Photochemistry of Hydroxamic Acids and Derivatives

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Contents

Ewa Lipczynska-Kochany received her Ph.D. and habilitation degree at Warsaw Technical University in Warsaw. She is currently on the faculty of the Department of Chemistry at this univerity. She has published extensively in the field or organic chemistry and organic photochemistry with a special interest in hydroxamic acids. She spent 18 months at the Institute for Molecular Science in Okazaki, Japan, and several months at the Technical University of Munchen in Germany. At present she is visiting the Department of Chemistry at The University of Western Ontario in London, Canada. In addition, she is collaborating with scientists from the United States.

I. Introduction

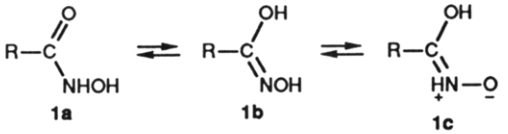
A. Hydroxamic Acids in the Ground State

Hydroxamic acids have exhibited many interesting facets of chemistry since they were first reported by H. Lossen in 1869.[1] Extensive work has been carried out on their formation, reactions, and structure in the ground state. A review of these papers is far beyond the scope of the present article, especially since various aspects of hydroxamic acid chemistry have already been reviewed.[2-6] Consequently, only a few examples will be mentioned here.

W. Lossen, in an early report,[7] observed that *O*-acyl derivatives of hydroxamic acids undergo a rearrangement reaction which bears his name. Modifications of the Lossen rearrangement, for instance, the "formamide modification",[8] have found applications in organic synthesis. Sheradsky et al.[9] described a procedure for arylation of benzene and heterocycles, which consists of the reaction of *N*-phenylbenzenehydroxamic acid with active halo-substituted benzenes and halo-substituted heterocycles, respectively; the reaction evidently proceeds via [5,5] sigmatropic rearrangement of the intermediate *N*,*O*-diarylhydroxylamines. Another reaction, the [3,3] sigmatropic rearrangement of *O*-vinyl derivatives of *N*-arylhydroxamic acids, affords a new method for O-alkylation of aromatic rings.[10]

Hydroxamic acids and their N-substituted derivatives serve as bidentate ligands toward many metal ions such as Fe(III) and Cu(II); the resultant complexes are highly colored and are therefore useful in colorimetric analyses of metal ions or hydroxamic acids.[2]

In spite of their interesting properties, hydroxamic acids have remained one of the less well characterized classes of organic compounds for a long time. A major difficulty has been the assignment of the correct structure from several possible tautomeric forms (**1a–c**):

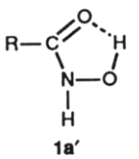


1a **1b** **1c**

R = alkyl or aryl group

Possibilities of geometrical isomerism and internal hydrogen bonding have added to the complexity.

The controversy has been resolved by the application of IR and UV spectroscopy.[2,11] Results of ^{17}O NMR studies[11] support the "amide" (**1a′**) structure of hydroxamic acids (internal hydrogen bonding in the syn configuration):



1a′

The structure of hydroxamate anions in solution (**1d–1d′**) have long remained contentious. The results

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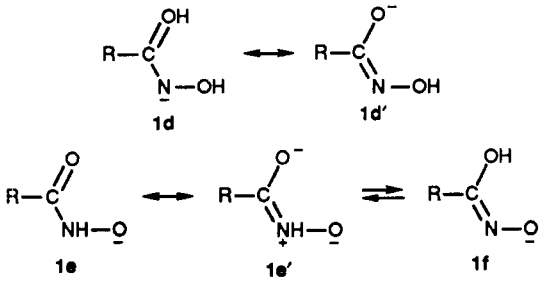
of ^{13}C NMR and ^{17}O NMR investigations, as well as ab initio calculations,[11] show that deprotonation occurs from the N atom (structures **1d–1d'**) of benzenehydroxamic acid, rather than from the O atom (structures **1e–1f**).



Recent progress in hydroxamic acid chemistry has been stimulated by the isolation of naturally occurring compounds, found mainly in fungi, which are active as antibiotics, antitumor agents, fungistatics, and growth and cell division factors.[12] They also play an important role in iron uptake and metabolism.[6,12] Many synthetic hydroxamic acids also show fungicidal, antimalarial, and antibacterial activities and thus find therapeutic applications.[13] Desferrioxamine is an iron-chelating drug for human use,[14] while other compounds have been reported to inhibit stone formation in the urinary tract.[15] Some hydroxamic acids inhibit DNA biosynthesis.[16,17] A number of synthetic hydroxamic acids have been reported to be active as pesticides, as plant growth promoters, and as soil enhancers.[18] On the other hand, many of them are powerful mutagens[19] and carcinogens.[20] The biological activities of hydroxamic acids have been reviewed by several authors.[2,3,21,22]

Strangely enough, the photochemical properties of hydroxamic acids have been generally ignored for a long time. However, recently a number of papers on the photochemical formation and behavior of these compounds have appeared.

B. Organization of the Review

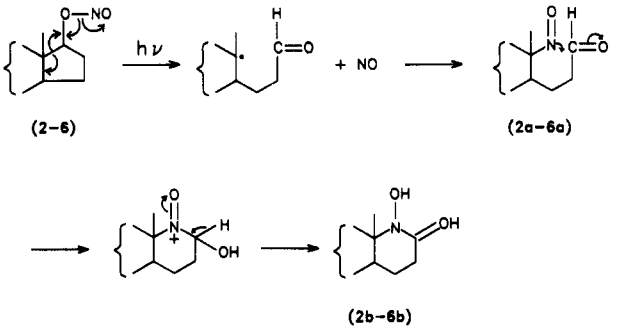
The purpose of the review is threefold: (1) to provide the reader with an overview of the literature of hydroxamic acid photochemistry, (2) to show that this group of organic compounds, known for a variety of biological activities, is also interesting from a photochemical point of view, and (3) to make clear that our knowledge in this field has only begun to evolve.

First, the photochemical formation of hydroxamic acids and acyl aminoxyl radicals is summarized. Then in the main section, some photophysical and photochemical properties of acyclic hydroxamic acids and their derivatives are presented. This section closes with a discussion of the photochemical reactions of some heterocyclic compounds, formally regarded as hydroxamic acids.

The review is limited to the photochemistry of hydroxamic acids (i.e. compounds with –CO–N–O– group(s)). The preparative photochemistry of thiohydroxamic acids (i.e. compounds with –CS–N–O– group(s)), developed by Barton and co-workers, has been discussed recently in an excellent review by Crich and Quintero,[5] and therefore is only mentioned in the last section of this paper.

The literature until the end of 1989 has been covered along with some contributions published in 1990.

SCHEME 1



II. Photochemical Formation of Hydroxamic Acids and Acylaminoxyl Radicals

A literature survey reveals that carbohydroxamic acids are products in some photochemical reactions. The formation of hydroxamic acids by (a) photolysis of organic nitrites, (b) photorearrangement of nitronate anions, and (c) photooxidation of nitrones is presented in this section. The photochemical generation of acyl aminoxyl radicals from nitroso compounds (d) is also discussed.

A. Photolysis of Organic Nitrites

The photolytic decomposition of nitrites[23] to nitric oxide and alkoxy radicals, followed by a stereoselective intramolecular hydrogen abstraction by the latter and recombination of the resulting carbon radicals with NO to form oximes and nitroso monomers and dimers, is known as *the Barton reaction* in honor of the inventor. It has found a number of applications including also the preparation of the cyclic hydroxamic acids **2–6**.[24,25]

Barton et al.[24] described the preparation of new steroidal hydroxamic acids **2b–6b** by photochemical rearrangement of the C-17β-nitrite esters **2–6** in benzene. The proposed mechanism suggested the initial photolytic fission of the O–NO bond and the formation of the C-13 nitroso intermediate(s) **2a–6a** as shown in Scheme 1.

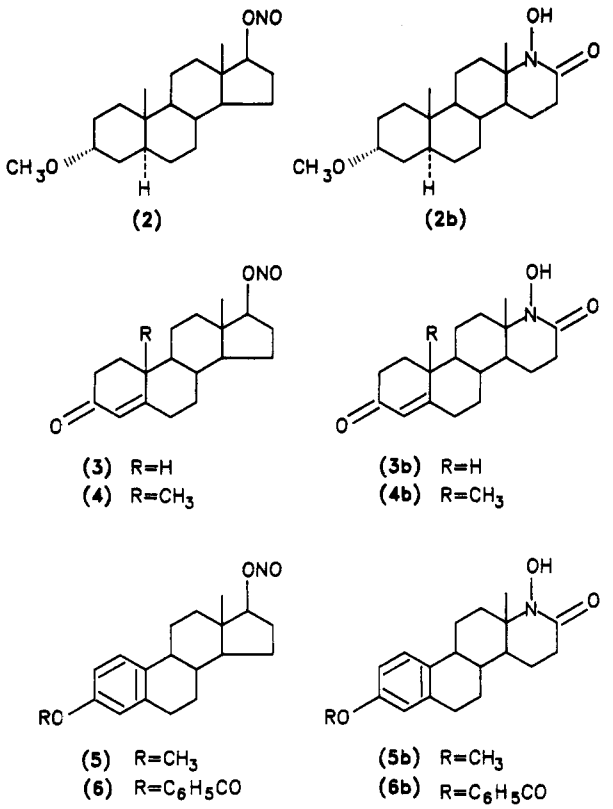
Nakazaki and Naemura[25] observed formation of cyclic hydroxamic acid **9** during the photolysis of isobornyl **7** and bornyl **8** nitrites (Scheme 2).

B. Photorearrangement of Nitronate Anions

An interesting method of introducing the hydroxamic acid function, namely the photochemical rearrangement of nitronate anions, was discovered by Marples and co-workers.[26,27] The photoreaction of 3β-acetoxy-17β-nitro-5α-androstane (**10**) in ethanol/NaOEt generated the hydroxamic acid **11** in 30% yield (Scheme 3).

