# The free radical chemistry of the azoxy group

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**Dedicated to Professor Henry J. Shine on the occasion of his 80th birthday**

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**Abstract**

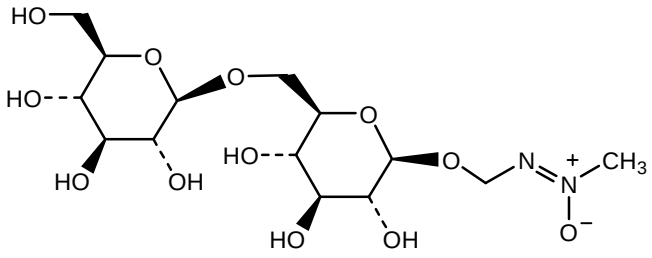
The azoxy functional group, though relatively uncommon, is found in several natural products and in liquid crystalline compounds. Azoxyalkanes are generally very stable to heat and light and are not subject to attack by radicals. Intramolecular radical reactions, however, can lead to cyclic aminyl nitroxides and hydrazyls, which rearrange further or undergo fragmentation. The azoxy group greatly stabilizes an attached carbon-centered radical but the chemistry of the resulting α-azoxy radicals is not completely understood.

**Keywords:** Azoxy, radical, aminyl nitroxide, hydrazonyloxide

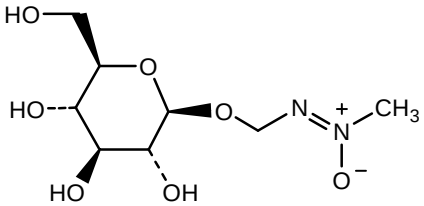
## Introduction

Azoxyalkanes (R-N=N(O)-R') are among the less common organic nitrogen-containing compounds. In terms of oxidation-reduction, they are related to the hydrazines (RNH-NHR), azoalkanes (R-N=N-R'), hydrazones (RR'C=N-NH-R'') and diazoxy compounds (RN(O)=N(O)-R').[1] While azoxybenzene derivatives exhibit liquid crystalline properties and have been incorporated into polymers,[2-4] compounds containing the azoxymethylene group are carcinogenic because they can be metabolized to carbocations that attack DNA.[5-9] Most 1,2-disubstituted aliphatic hydrazines and azoalkanes are metabolized in humans via azoxy intermediates.[5] Since the discovery of macrozamin in 1951,[10-14] a number of naturally occurring azoxy compounds have been identified, including cycasin,[15,16] elaiomycin,[17] maniwamycin I,[18,19] azoxybacillin,[20,21] and valanimycin.[22] The known biological pathways of azoxy compounds do not involve free radicals; nevertheless, the free radical chemistry of azoxy compounds has received some attention since the subject was last reviewed in 1975.[23]

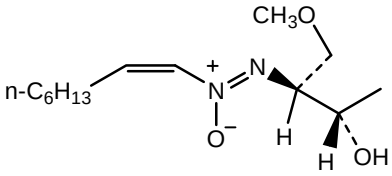
 



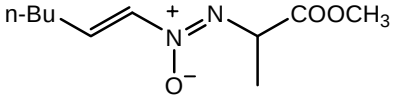
macrozamin



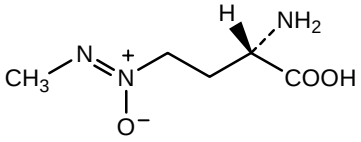
cycasin



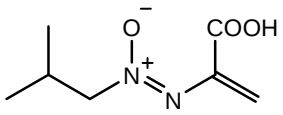
elaiomycin



maniwamycin I



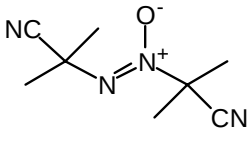
azoxybacillin



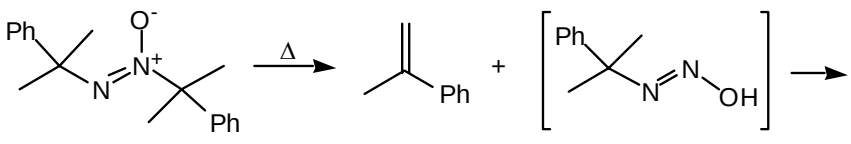
valanimycin

## Thermolysis and photolysis of azoxyalkanes

Unlike deazatation (denitrogenation) of azoalkanes,[24] loss of $N_2O$ from aliphatic azoxy compounds is rarely observed. Thus they are neither free radical initiators nor thermally labile, contrary to published comments.[25] For example, the common free radical initiator azoisobutyronitrile (AIBN) decomposes readily at 80 $^oC$ but the azoxy analog **1** is stable up to 180 $^oC$.[26-28] Thermolysis of azoxycumene **2** is very slow and does not yield $N_2O$, leading instead to a Cope amine oxide elimination.[27] The same reaction takes place at 190 $^oC$ in azoxy-t-butane **3**, which affords mostly nitrogen and isobutene, accompanied by a 20% yield of $N_2O$ and a little isobutane.[29]



