60 °C; ^1H NMR (acetone-d_6) δ 3.59 (s, 3 H, H_3CO), 2.27 (t, 2 H, J = 6 Hz, $H_2CC{=}O$), 1.8–1.1 (m, 6 H, CH_2's), 0.87 (t, 3 H, J = 6 Hz, H_3CC); retention time and ^1H NMR identical with authentic material (Eastman Organic Chemicals).

Acetophenone: 8.5 min, 88 °C; retention time and ^1H NMR identical with authentic material.

6-Methyltetrahydropyran-2-one (9): 10.0 min, 95 °C; retention time and ^1H NMR identical with authentic material.

Methyl 5-phenylhexanoate (11): 18.5 min, 139 °C; retention time and ^1H NMR are identical with authentic material.

1,7-Dimethyl-7-phenyl-6,8-dioxobicyclo[3.2.1]octane (13): 21.0 min, 150 °C; ^1H NMR ($CDCl_3$) δ 7.27 (s, 5 H, phenyl), 5.73 (br s, 1 H, $HC(OR)_2$), 1.72 and 0.78 (s, 3 H, each, CH_3's), 2.0–1.2 (m, 6 H, CH_2's); ^{13}C NMR ($CDCl_3$) δ 128.0, 127.2, 126.4 (d, phenyl), 101.4 (d, $HC(OR)_2$), 32.4, 29.1, 17.0 (t, CH_2's), 22.9, 19.9 (q, CH_3's);[20] mass spectrum (70 eV), *m/e* (relative intensity) 218 (23), 147 (20), 145 (13), 129 (18), 119 (15), 117 (12), 105 (26), 104 (17), 103 (13), 98 (100), 97 (10), 91 (19), 80 (11), 78 (12), 77 (30), 51 (10), 43 (54), 41 (12).

2-Methoxy-2-(1-phenyl-1-hydroxyethyl)-6-methyltetrahydropyran (12): 26.75 min (2 broad signals), 179 °C; ^1H NMR (acetone-d_6) δ 7.3 (m, 5 H, phenyl), 3.74 (br, 1 H, CH_3CHO), 3.56, 3.53, 3.50 (all singlets, 3 H, OCH_3, mixture of isomers), 2.88 (br s, 1 H, OH), 1.9–1.2 (m, 6 H, CH_2's), 1.49–1.43 (3 s, 3 H, H_3CCPh, mixture of isomers), 0.7–0.9 (m, 3 H, H_3CCH);[21] mass spectrum (70 eV), *m/e* (relative intensity) 250 (0.4), 232 (5.7), 143 (12), 132 (14), 121 (100), 117 (16), 105 (20), 91 (20), 87 (13), 77 (15), 42 (27).

2,3-Diphenylbutane-2,3-diol (14): 29.0 min, 190 °C; retention time and ^1H NMR identical with authentic material prepared by a published procedure.[21]

Oxidative Photochemical Reaction. A mixture of 0.062 g of **7**, 0.108 g of acetophenone, and 10.0 mL of benzene was placed in a Pyrex ampule fitted with a ground-glass joint to a condenser with a gas-purge tube. The system was purged with air in the same way that the preparative reaction was purged with nitrogen. The mixture was irradiated for 20 h and analyzed via gas chromatography.

Kinetic Study. Acetophenone (0.160 g) and **7** were dissolved in benzene (10.0 mL). Aliquots (1.0 mL) were placed in eight Pyrex ampules. The ampules and their contents were degassed via four freeze–pump–thaw cycles below 0.01 mm. The ampules were sealed and seven were placed in the merry-go-round of the Rayonet reactor. One ampule was wrapped with aluminum foil and stored at 40 °C for 720 min. The seven others were irradiated at ca. 40 °C with periodic removal of an ampule at 30, 60, 120, 240, 480, and 720 min. At the end of the reaction, the ampules were opened, a known amount of internal standard (biphenyl) was added to each sample, and the samples were stored at 10 °C in the dark until gas chromatographic analysis.