In ethanol/NaOEt it is assumed that the nitro compound **10** exists essentially as the anion, and presumably the hydroxamic acid **11** is formed through the oxaziridine **12** via selective migration of the quaternary carbon substituent (Scheme 4). This rearrangement appears to have analogies in the photochemistry of nitrones and oximes.[28]

Similar results have been observed by Yamada and co-workers,[29–32] who have investigated the rearrangement of the nitro compounds **13–22** into the hydroxamic acids **13a–22a** in detail. Their results[30,31] imply that the photorearrangement often proceeds almost quantitatively (Table 1).



(2) (2b)

(3) R=H (3b) R=H
(4) R=CH_3 (4b) R=CH_3

(5) R=CH_3 (5b) R=CH_3
(6) R=C_6H_5CO (6b) R=C_6H_5CO

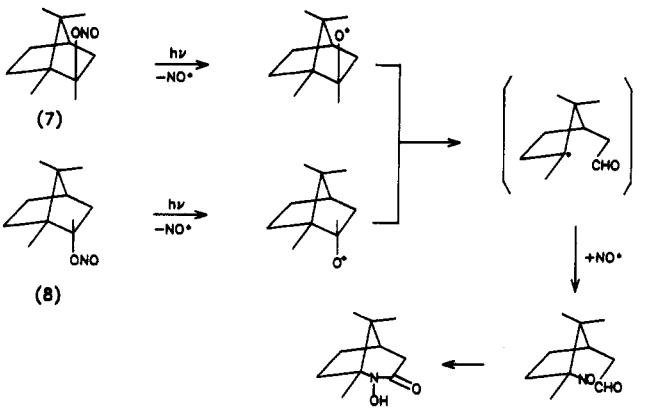
The influence of pH on the photoreaction of the nitronate anion of nitroethane was investigated in aqueous sodium hydroxide and in aqueous methylamine solution.[30] It was found that the rate of the reaction increased with pH. Methylamine, which is known to remove protons effectively from nitroalkanes, was found to be a useful base as it is easily removed from the reaction mixture.[30]

Nitronate anion formation is a key step in the mechanism of the photorearrangement. The relationship between kinetic acidity (the deprotonation rates) of nitroalkanes (21, R = H) and yield of photoreaction (Table 1) suggests that the faster the formation of nitronate anion, the higher are the yields of hydroxamic acids. The introduction of substituent groups generally results in an increase in the yields of the hydroxamic acids.[30] The regioselectivity of the photorearrangement of nitronate anion is high. The reaction is apparently controlled by the number of substituents at the β-carbon atoms, and in the case of the same number of substituents the β-carbon atom with an electron-withdrawing group migrates to the nitrogen atom. The stereospecificity of the photorearrangement was investigated in detail using nitro compounds 16, 17, and 20.[31] The results indicated almost complete retention of the stereochemistry.

Photosensitization and quenching processes which involve energy transfer of the type $D^* + A \rightarrow D + A^*$ are often used to control photochemical sequences and to study reaction mechanisms.[33] Triplet energy transfer may be used to populate indirectly the $^3A^*$ states or to quench the $^3D^*$ states.

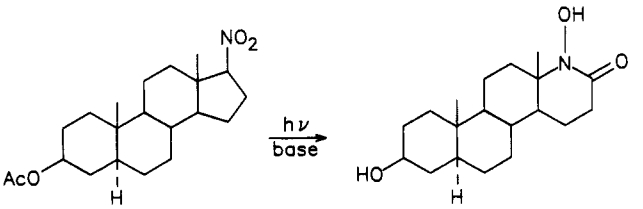
The results of quenching experiments, carried out with azulene as quencher, indicated that for 3α-acetoxy-17β-nitro-5α-androstane (22), and some other nitro compounds, the reaction proceeds through the triplet excited state. It is concluded that rehybridization occurs on $\pi-\pi^*$ excitation.[30] The same Japanese group has successfully applied the route of the intramolecular photorearrangement of the nitro group for the incorporation of the –CO–N(OH)– linkage into polymer chains.[32] The irradiation of poly(β-nitrostyrene) in basic

SCHEME 2



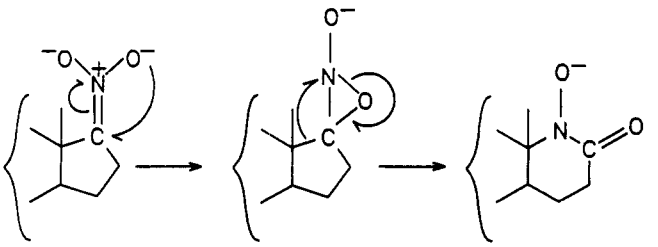
(7) (8) (9)

SCHEME 3



(10) (11)

SCHEME 4



(10) (12) (11)

SCHEME 5

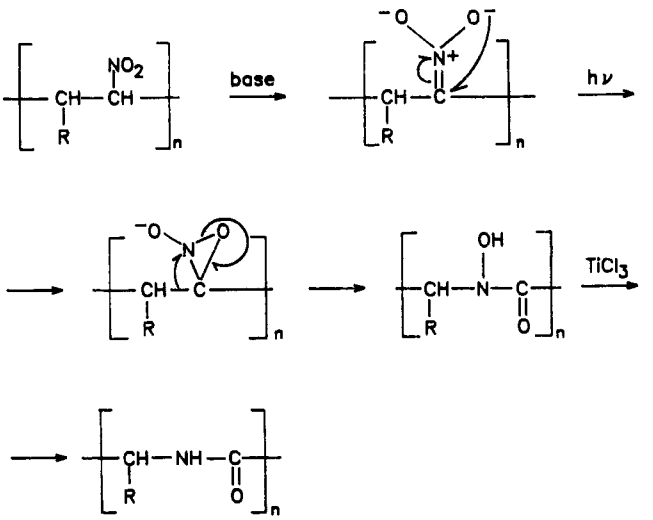
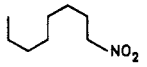
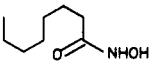
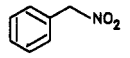
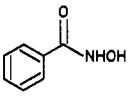
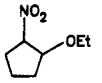
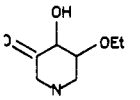
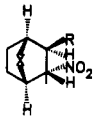
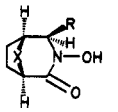
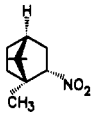
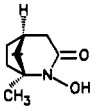
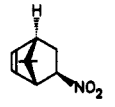
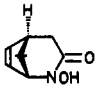
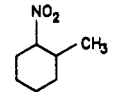
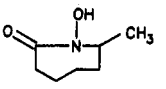
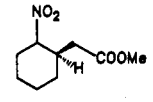
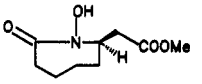
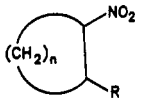
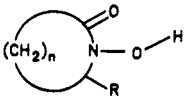
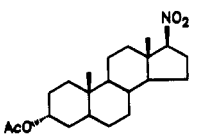
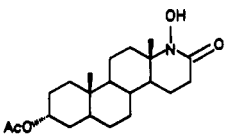


TABLE 1. Hydroxamic Acids 13a–22a from Nitronate Anions 13–22

nitroalkane		hydroxamic acid			
no.	structure	no.	structure	yield, %	ref
13		13a		85[a]	30
				30[b]	
14		14a		91[a]	29, 30
				30[b]	30
15		15a		75[b]	29,30
16		16a			
R = Ph, X = CH_2				81,[c] 65[b]	31
R = CONHBu, X = CH_2				62[c]	31
R = CONHBu, X = O				42[c]	31
17		17a		76[b]	30
				47[c]	31
18		18a		95[a]	30
19		19a		23[d]	30
20		20a		14[d]	31
21		21a			30
R = H, n = 2		R = H, n = 2		37[b]	
R = H, n = 3		R = H, n = 3		26[b]	
R = H, n = 4		R = H, n = 4		6.4[b]	
R = H, n = 5		R = H, n = 5		0[b]	
R = OEt, n = 3		R = OEt, n = 3		7.5[b]	
R = OEt, n = 4		R = OEt, n = 4		68[b]	
R = CH_3, n = 4		R = CH_3, n = 4		28[b]	
R = Ph, n = 4		R = Ph, n = 4		68[b]	
22		22a		78[d]	29

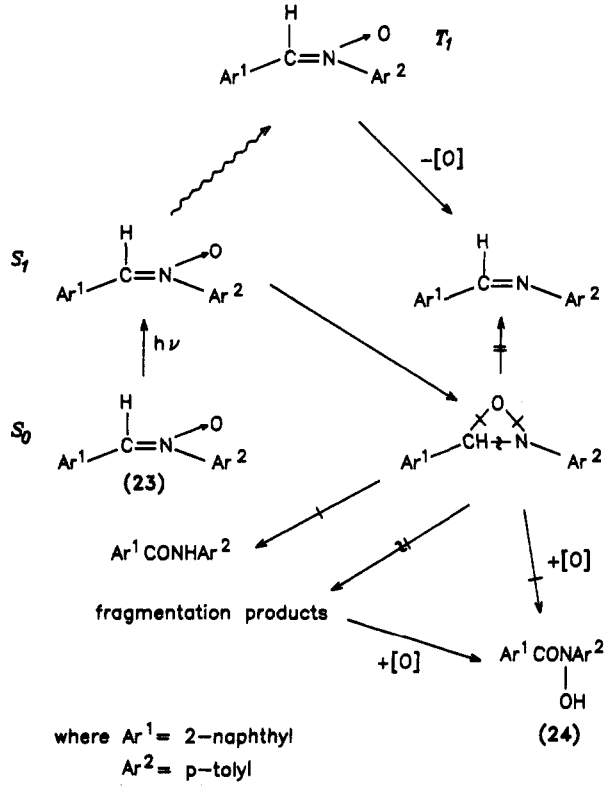
[a] $MeNH_2$/MeOH. [b] EtONa/EtOH. [c] NH_3/MeOH. [d] MeONa/MeOH.

media resulted in a photoproduct containing hydroxamic acid groups, which after reduction gave a modified polymer (Scheme 5).