**1**



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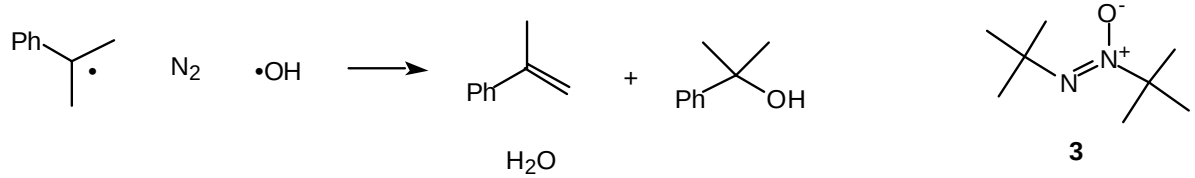
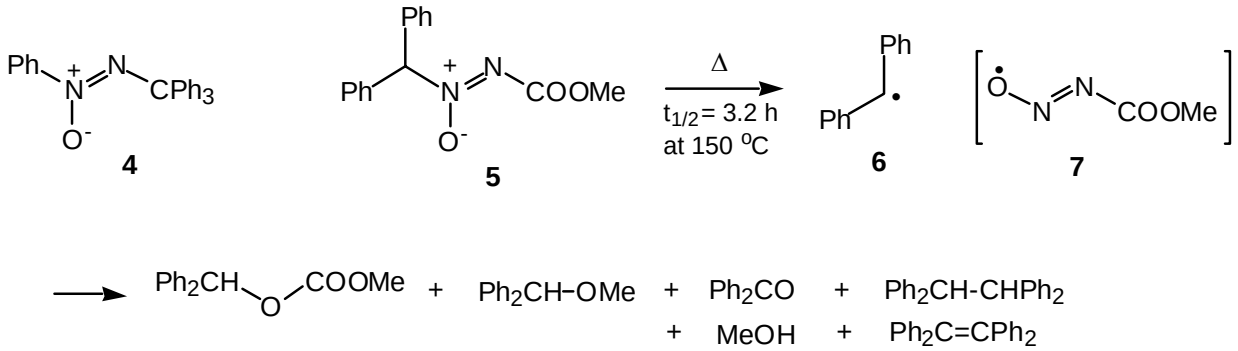


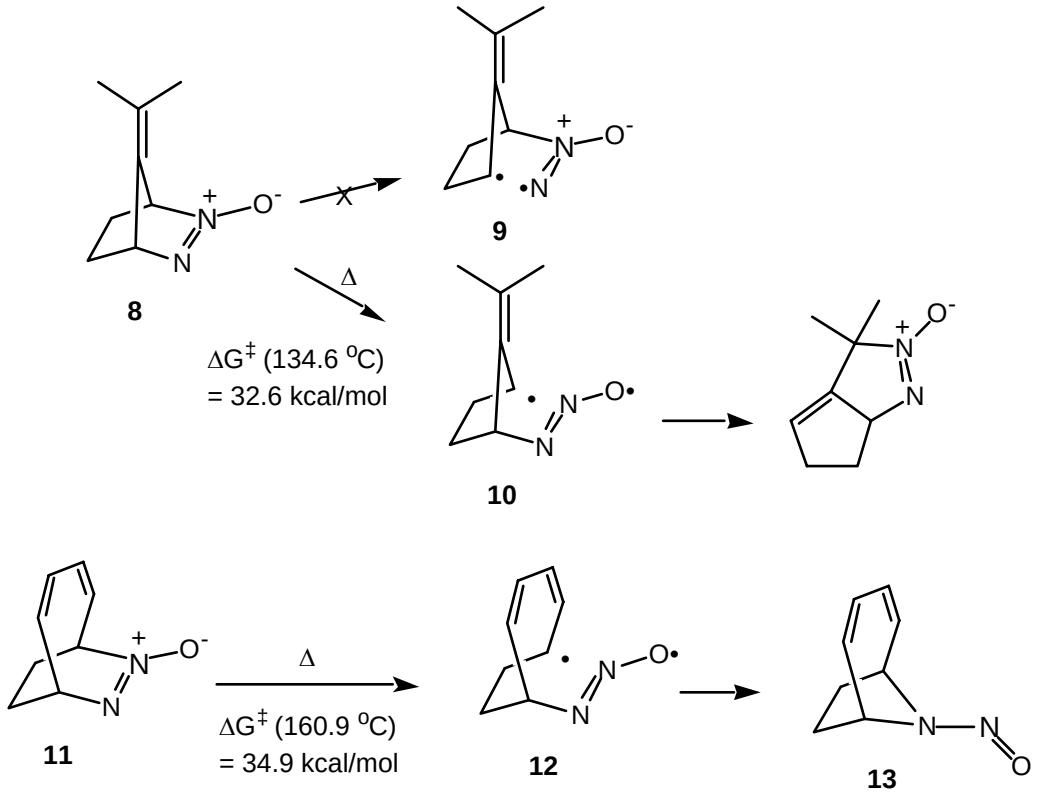
$H_2O$

**3**

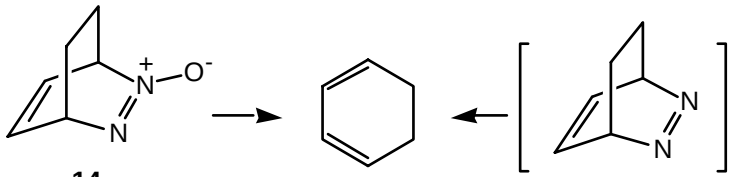
Even a triphenylmethyl group distal to oxygen does not accelerate azoxyalkane thermolysis, as illustrated by **4**, which decomposes with $\Delta G^{\ddagger}$(290 °C) = 43.0 kcal/mol ($t_{1/2}$ =~50 min.)[27] When oxygen is placed proximal to the radical stabilizing substituent as in **5**, homolysis of the benzhydryl to N bond is greatly facilitated.[27] Now both radicals **6** and **7** benefit from resonance stabilization, reducing $\Delta G^{\ddagger}$ (150 °C) to 33.3 kcal/mol ($t_{1/2}$ = 3.2 h). The same effect is




seen in **8**, which cleaves only the C-N bond proximal to oxygen to generate the resonance stabilized **10**.[30] Similarly, thermolysis of **11** affords **13** via the intermediate diazenyloxy biradical **12**.[31]