Photoreaction of Optically Active 7. Acetophenone (0.317 g) and (+)-**7** (0.209 g) were dissolved in benzene (12 mL). This mixture was placed in six Pyrex ampules provided with ground-glass joints and tapered to facilitate sealing under vacuum. The ampules were degassed, sealed under vacuum, and irradiated for 11 h in the Rayonet reactor with the merry-go-round. The contents of the vials were analyzed via gas chromatography. Preparative gas chromatography was used to isolate acetals **7** and **8** and lactone **9**. A duplicate run, using slightly larger amounts

(19) W. H. Bentley and W. H. Perkin, Jr., *J. Chem. Soc.*, **69**, 1510 (1896).

(20) The fairly high noise in the spectrum of the dilute sample did permit a definitive assignment of the tetrasubstituted carbons.

(21) The appearance off the anticipated OH signal was obscured by the presence of small amounts of water in the sample, due either to water in the NMR solvent or to water obtained during the −78 °C collection off the GC column. The exact location of the methine signals was difficult to decipher since (a) the intensity will be low, (b) there should be about three different signals because of the isomers present, and (c) interference of column bleed peaks at this temperature. A multiplet at about δ 2.2 could account for some of the methine signals; molecular models indicate that the C-6 proton can be quite shielded by the phenyl group for certain stereoisomers.

(22) C. Wiezmann, E. Bergmann, and Y. Hirshberg, *J. Am. Chem. Soc.*, **60**, 1530 (1938).

of starting materials, was also performed. The purities of the isolated samples were checked by GC and found to be quite high in all cases except one. By using an internal standard and response factors, we were able to determine the concentrations of the various samples in ethanol prior to determination of the rotations. The results of the optical activity measurements, done in absolute ethanol, were as follows: 7, $[\alpha]_D$ +107°, +104°; 8, $[\alpha]_D$ +34°, +32°; lactone 9, $[\alpha]_D$ −52° (the second sample of 9 was contaminated).

Thermal Reaction of Tri-*n*-butyltin Hydride with Methyl 5-Bromopentanoate (15). Into a 50-mL, round-bottomed flask fitted with a magnetic stirrer, a pressure-equalizing addition funnel, a condenser and an inlet for nitrogen were placed 0.5480 g (2.810 mmol) of methyl 5-bromopentanoate and 15 mL of reagent grade benzene. The flask was placed in an oil bath maintained at 80 °C, the apparatus was deoxygenated, and a solution containing 0.8675 g (2.981 mmol) of tri-*n*-butyltin hydride and 0.0008 g (0.0049 mmol) of azobis(isobutyronitrile) in 15 mL of benzene was added over a period of 6 h. The reaction mixture was allowed to reflux at 80 °C for an additional 10 h. A variety of reaction times, dropping rates, and concentrations were also employed; comparable results were obtained.

The crude product was analyzed directly by GC, using a 3% OV-17 on 100–120-mesh Gas Chrom Q for support in a $^1/_8$ in. × 5 ft column, a carrier gas flow of 30 mL/min, and a temperature program consisting of an initial 10-min isothermal period at 70 °C followed by a 10 °C/min increase to 230 °C and a final 10-min period at 230 °C. The identity of the products was based on GC retention time comparison with known samples and mass spectra (by using the Du Pont GC/MS described earlier). Yields were determined from response factors for samples which were available and estimated, based on the number of carbons, for the other reaction products.

The compounds identified were the following (name, retention time, yield): methyl pentanoate, 1.4 min, 30.5%; methyl 5-bromopentanoate, 13.9 min, 19.7%; tri-*n*-butyltin hydride, 15.2 min, 5.5%; tetrabutyltin, 18.5 min, 1.3%; unidentified tin compound, 19.5 min, 1.8%; tributyltin bromide, 20.1 min, 35.7%; hexabutylditin, 25.8 min, 5.5%.