C. Photooxidation of Nitrones

Bluhm and Weinstein observed[34] that photoirradiation of α-phenylnitrones in nonpolar deaerated solvents produced long-lived radicals, identified as acyl aminoxyl radicals. *N*-*p*-Tolyl-2-naphthalenehydroxamic acid (**24**) was detected among the products of the photoirradiation of α-(2-naphthyl)-*N*-*p*-tolylnitrone (**23**)[35] (Scheme 6). The fact that the hydroxamic acid was found in deaerated solutions suggested that oxygen is liberated or transferred from nitrones under photoirradiation.

SCHEME 6



The photoreaction of the singlet state of nitrones leads to a stereospecific photoclosure giving oxaziridines,[28] which undergo thermal decomposition to amides and products of fragmentation.[36] Molecules excited to the triplet state undergo photodeoxygenation to imines.[28] Thus, hydroxamic acids presumably result from an oxidation of oxaziridines. Another route might involve a recombination of the fragmentation products as shown in Scheme 6.

D. Photoreactions of Nitroso Compounds

1. Combination of Acyl Radicals with Nitroso Compounds

Acylalkylaminoxyl radicals, formed in the photochemical and thermal decomposition of nitrosoalkanes in the presence of an excess of aldehyde, have been detected by EPR spectroscopy:[37]

$$t\text{-}C_4H_9NO + CH_3CHO \xrightarrow{h\nu} CH_3CON(-O^{\bullet})\text{-}t\text{-}C_4H_9 + H^{\bullet} \quad (1)$$

Acylalkylaminoxyl radicals have also been generated by the photolysis of *primary* nitrites in cycloalkanes or alkylbenzenes; the formation of these radicals takes place via addition of intermediate acyl radicals to nitroso compounds, which are products of the photolysis of alkyl nitrites in hydrocarbons and are formed in the following sequence of reactions:[37]

$$R^1CH_2ONO \xrightarrow{h\nu} R^1CH_2O^{\bullet} + NO^{\bullet} \quad (2)$$

$$R^1CH_2O^{\bullet} + R^2H \rightarrow R^1CH_2OH + R^{2\bullet} \quad (3)$$

$$R^{2\bullet} + NO^{\bullet} \rightarrow R^2NO \quad (4)$$

R^1 = CH_3, n-C_3H_7, C_6H_5, etc.

R^2H = toluene, ethylbenzene, cyclohexane, cumene, 2,3-dimethylbutane

Primary nitrite esters gave *primary* alkoxy radicals after photodissociation and from these aldehydes are formed by disproportionation:

$$2R^1CH_2O^{\bullet} \rightarrow R^1CH_2OH + R^1CHO \quad (5)$$

Acyl radicals may arise by H abstraction from the aldehyde R^1CHO, by alkoxy radicals:

$$R^1CH_2O^{\bullet} + R^1CHO \rightarrow R^1CH_2OH + R^1CO^{\bullet} \quad (6)$$

In the presence of a small amount of nitroso compound the acyl radicals add to the nitroso group:

$$R^1CO^{\bullet} + R^2NO \rightarrow R^1CON(-O^{\bullet})R^2 \quad (7)$$

Disproportionation of *secondary* alkoxy radicals yields ketones. However, these radicals can also *decompose*, giving aldehydes. Decomposition of a secondary alkoxy radical requires a higher activation energy than H abstraction or disproportionation; consequently, in this case aldehydes are formed only with difficulty. For example, an EPR signal of acetylcumylaminoxyl radical observed in the photolysis of *sec*-butyl nitrite in cumene is weak, while the signals of dicumyl- and *sec*-butoxyaminoxyl radicals, produced in the same system, are strong. None of the known reactions for *tertiary* alkoxy radicals gives rise to the formation of aldehydes. Thus, no acylalkylaminoxyl radicals were observed during photolysis of *tert*-butyl nitrite in secondary and tertiary hydrocarbons.[37]

2. Acyl Nitroso Compounds

(Acyloxy)amidyl radicals are generated by hydrogen abstraction from the corresponding (acyloxy)amides in di-*tert*-butyl peroxide or di-*tert*-butyl peroxide/*tert*-butyl alcohol.[38] They readily fragment to give acyl nitroso compounds:

$$R^3CONHOCOR^4 \xrightarrow{-H^{\bullet}} R^3CON^{\bullet}OCOR^4 \rightarrow R^3CONO + R^4CO^{\bullet} \quad (8)$$

R^3 = CH_3 or C_6H_5, R^4 = CH_3

which, on the irradiation at 100 °C, give the monoacylaminoxyl $R^3CONHO^{\bullet}$

$$R^3CONO \xrightarrow[\text{solvent}]{h\nu} R^3CONHO^{\bullet} \quad (9)$$

Acylaminoxyl radicals are also observed[39] when (nitrosocarbonyl)benzene is irradiated (or heated) in the presence of aryl, alkyl, or *tert*-butoxyl radical precursors such as, for example, peresters $R^5CO_3Bu^t$:

$$C_6H_5CO{-}NO \xrightarrow{R^{5\bullet}} C_6H_5CO{-}N(O^{\bullet}){-}R^5 \quad (10)$$

R^5 = $(C_6H_5)_2CH$, $C_6H_5OCH_2$, $C_6H_5OC(CH_3)_2$, etc.

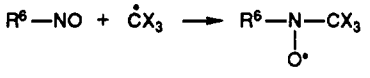
Acylalkylaminoxyl radicals are also generated by the photolysis of *N*-nitrosoamides.[40]

3. Peroxy Radicals and Nitric Oxide

It is found that nitric oxide reacts, with photochemically generated alkyl radicals, giving dialkylaminoxyl radicals. In the presence of traces of oxygen, the amoung of dialkyl radicals formed is drastically decreased and acylalkylaminoxyl radicals appear.[41]

4. Photolysis of Polyhalomethanes in the Presence of Nitrosoalkanes

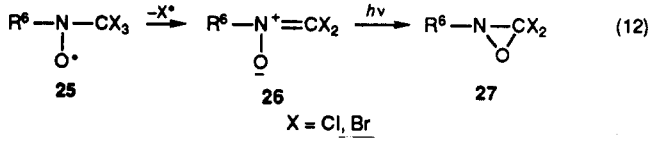
The formation of acylalkylaminoxyl radicals is observed when tri-, di-, and monohalomethyl radicals are photochemically generated in the presence of a monomeric nitrosoalkane, e.g. R^6—N=O (R^6 = *t*-Bu). The initial formation of (polyhalomethyl)alkylaminoxyl radicals has been proposed.[42]



(11)

X = Cl, Br; radical precursors: CCl_4 ($CCl_3^\bullet$), $CBr_3^\bullet$), $CHBr_3$ ($CHBr_2^\bullet$) CHI_3 ($CHI_2^\bullet$), CH_2I_2 ($CH_2I^\bullet$)

Elimination of a β-halogen atom (very easy in free radicals) produces the halo nitrones **36**, which undergo photochemical cyclization to oxaziridines **27**:

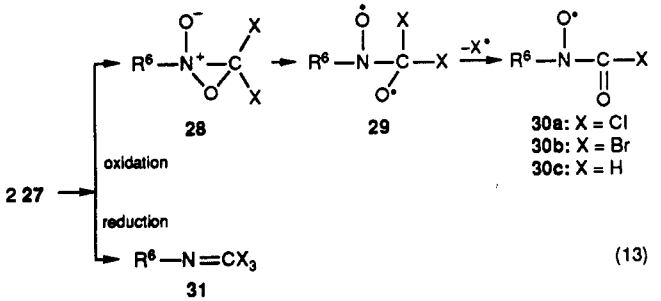


(12)

25 **26** **27**

X = Cl, Br

It is assumed that oxaziridine **27** might undergo disproportionation in solution:



(13)

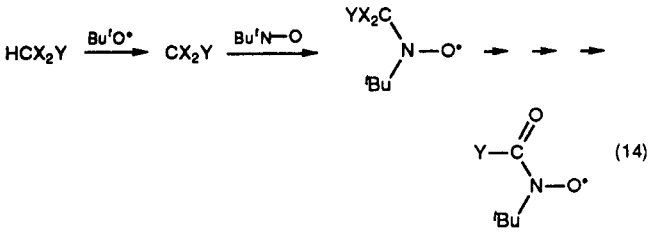
28 **29** **30a**: X = Cl; **30b**: X = Br; **30c**: X = H

31

It seems likely that **28** undergoes ring opening (possibly concerted) and elimination of a halogen atom to yield **30**. When dihalomethyl radicals are trapped by 2-methyl-2-nitrosopropane, similar reactions take place, ultimately leading to **30c**. The acylaminoxyl radical **30c** is also formed even when monohalomethyl radicals are generated in the presence of the nitroso compound. The initially formed (monohalomethyl)-*tert*-butylaminoxyl radical loses a halogen to give the halogen-free aminoxyl radical **29** (X = H). Abstraction of hydrogen (e.g., by oxaziridine) leads to **30c**.

Another possible route, which has not been excluded, is that certain aminoxyl radicals react with nitrones to form addition products, which then decompose into acylalkylaminoxyl radicals.[42]

EPR evidence has also been obtained[43] to show that the spin adduct of a radical $^\bullet CX_2Y$ with 2-methyl-2-nitrosopropane is converted into a carbonylaminoxyl radical (YC=O)N(Bu^t)O$^\bullet$:



(14)

X = Cl, Br; Y = H, CH_3, CH_2Cl, C_6H_5, Cl, Br, F

When Y in the carbonylaminoxyl is F, Cl, or Br, it can be displaced by methanol, ethanol, or dimethylamine to give alkoxycarbonyl or aminocarbonyl radicals.

III. Photochemical Behavior of Hydroxamic Acids and Derivatives

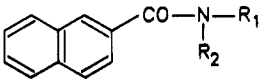
Until the 1980s, the photochemical properties of hydroxamic acids were generally neglected. In 1960 an observation of the photolytic (or thermal) scission of the N–O bond in *N,O*-diacylbenzoylhydroxylamine was reported by Walling and Naglieri.[44] Three reports of the photolytic (or thermal) homolysis of the N–O bond in appropriately N-substituted heterocyclic compounds, formally regarded as cyclic hydroxamic acids, appeared in the late 1970s. Apart from these reports, no other data about the photochemical lability and photophysical characteristics of the compounds were available in the literature prior to the 1980s. Thus, the excited-state properties of this interesting group of organic compounds have long remained uncharacterized.