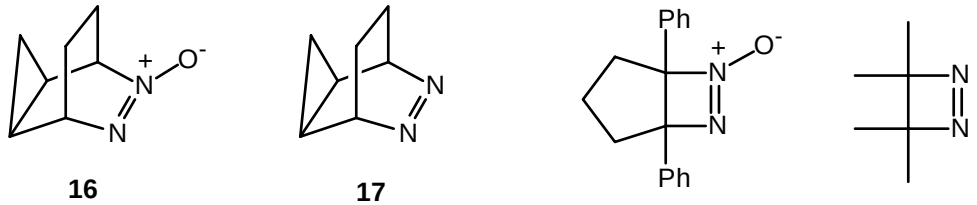


The greater thermal stability of azoxyalkanes than azoalkanes carries over to compounds that lose $N_2O$ or $N_2$ by concerted pericyclic retrocycloaddition. Thus the activation energy for $N_2O$ extrusion from **14**[32] is at least 23 kcal/mol higher than that for deazatation of **15**, which is unstable even at –78 °C.[33] Likewise, **16** undergoes no detectable decomposition on heating at



**14** **15**

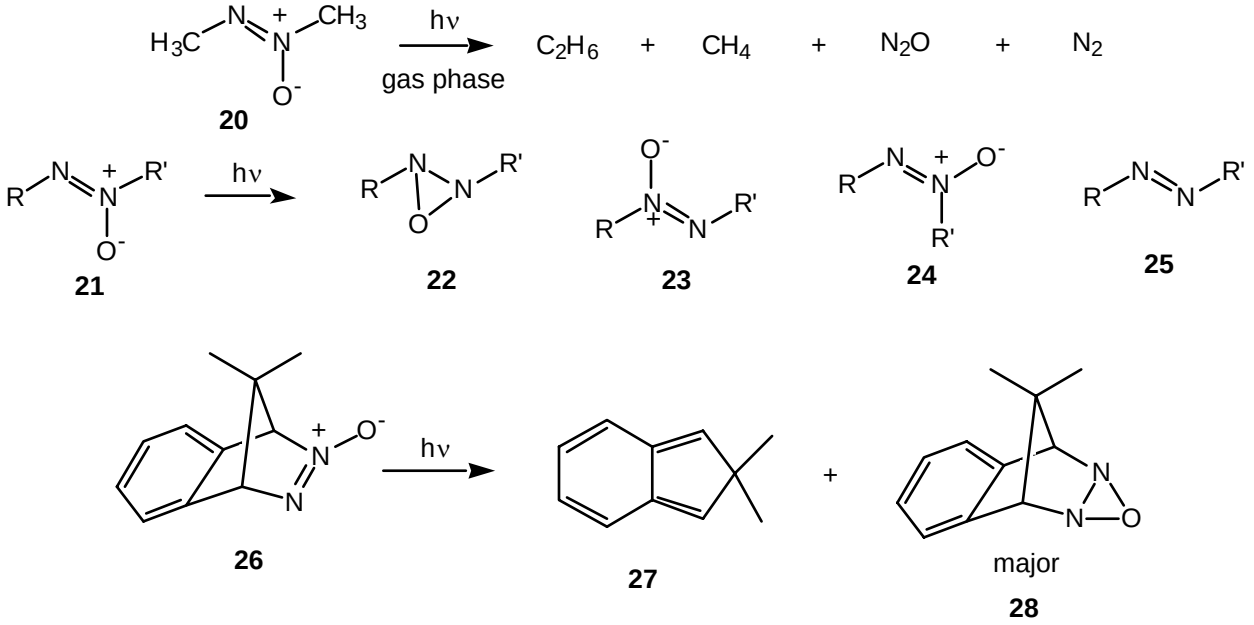
190 °C for 28 h[32] in contrast to the azo analog **17**, whose half life is 81 s at 25 °C.[34] In the case of a four membered ring, the thermolysis half life of **18** is 14 h at 161 °C [35] while that of the related diazetine **19** at this temperature is 8.8 min,[36] even though **18** possesses radical stabilizing phenyl groups.



**16** **17** **18** **19**

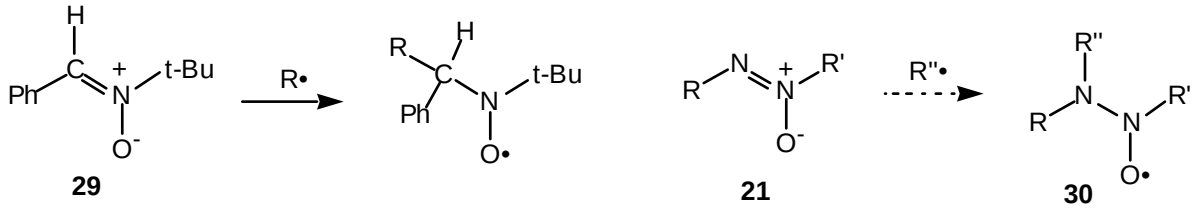
These large differences in stability are a consequence of thermodynamics. The endothermicities associated with loss of $N_2$ from azo-t-butane and $N_2O$ from **3** are 31.9 and 68.5 kcal/mol, respectively. Likewise, deazatation of **15** is exothermic by 45 kcal/mol while $N_2O$ loss from **14** is far less exothermic ($\Delta H$ =13 kcal/mol.) The more exothermic deazatation is associated with a lower activation energy ($E_a \leq 14$ kcal/mol for **15**) while loss of $N_2O$ from **14** exhibits $E_a = 37$ kcal/mol.[37]

Irradiation of azoxy compounds in solution does not lead to production of radicals as it does with azoalkanes.[24] Although gaseous azoxymethane **20** undergoes photofragmentation,[38] the solution phase photoreactions of azoxy compounds **21**[39-42] are ring closure to oxadiaziridines (**22**),[43-46] positional and geometric isomerization (**23**, **24**),[45,47,48] and deoxygenation (**25**).[44,45] The last of these reactions, however, is usually caused by ketyl radicals.[41,49-51] Irradiation of **26** afforded small amounts of isoindene **27** but the major reaction was closure to oxadiaziridine **28**.[46,52,53]