A sample of tetrahydropyran-2-one (**6a**) was available and was shown by GC retention time to not be a part of the above reaction mixture.

Irradiation of Methyl 5-Bromopentanoate (15). A solution consisting of 0.0171 g (0.0877 mmol) of methyl 5-bromopentanoate in 15 mL of *tert*-butyl alcohol was placed in a quartz tube fitted with a serum seal and magnetic stirrer. Two needle tubes were passed through the seal to permit the bubbling of nitrogen through the solution and venting. The reaction vessel was deoxygenated for a period of 0.5 h, the inlet and outlet tubes were removed, and GC analyses were run for samples after periods of 1.5, 13.5, 24.5, 39, and 63.5 h of irradiation in the Rayonet reactor described earlier.

The GC analysis and procedures were the same as those described in the previous experiment. The compounds identified from the 63.5-h sample were the following (name, retention time, yield): methyl pentanoate, 1.4 min, 40.6%; methyl 5-bromopentanoate, 13.9 min, 53.9%; dimethyl decanedioate, 21.7 min, 2.5%; unidentified component, which, on the basis of its long retention time, was assumed to be a branched isomer of **16**, 22.4 min, 3.0%.

Registry No. [4]a, 624-34-8; *cis*-(±)-**7**, 76024-08-3; (2*S*,6*S*)-(+)-[7], 76024-09-4; *trans*-(±)-**8**, 76024-10-7; (2*R*,6*S*)-(−)-**8**, 76024-11-8; (2*S*,6*R*)-(+)-**8**, 58801-54-0; (6*S*)-(−)-**9**, 16320-13-1; **10**, 106-70-7; **11**, 13317-80-1; **12**, 75993-77-0; **13**, 75993-78-1; **14**, 1636-34-6; **15**, 5454-83-1; **16**, 106-79-6; 2-methoxy-6-methyl-2,3-dihydropyran, 28194-35-6; 2-hydroxy-6-methyltetrahydropyran, 18545-19-2; methyl 5-oxohexanoate, 13984-50-4; methyl 5-phenyl-5-hydroxyhexanoate, 75993-79-2; 6-methyl-6-phenyltetrahydropyran-2-one, 28771-65-5; 5-phenylhexanoic acid, 2972-25-0; Acetophenone, 98-86-2; tri-*n*-butyltin, 688-73-3; tetrabutyltin, 1461-25-2; tributyltin bromide, 1461-23-0; hexabutylditin, 4808-30-4.

Stereochemistry of Iminoxy Radicals

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Iminoxy radicals of general structure Ar—C(X)=N—O·, where X = H, CH_2OH, *n*-Bu, *t*-Bu, $SiEt_3$, $SiPh_3$, $GePh_3$, $SnMe_3$, $SnBu_3$, $SnPh_3$, SMe, SBu, SPh, Cl, and Br, have been photolytically generated from the parent oximino compounds or from aromatic nitrile *N*-oxides in an aprotic solvent. Two configurational isomers, interconvertible in solution, have been detected by electron spin resonance spectroscopy for the majority of these radicals. The preferred geometry of iminoxyls derived from ortho-unsubstituted benzaldoximes is that which places the aryl ring and the oxygen atom on the same side of the C=N double bond (anti). Substitution of the azomethine proton leads to a stabilization of the syn configuration, the effect being larger the greater the atomic number of the leading atom of the substituent group. The relative stability of the syn isomer is also increased by substitution of the aromatic ortho protons. INDO calculations have been carried out on several model systems in order to rationalize the experimental results. The effects responsible for the configurational preference of the different terms of this series of radicals are discussed in terms of a perturbation molecular orbital (PMO) approach.

Iminoxyls belong to one of the few classes of σ radicals long lived enough to be studied in solution under different experimental conditions.[1] Owing to their persistency, they are especially suitable substrates to investigate the char-

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