However, the last decade has brought significant progress in this field. In 1982, an unusual fluorescence behavior for *N*-methylanthranilohydroxamic acid was observed.[45] An examination of the photophysical and photochemical characteristics of aromatic acyclic hydroxamic acids and some model compounds such as nitrones, amides, and anilides was carried out. A number of interesting papers on the photochemistry of derivatives of cyclic and acyclic hydroxamic acids have also been published. These results are summarized in this section.

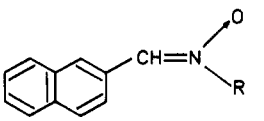
A. Acyclic Hydroxamic Acids

1. The Photophysics of Naphthalenehydroxamic Acids and Related Compounds

The finding of fluctuations in the fluorescence intensity of hydroxamic acids,[45,46] described in detail in the next section, suggested that fluorescence quantum yields of their photoproduct(s) and/or intermediate(s) differed significantly from those of the parent compounds. Therefore, an examination of the photophysical properties of selected naphthalenehydroxamic acids **24**, **32–37**, amides **38–41**, anilide **42**,[46–56] and nitrones **23**, **43**, and **44**[35] was undertaken.



	R_1	R_2		R_1	R_2
32	H	OH	**38**	H	H
33	CH_3	OH	**39**	CH_3	H
34	$C(CH)_3$	OH	**40**	$C(CH)_3$	H
35	Ph	OH	**41**	CH_3	CH_3
36	CH_3	OCH_3	**42**	Ph	H
37	H	OCH_3			



43: R = CH_3
44: R = $C(CH_3)_3$

The results of the UV absorption and fluorescence studies of **32–42** in nonpolar and polar solvents (at room

TABLE 2. Phosphorescence Data for Compounds 32, 35, 36–39, and 41 in Butanol (T = 123 K)[52]

no.	ϕ_p	τ, s	ϕ_p/ϕ_f(123 K)
32	0.008	1.8	0.02
33	0.020	1.4	1.25
36	0.038	2.3	0.52
37	0.007	2.4	0.02
38	0.009	1.8	0.03
39	0.012	1.3	0.03
41	0.29	1.8	4.02

TABLE 3. Fluorescence Quantum Yields (ϕ_f) of 32, 33, 36–39, and 41 in Butanol at 290 K and 123 K[52]

	ϕ_f		
no.	290 K	123 K	ϕ_f(123 K)/ϕ_f(290 K)
32	0.004	0.340	85
33	0.002	0.016	8
36	0.002	0.073	36.5
37	0.280	0.365	1.3
38	0.190	0.303	1.6
39	0.260	0.400	1.5
41	0.002	0.072	36

temperature) have been reported in detail.[46,48,53] An effect of hydrogen bonding and substitution at the amide nitrogen on the UV–vis absorption and fluorescence characteristics were observed. For example, the introduction of a second methyl group affects both the UV absorption and fluorescence characteristics. Broadened vibrational structures and smaller values for the molar absorption coefficients can be observed in the UV absorption spectra of **36** and **41**. The fluorescence emission spectra of these compounds are almost structureless; the ϕ_f values are much lower than those of the corresponding compounds with an NH group (**37–39**) and are more influenced by hydrogen bonding than those of **37–39**.[46,53]

The results of calculations (by the INDO/S method)[51,53] of energies of the S_0–S_n and S_0–T_n transitions of the compounds **32, 33, 36,** and **41** suggest that effective intersystem crossing (ISC) processes are dominant in the nonradiative deactivation of the S_1 state of compounds **33, 36,** and **41**, while internal conversion (IC) is responsible for efficient nonradiative deactivation in the case of 2-naphthalenehydroxamic acid (**32**).

The ϕ_p/ϕ_f ratio (where ϕ_p and ϕ_f are the phosphorescence and fluorescence quantum yields at 123 K) is higher for the compounds containing two substituents at the nitrogen atom than for the compounds with the –CONH– group (Table 2). This fact, as well as the temperature effect on the fluorescence emission of naphthalenecarbohydroxamic acids and amides[52,53] (Table 3), supports the hypothesis based on the theoretical calculations,[53] namely that ISC processes are important in the efficient nonradiative deactivation of the S_1 state of the compounds **33, 36,** and **41**.

Results of the preliminary experiments suggested that the fluorescence lifetimes of the "fluctuating" naphthalenehydroxamic acids are in the picosecond range.[47,53] Further attempts at picosecond experiments, sensitive enough to detect even minor contributions to a multicomponent fluorescence decay, gave results which were difficult to interpret.[53] The possibility of aggregation and photochemical reaction, which may occur during a laser experiment, can easily lead to erroneous conclusions. Thus, this problem remains as one to be studied in the future.

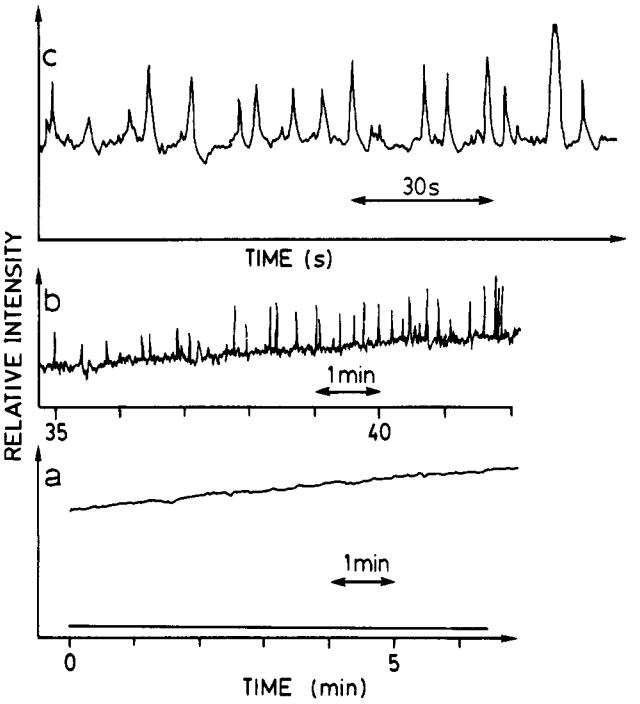


Figure 1. Plot of the fluorescence emission intensity vs time for a 6.0×10^{-4} M solution of *N*-methylanthranilohydroxamic acid in methanol at 25 °C; $\lambda_{exc} = 370 \pm 7$ nm, $\lambda_{em} = 425 \pm 3$ nm. The base line for a and b is the bottom (solid horizontal line). The time scale of the curve c is expanded.[45]

2. An Examination of the Unusual Fluorescence Behavior

The results of the preliminary studies on the excited states of acyclic aromatic hydroxamic acids have revealed an interesting fluorescence behavior for *N*-methylanthranilohydroxamic acid in methanol.[45] An increase, as well as oscillations, in the fluorescence intensity during irradiation of the solution are observed, followed by the spontaneous regeneration of the initial state in the dark (Figure 1). The fluorescence behavior observed in the steady-state studies was confirmed in transient studies by use of the picosecond technique.[47,53] The observed fluorescence lifetimes of the "fluctuating" hydroxamic acids (**32, 33, 36**) appeared to be shorter than the time resolution (ca. 15 ps) of the laser (Figure 2a). On irradiation of the unstirred solution with a xenon lamp ($\lambda_{irr} = 290 \pm 20$ nm), the original species disappeared and others (with observed fluorescence lifetimes of ca. 2 ns) were formed (Figure 2b). This phenomenon seemed to be reversible; after a certain time in dark the original species were regenerated (Figure 2c).

Nitzan and Ross[57] predicted that the absorption of light by chromophores, followed by radiationless transitions and conversion of light into heat on a short time scale compared with the chemical reaction time scale, offers the possibility of oscillations. It is possible to imagine that a reaction cell is a pseudo-flow reactor, with an illuminated portion playing the role of the reactor and the dark portion and the light source serving as the reservoir. Thus it is not unreasonable that such a system might undergo (photo)chemical oscillations.

Results of the investigations of the influence of substituents, solvents, and concentration on fluctuations in the fluorescence intensity of naphthalenehydroxamic acids **32–36**[46,48] suggest that the phenomenon is a gen-

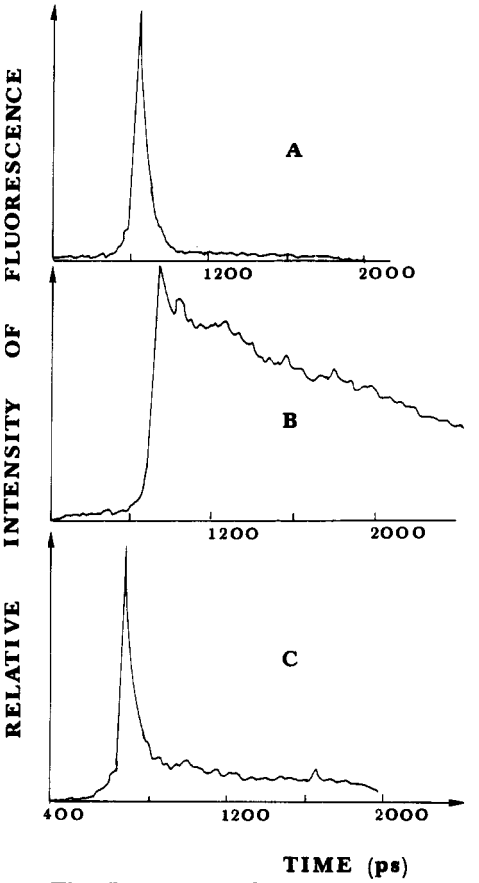


Figure 2. The fluorescence decay curves of *N*-methyl-2-naphthalenecarbohydroxamic acid (**33**) in methanol ($c \sim 10^{-5}$ M): (A) before irradiation; (B) after 15 min of irradiation (λ_{irr} = 290 ± 20 nm); (C) after ca. 1 h in the dark.[47]

eral property of aromatic hydroxamic acids.[46]

Rapid and efficient nonradiative deactivation processes of the S_1 state, found for the hydroxamic acids **32–36**,[46] might cause a small temperature gradient in the cell. The process of reversible generation of efficiently emitting phototautomers, which under prolonged irradiation leads to photoproduct formation, could serve as an effective feedback mechanism.