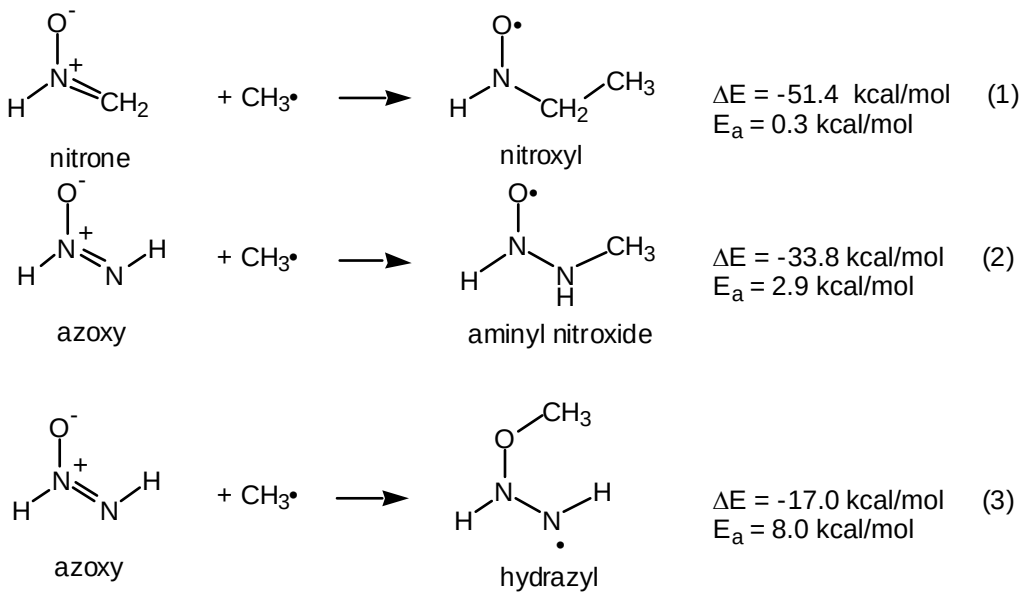



**Reactions of radicals with azoxyalkanes**

The fact that nitrones (e.g. **29**) are commonly used "spin traps"[54,55] might suggest similar behavior for azoxy compounds **21**. However, we have been unable to find any published examples of this reaction. Gas phase photolysis of **20** gave no products above m/e = 80, ruling out addition of one $CH_3$• to nitrogen of **21** to give **30** (R = R' = R'' = $CH_3$) followed by recombination of a second $CH_3$• with **30**.[38] We irradiated azomethane to completion with neat azoxy-t-butane (**3**) at ambient temperature to test the possibility of methyl radical attack on **3**; however, both NMR and GC analysis showed no disappearance of **3** and no new products.[56]

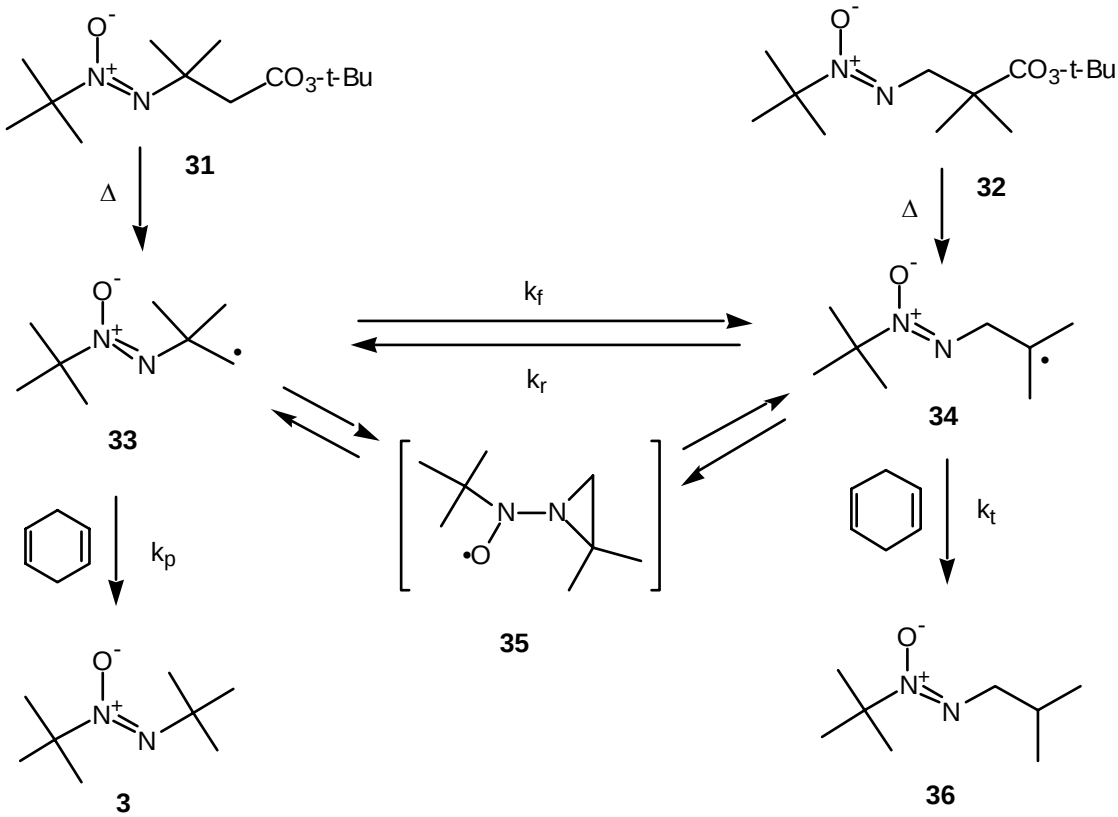



Theoretical calculations at the UB3LYP/6-311+G(d) level[57] are consistent with these results. While addition of methyl radicals to the basic nitrone structure is exothermic by 51.4 kcal/mol (eq. 1), reaction at nitrogen of an azoxy group is exothermic by only 33.8 kcal/mol (eq. 2). The much greater driving force for the nitrone case leads to a lower activation energy for radical trapping ($E_a$ (1) = 0.3 kcal/mol, $E_a$ (2) = 2.9 kcal/mol), allowing the use of nitrones as spin traps. Attack of methyl radical on oxygen of the azoxy structure (eq. 3) is also plausible but is considerably less exothermic and has a higher activation energy than aminyl nitroxide formation (eq. 2).