However, the apparent need for an irradiated volume less than the total volume of the sample, the effect of solvent on the fluctuation amplitude, and the instant cessation of fluctuations on stirring suggest that the observed fluctuations are spatial, not temporal; i.e. the system is of hydrodynamic rather than chemical interest. It should be pointed out that oscillations have been reported in a number of other photochemical systems, but they have been found to be Rayleigh–Bernard systems, not photochemical oscillators.[46] Since "fluctuating" hydroxamic acids fluoresce very weakly,[46] the formation of small amounts of efficiently fluorescing photoproduct(s) or intermediate(s) has been proposed as the probable cause of the observed increase in the fluorescence intensity of the irradiated solutions.[46]

It was shown that oxygen acts as an inhibitor in the observed processes.[46] The fluorescence intensity of solutions saturated with oxygen increased only slowly (Figure 3) or not at all, while the oscillations ceased.

The fastest increase and the highest fluctuation amplitudes were observed for nonpolar solutions of hydroxamic acids and the slowest for solutions in protic solvents.[46] This observation is consistent with the in-

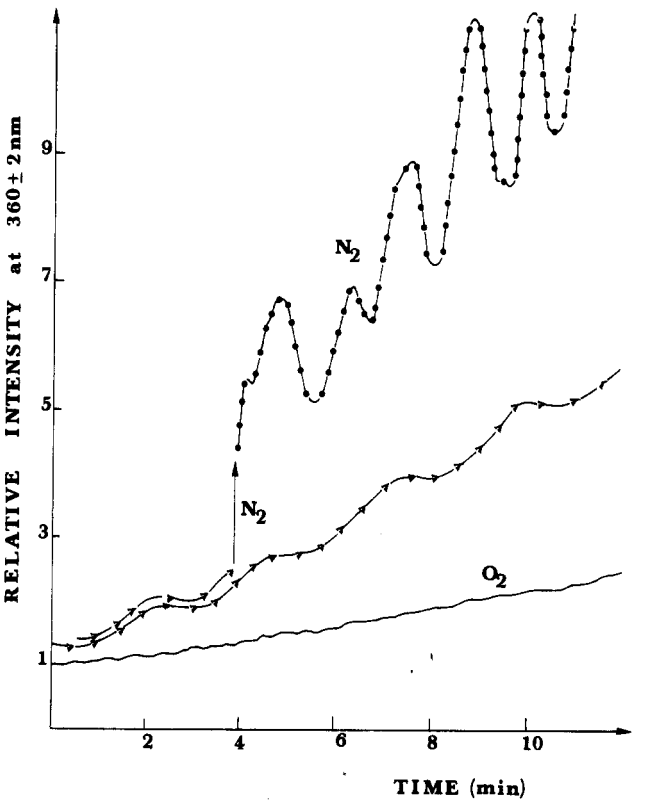
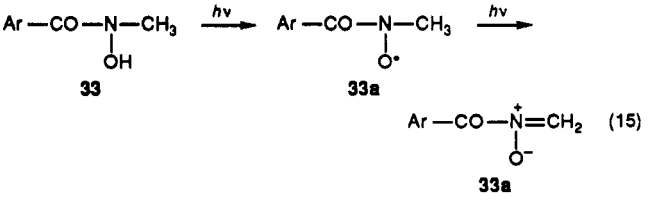


Figure 3. Fluctuations in the fluorescence intensity (at λ_{em} = 360 ± 2 nm) of an unstirred solution of *N*,*O*-dimethyl-2-naphthalenecarbohydroxamic acid (**36**, 5×10^{-5} M) in cyclohexane; λ_{exc} = 290 ± 20 nm; (–>–) undegassed solution, (–O–) solution saturated with nitrogen, (—) solution saturated with oxygen.[46]

fluence of protic solvents on the quantum yields of the photochemical reactions of these compounds.[55,56] It was suggested that the disturbing effect of oxygen on the fluctuations in fluorescence intensity of naphthalenehydroxamic acids (**33**, **36**) arises from a free-radical mechanism and/or a process involving molecules excited to the T_1 state.[46] The results of photochemical investigations have confirmed this hypothesis.[56]

In the case of the compounds containing *N*-aryl substituents, for instance *N*-*p*-tolyl-2-naphthalenehydroxamic acid (**24**), the fluorescence quantum yields are not high ($\phi_f \sim 10^{-4}$), the difference between the ϕ_f values of hydroxamic acids and their photoproducts (and/or intermediates) is not large, and the observed changes in fluorescence intensity are not spectacular.[46]

N-Methyl-2-naphthalenehydroxamic acid (**33**) exhibited the most extreme fluctuation behavior among the compounds studied.[46] This may be connected with the formation of the unstable primary photoproduct, probably *N*-acylnitrone **33b**, detected by HPLC during the first 30 min of irradiation of **33** in the spectrofluorometer:[46,56]



33 33a 33a (15)

This conclusion is supported by results of photochemical investigations of α-(2-naphthyl)nitrones **23**, **43**, and **44**.[35] It has been shown that the increase and

TABLE 4. EPR Parameters for the Radicals Generated by Photolysis[a] of the Compounds 33, 34, and 45[50]

no.	T, K	a_N, G	$a_H^{o,p}$, G	a_H^m, G	a_H^β, G	g
33	170	7.0			7.9	2.0077
34	170	7.7				2.0062
34	300	7.9				2.0060
45	170	7.05	1.61	0.67		2.0072

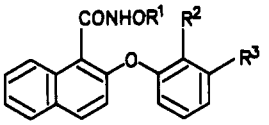
[a] Degassed solutions in 3-methylpentane (3MP), λ_{irr} = 300–380 nm.

fluctuations of the fluorescence intensity of α-(2-naphthyl)methylnitrone (43) result from the formation of the corresponding efficiently emitting oxaziridine. Generation of nitrone- and oxaziridine-like intermediates may therefore be one of the reasons for the unusual fluorescence behavior or hydroxamic acids.

3. Photochemistry of Aromatic Acyclic Hydroxamic Acids

Photoirradiation of N-substituted naphthalenehydroxamic acids 33 and 24[56] and *N*-phenylbenzenehydroxamic acids 45,[49,55] as well as 2-(arylthio)benzenehydroxamic acids[58,59] 46 (Scheme 7) and 2-(aryloxy)benzenehydroxamic acids[60] 47 gives the corresponding anilides and amides as the main products. Their formation appeared to be consistent with the initial homolysis of the N–O bond.[49,58-60]

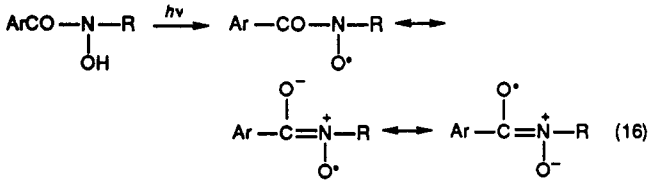
No attempt was made to characterize the radicals generated during the photochemical reactions of 46 and 47.[58-60]



(47)

	R^1	R^2	R^3		R^1	R^2	R^3
a:	H	Me	H	e:	Ph	H	H
b:	Me	H	H	f:	Ph	Me	H
c:	Me	Me	H	g:	Ph	H	Me
d:	Me	H	Me				

The results of EPR studies of 33, 34, 35, and 45 suggest[50] that photoirradiation of these compounds leads to acylaminoxyl radical generation and not to the homolysis of the N–O bond. UV irradiation of the compounds in the EPR cavity produced relatively short-lived radical species[50] with hyperfine patterns and a_N values typical of acylaminoxyl radicals[61] (Table 4).



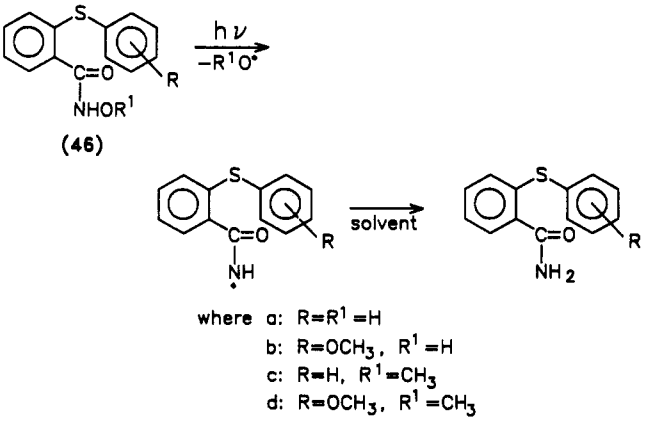
33: Ar = 2-naphthyl, R = methyl
34: Ar = 2-naphtyl, R = tert-butyl
45: Ar = phenyl, R = phenyl

On prolonged irradiation in 3-methylpentane, formation of the acylaminoxyl radical of 34, which was stable enough to be observed at room temperature, was replaced by a more stable secondary radical (a_N = 14 G, g = 2.0054) identified as having the amidyl structure.[50]

The results of detailed investigations of the photochemical reactions of 24, 33, and 45 suggest that the acylaminoxyl radicals observed during the EPR experiments are primary intermediates in the photochemical reaction of N-substituted hydroxamic acids containing the hydroxyl groups.[55,56] The reaction mimics the well known ground-state oxidation of these compounds. Benzanilide[49,55] and *N*-(2-naphthoyl)-*p*-toluidine[56] were the main products of the irradiation of 45 and 24 in dilute solutions in nonpolar and polar protic and aprotic solvents, while photoirradiation of more concentrated solutions (>5 × 10^{-4} M) of 45 resulted in formation of *N*,*O*-dibenzoyl-*N*-phenylhydroxylamine, which decomposed to benzanilide and benzoic acid on prolonged irradiation (Scheme 8).[55]