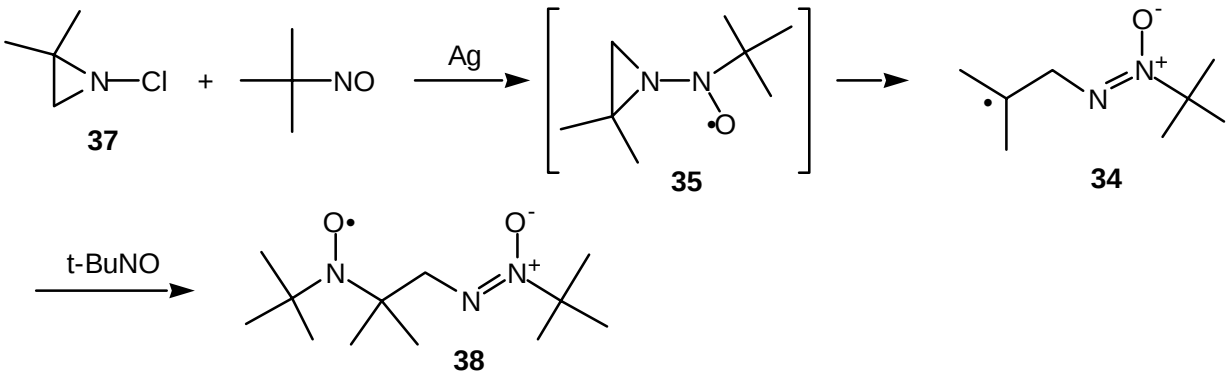



## β-Azoxy radicals

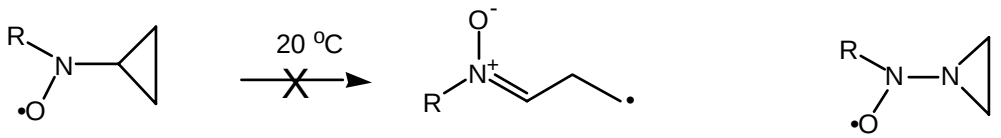
In contrast to intermolecular radical attack on the azoxy group, the intramolecular case is well established. Thermolysis of **31** or **32** at 120 °C affords a mixture of azoxyalkanes **3** and **36**,



presumably via intermediate **35**.[58] This intermediate nitroxyl radical was not detected by ESR in this experiment nor when generated independently at room temperature by trapping the aziridinyl radical from **37**[59,60] with nitroso-t-butane.[61] Instead, the observed ESR signals were consistent with structure **38**, suggesting that **35** is quite labile even at 25 °C. This behavior stands in contrast to the persistence of carbon analog **39a**.[62] Part of the reason for the greater lability of **35** is surely the gem dimethyl group[63] but theoretical calculations at the U3BLYP/6-311G(2s,2p)



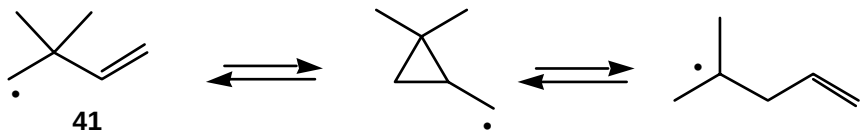

level also indicate that ring opening of **39b** ($\Delta E_r$ = 15.1 kcal/mol) is 3.7 kcal/mol more endothermic than opening of **40b**.[57] If the activation energies for ring opening run parallel to the endothermicities, **40a** and **40b** are less likely to persist at ambient temperature than are **39a**, **39b**.




**39a** R = t-Bu
**39b** R = H

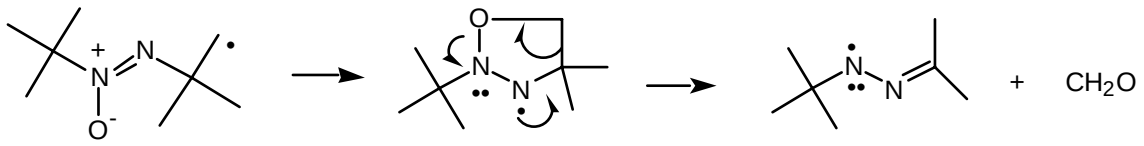
**40a** R = t-Bu
**40b** R = H

The interconversion rate of β-azoxy radicals **33** and **34** was determined by the radical clock technique to be $k_f = 1.5 \times 10^7\ s^{-1}$ and $k_r = 1.5 \times 10^3\ s^{-1}$ at 120 °C. This value of $k_f$ is a factor of 3.6 slower than that of the carbon analog **41**[64] but both rates are enhanced by the Thorpe-Ingold effect.[65-67]



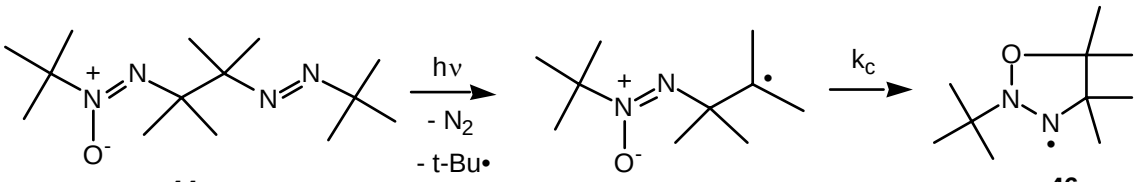
**41**

Surprisingly, cyclization of **33** occurred not only at nitrogen but also at oxygen to form proposed intermediate **42**, which then fragmented to hydrazonyl radical **43**. A similar



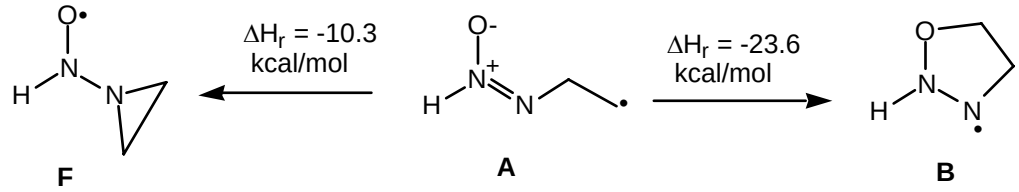

**33** **42** **43**

intermediate was generated at 25 °C by irradiation of azo-azoxy compound **44**. The β-azoxy radical **45** cyclized to **46** in competition with its usual reactions with t-butyl radical;[58] then, **46** fragmented to **43** plus acetone. The photolysis of **44** was clean enough to determine the cyclization rate of **45** as $k_c$ =1.7 x $10^6$ $s^{-1}$ at 25 °C and to estimate its activation energy as $E_C$ ~3 kcal/mol.




**44** **45** **46**

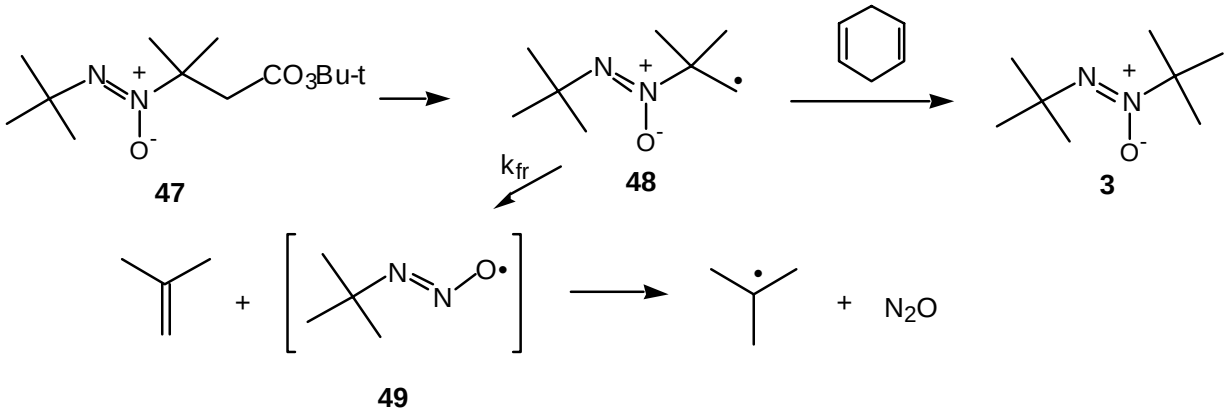
In 1999, we reported the results of UQCISD-FC/6-31+G(d) calculations on simplified models **A**, **B**, and **F** of the **33**→**35** and **33**→**42** cyclizations, where the lettered structures are the same as in the published paper.[29] Aminyl nitroxide **F** is the analog of **35** while **A** and **B** are analogous to **33** and **42**, respectively. The computed exothermicity of the **A**→**F** process was



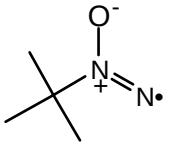

**F** **A** **B**

–11.4 kcal/mol while that of **A**→ **B** was –33.4 kcal/mol. Recalculation of these cyclizations at the UB3LYP/6-311+G(d) level (the same as for eq. 1-3) gave values of -10.3 kcal/mol and -23.6 kcal/mol, respectively. [57] Since **A**→**F** and **A**→ **B** are merely intramolecular versions of equations (2) and (3) above, their exothermicities should resemble those of the acyclic cases, if ring strain is taken into account. Under the crude assumption that the strain energy of **F** is the same as that of cyclopropane (27.6 kcal/mol) and the strain energy of **B** equals that of cyclopentane (6.3 kcal/mol) the corrected (strainless) exothermicity of **A**→**F** is –10.3 - 27.6 = -37.9 kcal/mol and that of **A**→**B** is –23.6 – 6.3 = -29.9 kcal/mol. Formation of the aminyl nitroxide is favored by 8.0 kcal/mol, which can be compared to the ΔE difference between equations (2) and (3) of 16.8 kcal/mol. Despite the disagreement in these numbers, one may conclude that aminyl nitroxide is more stable than hydrazyl in the acyclic series (eq. 2, 3) but ring strain reverses the order in the **B**, **F** comparison. This explanation rationalizes the initially surprising formation of **42** and **46** from β-azoxy radicals.