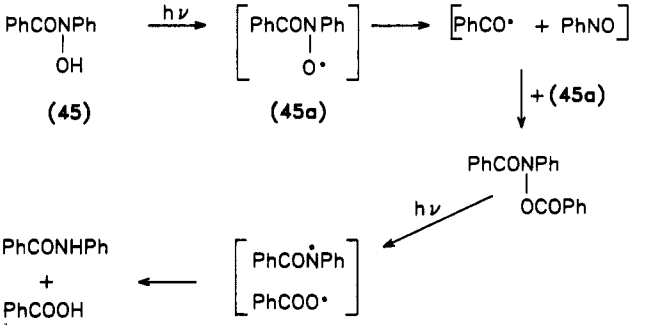
An unstable product of the analogous photolysis of 24, which decomposed to *N*-(2-naphthoyl)-*p*-toluidine and 2-naphthoic acid on prolonged irradiation or standing in solution, was identified as *N*,*O*-bis(2-naphthoyl)-*N*-*p*-tolylhydroxylamine.[56] *N*-Phenylbenzenehydroxamic acid also appears to undergo a photochemical reaction in basic solution, giving benzanilide[55,56] as the main product. Results of the ^{17}O NMR[11] and UV[49] (Figure 4) investigations indicate that the nitrone-like structure 45b makes a major contri-

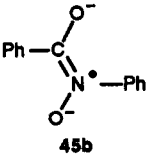
SCHEME 7



where a: R=R¹=H
b: R=OCH₃, R¹=H
c: R=H, R¹=CH₃
d: R=OCH₃, R¹=CH₃

SCHEME 8





45b

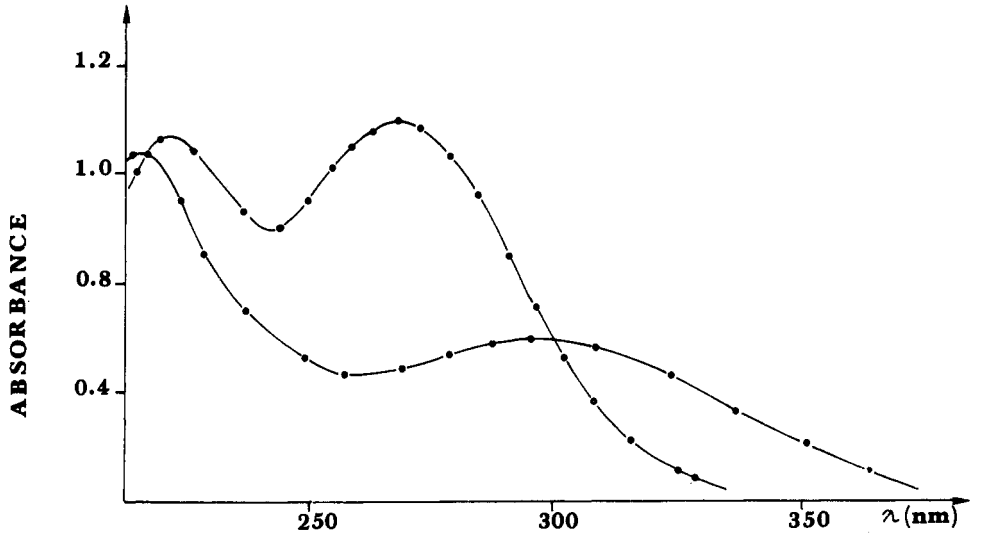
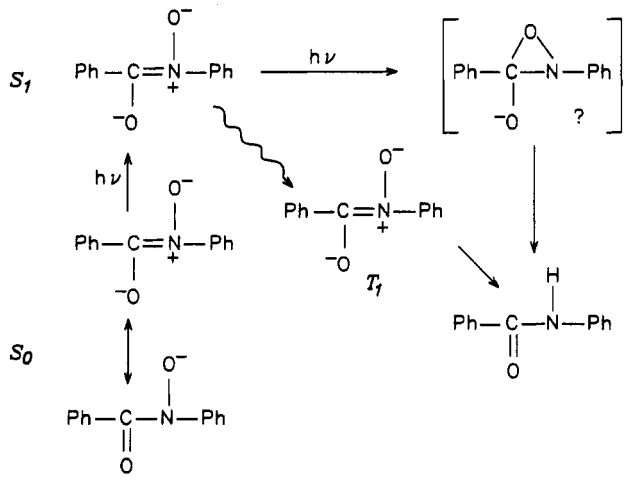
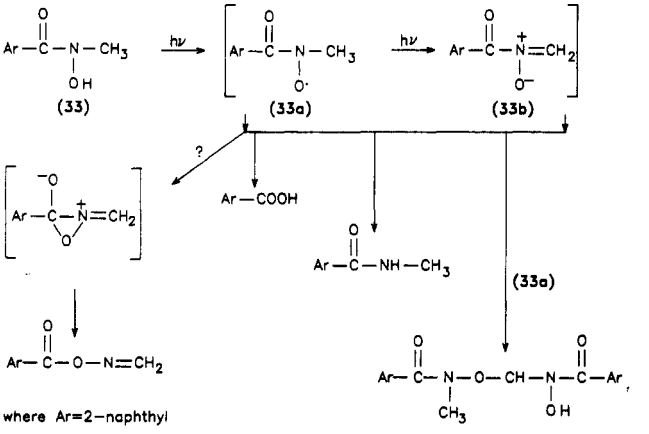


Figure 4. UV spectra of *N*-phenylbenzenecarbohydroxamic acid (**45**, 7×10^{-5} M); (○) methanol; (●) methanol/$NaOH_{aq}$ = 1:1, pH ~ 13.[55]

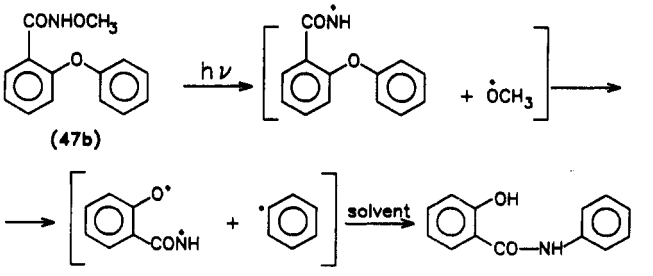
SCHEME 9



SCHEME 10



SCHEME 11



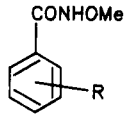
bution to the anion structure in the ground state. The latter structure resembles the nitrone chromophore, known to undergo photochemical reaction via an oxaziridine intermediate.[28] Thus, a similar mechanism for the photoreaction of *N*-phenylbenzenehydroxamic acid (**45**) was postulated[55] (Scheme 9). No oxaziridine ring formation was observed during the photochemical experiments;[55] however this is to be expected because *N*-aryl-substituted oxaziridines are not sufficiently stable to be isolated at room temperature.

Preparative irradiations of *N*-methyl-2-naphthalenecarbohydroxamic acid (**33**) in nonpolar, polar aprotic, and protic solvents result in a single photoproduct,[56] probably the *N*-acylnitrone **33b**, that is too unstable to be isolated. This compound, detected by the HPLC method,[62,63] eventually undergoes intramolecular reactions or acts as an acylating agent with **33a** (Scheme 10).

Acetophenone is a good triplet photosensitizer for the photodestruction of *N*-phenylbenzenehydroxamic acid (**45**),[55] while benzophenone sensitized the triplet states of naphthalenehydroxamic acids **33** and **24**.[56] 1,3-Dienes have been reported[32] to quench the $T_1(n-\pi^*)$ of alkanones with rate constants approaching those for diffusion. 1,3-Hexanediene quenched the photochemical reaction of **45**,[55] while 1,4-cyclohexadiene was used as a triplet quencher of **33** and **24**.[56] Stern–Volmer plots (i.e. plots of ϕ_0/ϕ_q vs [Q] for quenching data) obtained for **45**, **33**, and **24**[55,56] were nonlinear, reflecting the situation in which both the S_1 and T_1 states undergo the same reaction.

Hosangadi et al.[59,60] investigated O-substituted hydroxamic acids **47** and **48** and found that *O*-methyl derivatives of benzenehydroxamic acids **48** were quite photostable,[59] while irradiated solutions of *O*-methyl- and *O*-phenyl-2-(aryloxy)benzenehydroxamic acids, for example **47b**, in benzene afforded the corresponding *N*-arylsalicylamides[60] (Scheme 11).

No EPR evidence for the formation of free radicals was reported by Hosangadi et al.[59,60] However, since the irradiation of both methyl (**47b–d**) and phenyl (**47e–g**) O-substituted benzenehydroxamic acids gave rise to the same products irrespective of the nature of



(48)

where a: R=H d: R=4-OCH_3
b: R=2-Cl e: R=4-CH_3
c: R=3-NO_2

the substitution on the hydroxyl oxygen, and thermolysis of **47b–g** produces identical compounds, a process involving formation of amidyl radicals has been suggested.[60]

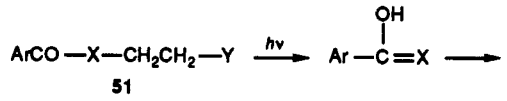
Recently, Johnson et al.[64] reported that photoirradiation of alkyl benzohydroxamates **48a** and **49a–e** in acetonitrile or hydrocarbon solvents gave benzamides **50**. Racemization occurred when 2-octyl (+)-benzohydroxamate (**49e**) was irradiated in cyclohexane. The

$PhCONR^3OCHR^1R^2$
49a–e

a: $R^1 = CH_3$; $R^2 = R^3 = H$ **d**: $R^1 = CH_3$; $R^2 = C_2H_5$; $R^3 = H$
b: $R^1 = C_6H_5$; $R^2 = R^3 = H$ **e**: $R^1 = CH_3$; $R^2 = n\text{-}C_6H_{13}$; $R^3 = H$
c: $R^1 = R^2 = CH_3$; $R^3 = H$ **f**: $R^1 = H$; $R^2 = C_6H_5$; $R^3 = CH_3$

reaction of **48a** and **49a–e** was found to be quenched by *cis*-piperylene and sensitized by benzophenone; thus a mechanism involving triplet biradical formation and a Norrish Type II photoelimination was suggested (Scheme 12).