In contrast to the behavior of **31**, isomer **47** did not lead to cyclization but instead gave $N_2O$ in ~80% yield.[58] The intermediacy of β-azoxy radical **48** was demonstrated by trapping




with 1,4-cyclohexadiene, an experiment that also provided the fragmentation rate $k_{fr}$ of **48** as 4.1 x $10^8$ $s^{-1}$ at 120 °C. Because the calculated enthalpy change for fragmentation of both **33** and **48** to t-Bu•, isobutene, and $N_2O$ is the same at 4.8 kcal/mol,[58] the very different chemical behavior of these two radicals is not a matter of overall thermodynamics. Instead, radical **49** is better resonance stabilized than the analogous radical **50** from **33**, similar to the cases of **4, 5** and **8**

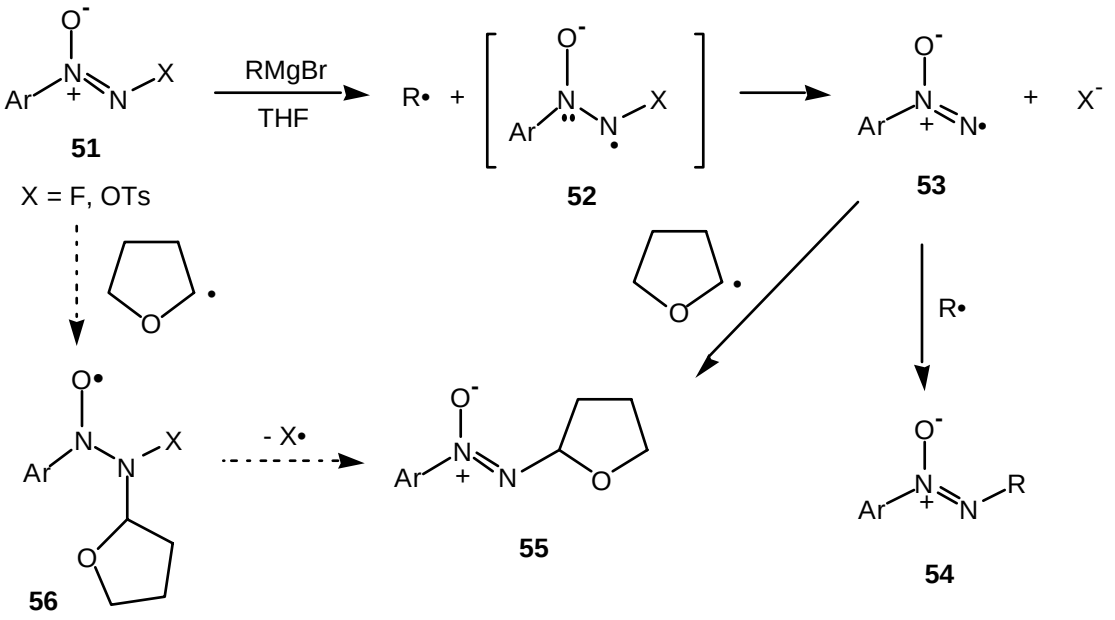


**50**

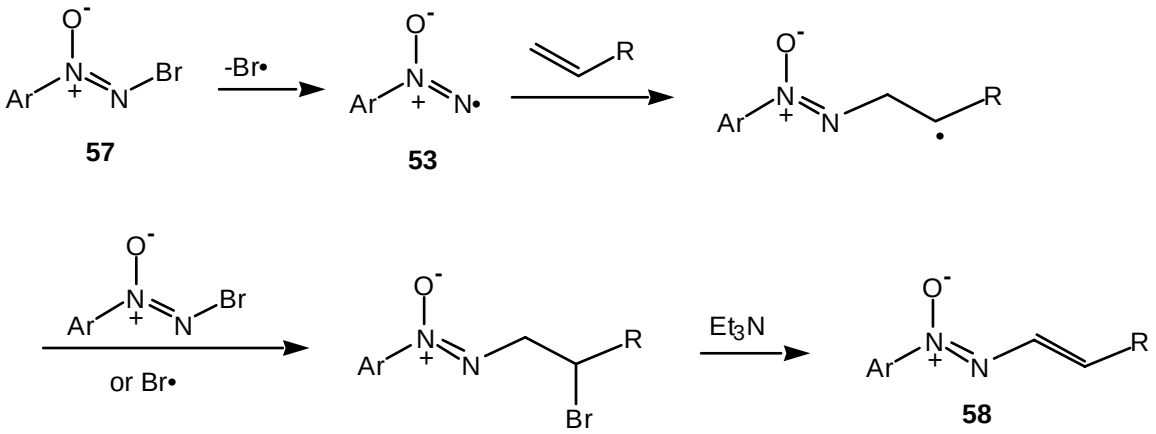
presented above. Also contributing to the divergent chemistry is the fact that cyclization of **33** to three membered ring **35** is much more favorable than the similar process in **48**, which would produce a four-membered aminyl nitroxide.[68-70] The 4.8 kcal/mol endothermicity for fragmentation of **48** is far below the 68.5 kcal/mol for thermal decomposition of azoxy-t-butane (**3**) to 2 t-Bu• + $N_2O$, where the starting material is not a radical. On this basis, we can understand why **47** falls into the small group of azoxy compounds that lose $N_2O$.

Despite their lack of stabilization, aromatic analogs of **50** are viable intermediates. Treatment of aryl-N'-fluorodiimide-N-oxides or aryl-N'-tosyloxydiimide-N-oxides (**51**) with Grignard reagents in THF yielded solvent-containing azoxy product **55**.[71] The proposed mechanism begins with electron transfer to the azoxy moiety followed by loss of $X^-$ to form radical **53**. This species recombines with the Grignard-derived alkyl radical or one generated by hydrogen abstraction from THF to afford the observed products **54** and **55**. An alternate mechanism wherein THF• adds to the azoxy moiety to give **56** suffers from the disadvantage that the azoxy group is not

readily subject to intermolecular radical attack. Radicals **53** are also likely intermediates in the reaction of N- bromodiazene oxides **57** with alkenes to form α,β-