No direct evidence for triplet biradical formation was given by Johnson et al.[64] Also, no spectroscopic data characterizing the nature of the lowest triplet state were reported. The lowest triplet state of the compounds was assumed to be the (n–π^*) state,[64] from the comparison with alkyl ketones **51a**, which are known to undergo very efficient (ϕ up to 1.0) Norris Type II photoeliminations from their (n–π^*) triplet excited states.[65]



51

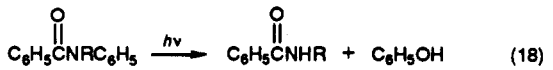
$$ArCO{-}XH + CH_2{=}CHY \quad (17)$$

a, X = CH_2; **b**, X = O; **c**, X = NH

The lowest excited states of closely related alkyl benzoates **51b** and N-substituted benzamides **51c** are usually (π–π^*), and the reaction is inefficient (ϕ < 0.01).[65] The compounds **48a** and **49a–e** undergo the photoreaction with moderate quantum efficiencies (ϕ = 0.16–0.28), but much higher ones than those for benzoates and benzamides,[64] supporting the hypothesis that **48a** and **49a–e** undergo a Norris Type II photoelimination.

The results of Johnson et al.[64] are at variance with those of Hosangadi et al.,[59] who have reported that methyl benzoate **48a** and its derivatives are quite photostable. According to Johnson et al.,[64] the compound **48a** cleanly undergoes a Norris Type II reaction.

Photolysis of *N*-phenylbenzohydroxamate **52a**, which cannot undergo the Norrish Type II photoelimination, was also investigated.[64] This resulted in the formation



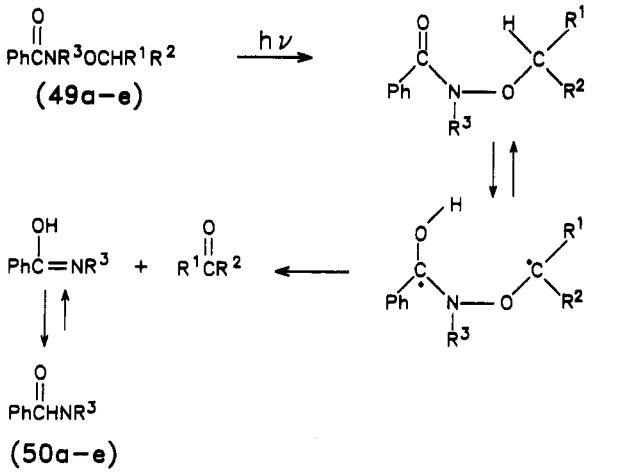
52

(18)

a, R = H; **b**, R = CH_3

of benzanilide and phenol with quantum yield lower (ϕ = 0.08) than those for hydroxamates **49a–e** (ϕ = 0.16–0.28). The reaction was sensitized by benzophenone but not quenched by *cis*-piperylene, and thus it was concluded[64] to occur from the singlet state. However, the excited-state energy levels of **52a** have not been determined, so it is not certain in that case if the quencher used was the most appropriate one.

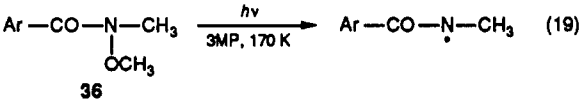
SCHEME 12



(49a–e)

(50a–e)

Benzyl *N*-methylbenzohydroxamate (**52b**) was suggested to undergo photoelimination in the singlet state through a mechanism involving N–O bond cleavage.[64] Photolytic N–O cleavage in *N,O*-dialkylhydroxamic acids has been confirmed by EPR.[54] An amidyl radical (a_N = 14.5 G, g = 2.0054) was detected during the irradiation of *N,O*-dimethyl-2-naphthalenehydroxamic acid (**36**) (in 3-methylpentane, 170 K) in the EPR cavity:[49]

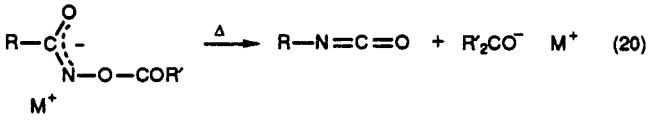


36

(19)

4. Photochemistry of N,O-Diacylhydroxylamines

In 1882, Lossen reported[7] that *N,O*-dibenzoylhydroxylamine, heated above its melting point, yields phenyl isocyanate. This reaction, known as the Lossen rearrangement, is generally considered to proceed via polar paths:[2]



(20)

Walling and Naglieri found[44] that the photolysis products are quite different from those of the thermal decomposition. No phenyl isocyanate or carbanilide is produced on photoirradiation of *N,O*-dibenzoylhydroxylamine. These results are consistent with an initial photolytic scission of the N–O bond:

$$C_6H_5CONHOCOC_6H_5 \xrightarrow{h\nu} C_6H_5\dot{C}ONH + C_6H_5COO^\bullet \quad (21)$$

followed by

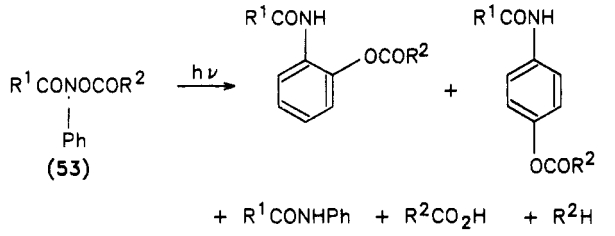
$$C_6H_5\dot{C}ONH + RH \rightarrow C_6H_5CONH_2 + R^\bullet \quad (22)$$

$$C_6H_5COO^\bullet + RH \rightarrow C_6H_5COOH + R^\bullet \quad (23)$$

$$C_6H_5COO^\bullet \rightarrow C_6H_5^\bullet + CO_2 \quad (24)$$

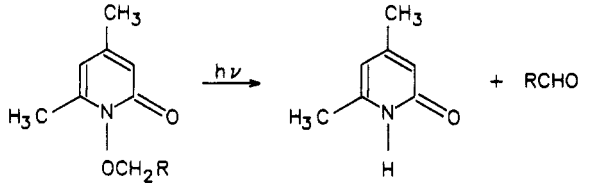
$$C_6H_5^\bullet + RH \rightarrow C_6H_6 + R^\bullet \quad (25)$$

SCHEME 13



where a: R^1 = 1-naphthyl, R^2 = p-tolyl
b: R^1 = p-tolyl, R^2 = 1-naphthyl
c: $R^1 = R^2$ = 1-naphthyl
d: $R^1 = R^2$ = p-tolyl

SCHEME 14



(54)

where a: R=H
b: $R=C_6H_5$

where RH represents the solvent.

The highly polar *N*-*p*-anisoyl-*O*-(*p*-nitrobenzoyl)-hydroxylamine, which shows a very rapid Lossen rearrangement, undergoes the same sort of homolytic photolysis as dibenzoylhydroxylamine itself. Photochemical decomposition of diacylhydroxylamines was proposed as an efficient photoinitiator of vinyl polymerization.[44]

Sakurai and co-workers observed[66] that the decomposition of *N*,*O*-diacyl-*N*-phenylhydroxylamines **53** yielded the rearrangement products derived from 1,3- and 1,5-aroyloxy migrations, in addition to fragmentation products (Scheme 13).

The results of crossover experiments performed by the same group[67,68] indicate an intramolecular rearrangement, probably involving homolysis of the N–O bond in the excited state.

The triplet-sensitized photolysis of *N*-(1-naphthoyl)-*O*-*p*-tolyl-*N*-phenylhydroxylamine (**53a**) and related *N*,*O*-diacylhydroxylamines gives no rearranged products; this provides evidence for the suggestion that "photoacyloxyl" migration proceeds mainly through the excited singlet state.[67] The singlet mechanism is also supported by the results of the pyrene-sensitized photolysis of **53a**.[69]

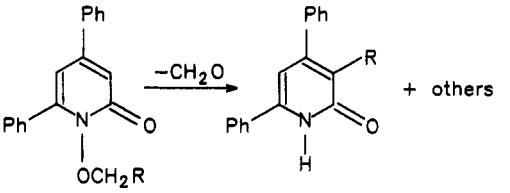
B. Cyclic Hydroxamic Acids

There are several reports concerning both thermal and photolytic homolysis of the N–O bond in various cyclic compounds,[66,70-76] formally regarded as hydroxamic acids.

Furrer found[70] that N-substituted 2-pyridones **54** undergo photolysis with the loss of the corresponding aromatic aldehydes (Scheme 14).

Katritzky and co-workers observed[71,72] that N-substituted derivatives of 1-hydroxy-4,6-diphenyl-2-pyridone **55–58**, 3-hydroxy-2-phenyl-4(3*H*)-quinazolinone **59**, and 2-benzenesulfonamidopyridine

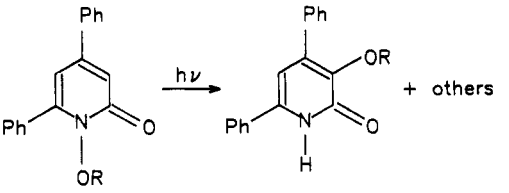
SCHEME 15



(55)

where a: $R=CH_2Ph$
b: $R=CH_2CH=CH_2$

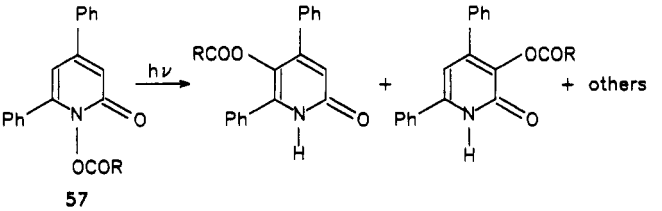
SCHEME 16



(56)

where $R=[CH_2]_7Me$

SCHEME 17



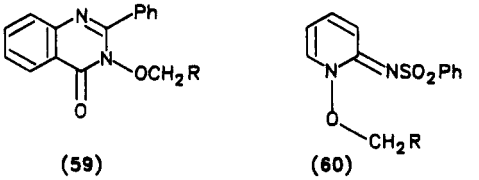
57

where R=p-tolyl

1-oxides **60** undergo similar photolysis (and thermolysis). Products of four novel rearrangements involving homolytic N–O fission and formation of 3- or both 3- and 5-substituted 4,6-diphenyl-2-pyridones were also isolated.[72] Photolysis of **55** (where R = vinyl or phenyl) gave 3-CH_2R (R = vinyl or phenyl) derivatives with elimination of CH_2O (Scheme 15). Photoirradiation of the 1-octyloxy derivative of **56** produced the 3-octyloxy derivative by simple transposition (Scheme 16).

Photolysis (and thermolysis) of *N*-acyloxy and *N*-benzoyloxy derivatives of 1-hydroxy-4,6-diphenyl-2-pyridones results in the generation of the corresponding 3- and 5-acyloxy and -benzoyloxy derivatives.[72] For instance, irradiation of 4,6-diphenyl-1-(*p*-toluoyloxy)-2-pyridone **57** in dry acetone gives 10% of the 5- and 16% of the 3-*p*-toluoyloxy isomers (Scheme 17).

1-Imidoyloxy compounds, for instance **58**, undergo photochemical rearrangement to 3- and 5-amido-2-pyridones[72] (Scheme 18).

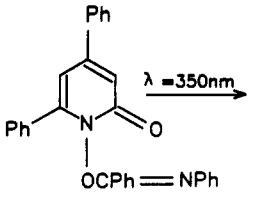


(59) (60)

where R=alkyl or aryl

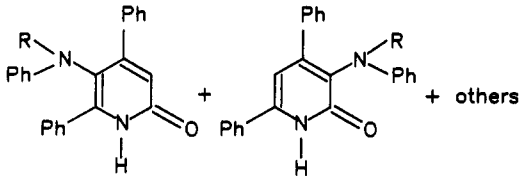
The results of triplet quenching and sensitization experiments, reported by Sakurai and co-workers,[73] indicate that the photolysis of 1-(benzoyloxy)-2-

SCHEME 18

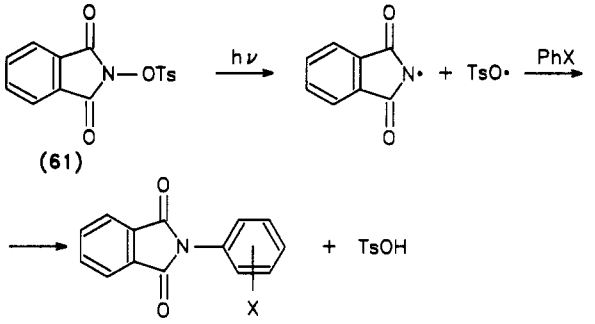


(58)

where R=COPh



SCHEME 19



where X=H, MeO, Me, Ph, Cl etc.

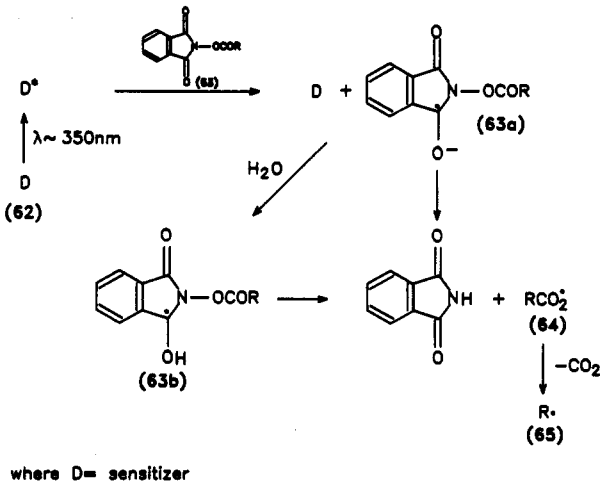
pyridone (**54b**) proceeds preferentially through the singlet excited state. A deuterium isotope effect on the quantum yield for the disappearance of the compound was studied with 1-(benzyl-α,α-d_2-oxy)-2-pyridone. From the magnitude of this effect a mechanism involving intramolecular hydrogen abstraction and cleavage of the N–O bond was suggested for the photolysis in polar solvents, while the homolysis of the N–O bond was believed to predominate in nonpolar solvents.[73]

Cadogan and Rowley[74] reported that *N*-(tosyloxy)-phthalimide (**61**) undergoes photolysis at room temperature in the presence of aromatic compounds to give *N*-arylphthalimides in good yields (Scheme 19).

Ready cleavage of the N–O bond in phthalimide derivatives has recently found a useful synthetic application. Okada and co-workers[75] have reported a practical method for photosensitized decarboxylation of *N*-(acyloxy)phthalimides via an electron-transfer reaction. The reaction proceeds in high yields on irradiation with visible light (Scheme 20). An electron transfer from the excited singlet state of 1,6-bis(dimethylamino)pyrene (**62**), the most effective sensitizer among the studied compounds, to *N*-(acyloxy)phthalimide **63** gives the anion radical **63a**. The carboxy radical **64**, resulting from the cleavage of the weak N–O bond in the anion radical **63a** or its protonated form **63b**, undergoes decarboxylation to the radical **65**. The reaction can be applied to various *N*-(acyloxy)phthalimides, including N-protected amino acid derivatives.

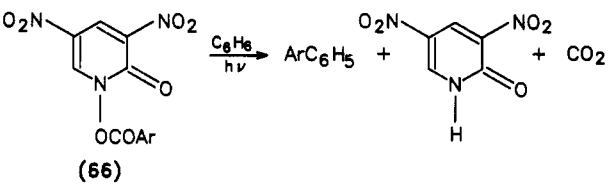
The generation of aryl radicals on direct irradiation of cyclic carbohydroxamic acids was previously sug-

SCHEME 20



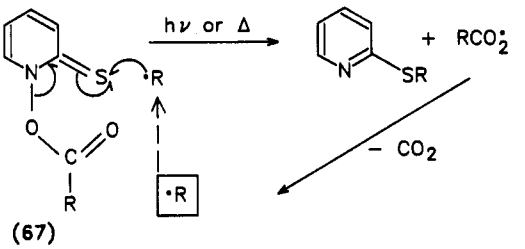
where D= sensitizer

SCHEME 21



(66)

SCHEME 22



(67)

gested by Taylor and co-workers,[76] who found that photoirradiation of 1-(acyloxy)-3,5-dinitro-2(1*H*)-pyridones **66** in benzene gave unsymmetrical biphenyls in low to moderate yield (Scheme 21).

The direct photolysis of cyclic carbohydroxamic acids has as yet not found synthetic applications. Instead, an elegant method for the decarboxylation of acids via their *N*-hydroxypyridine-2-thione esters has been developed by Barton and co-workers.[5,77-81] Thiohydroxamic acid esters **67**, derived from carboxylic acids and *N*-hydroxy-2-thiopyridone or other hydroxamic acids, undergo a smooth decarboxylative rearrangement to sulfides when irradiated or heated. This radical reaction, shown in Scheme 22, appears to be an exceptionally good source of carbon radicals and is useful for the transformations of many primary, secondary, and tertiary aliphatic and alicyclic carboxylic acids. The carbon-centered radicals can react with a variety of reagents, including Bu_3SnH, CCl_3Br, disulfides, diselenides, alkenes, and aromatics.

Barton and co-workers have recently compared[81] the thermal and photochemical reactivity of cyclic carbohydroxamic acids with those of *N*-hydroxy-2-thiopyridone. Acyl derivatives of a number of cyclic compounds, including *N*-hydroxybenzotriazin-4-one and *N*-hydroxy-2-pyridone, were reduced thermally by tributyltin hydride (with initiation of azobisisobutyronitrile) giving the corresponding nor hydrocarbons in

a radical chain. However, the dihydrocinnamyl derivative of *N*-hydroxybenzotriazin-4-one appeared to be photostable. The tin hydride reduction was also not affected by light. Thus one can conclude that the thiocarbonyl group of 2-hydroxy-2-thiopyridone is essential for propagating the chain reaction. Acyl derivatives of cyclic carbohydroxamic acids therefore cannot compete with the corresponding thiohydroxamic derivatives as a source of carbon radicals, generated by direct photolysis of these compounds.

IV. Summary

Considerable progress in the photochemistry of hydroxamic acids has been made through the 1980s. These investigations afforded a series of papers on the photochemical formation and reactions of acyclic and cyclic hydroxamic acids. An unusual fluorescence of hydroxamic acids has been found and a number of photophysical data collected in order to explain the observed phenomenon. Acylaminoxyl radicals, known active oxidants, have been suggested as primary intermediates in the photochemical reaction of N-substituted acyclic compounds. However, our knowledge of the excited-state behavior of this group of organic compounds is still at fairly primitive stage and major synthetic and physical challenges yet remain.

The synthetic value of the Barton method has already been well documented and the generation of carbon radicals via photochemical reactions of thiohydroxamic acid derivatives will certainly find many applications in the future. Some other reported reactions, for instance, photochemical rearrangement of nitronate anions and indirect photosensitized decarboxylation of *N*-(acyloxy)phthalimides, also show a considerable potential in synthetic chemistry. Possibilities of synthetic applications of the oxidative properties of the photogenerated acylaminoxyl radicals have not yet been explored.

In future studies, there is a great deal more to be learned about the photophysical properties of hydroxamic acids. Fluctuations in the fluorescence intensity of hydroxamic acids have been found to be of hydrodynamic rather than chemical interest and a formation of efficiently fluorescing species has been concluded to cause the observed increase in the fluorescence intensity. However, the "physical" description of the observed phenomenon is an unsolved problem in fluid dynamics, which may be of interest to physicists. There are some indications that oxaziridine-like phototautomers are the intermediates in the photochemical reactions of acyclic hydroxamic acids. However, direct proof has not yet been obtained.

The fact of the photochemical lability of hydroxamic acid derivatives present in the human environment has been generally ignored. Meanwhile, many of these compounds, on exposure to sunlight, may be transformed (directly or indirectly) to intermediates and photoproducts that are more toxic than the parent compounds. For instance, some acylaminoxyl radicals are known for their carcinogenic activity.

Thus, much work remains ...

V. Acknowledgments

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