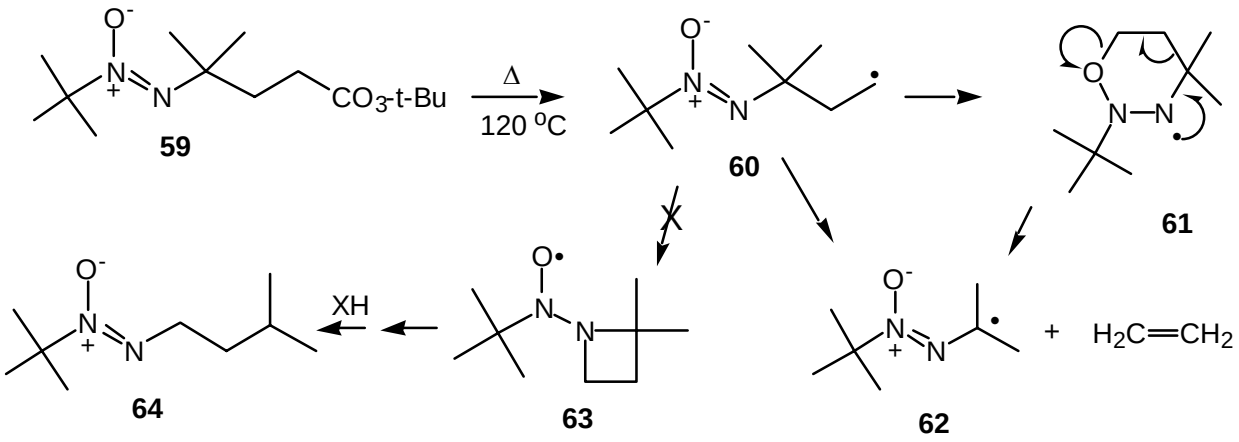

unsaturated azoxy compounds **58**.[72] The regiochemistry of the addition, the effect of alkene structure on reactivity, and the accelerating effect of light and added benzoyl peroxide all point to the radical mechanism shown below.



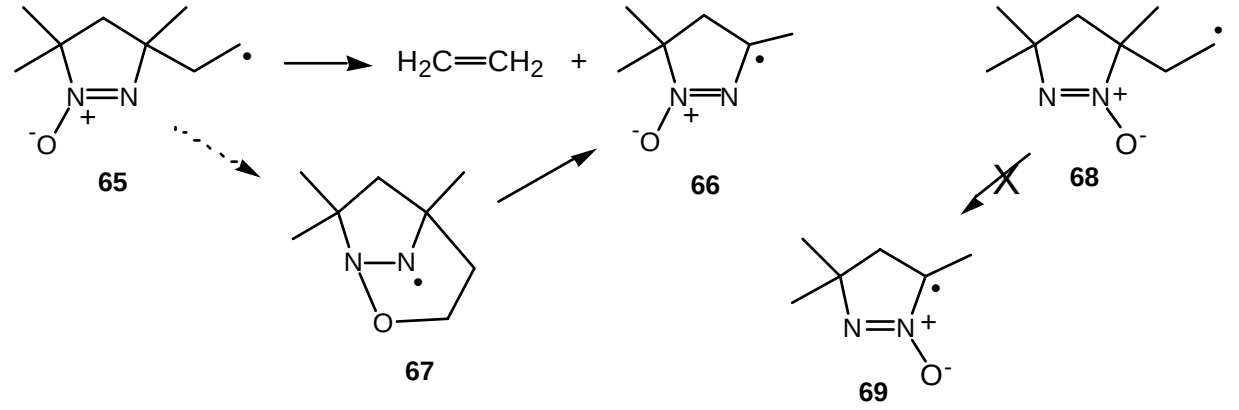

## γ and δ Azoxy radicals

Having discussed the chemistry of β-azoxy radicals, we now turn to higher homologs. Thermolysis of **59** gave typical perester products along with a 61% yield of ethylene.[29] This fragmentation, whose rate constant was 2 x $10^5$ $s^{-1}$ at 120 °C, might proceed via β-scission of **60** or it could involve prior cyclization to **61**, analogous to **33** → **42**. Theoretical calculations yielded no low energy transition structure for cyclization of **60**, suggesting that it fragments

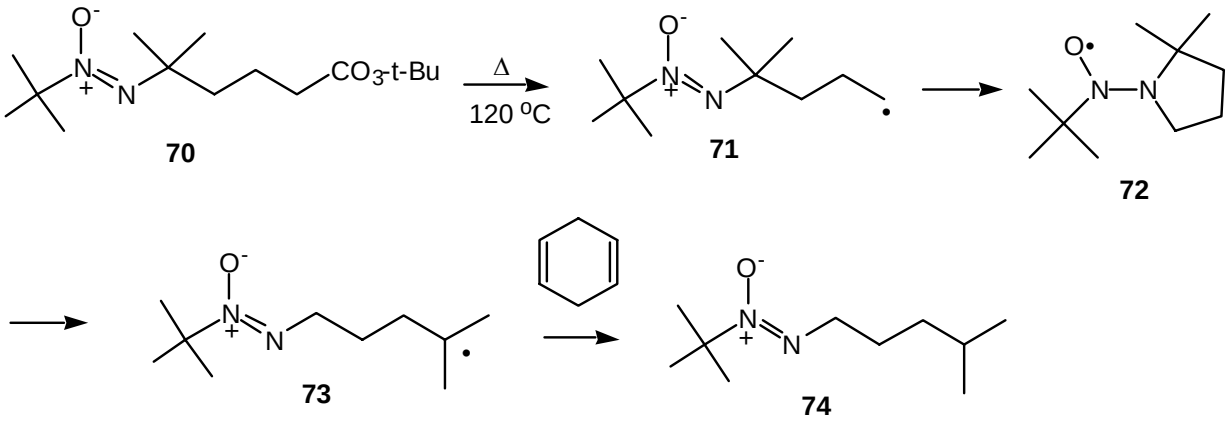
directly to **62**,[29] a radical whose chemistry will be discussed below. Since **64** was definitely absent, **60** does not cyclize to the four membered aminyl nitroxide **63**.




Experimental support for direct fragmentation of **60** was found in studies of pyrazoline oxide **65**, which cannot cyclize to **67** without engendering about 22 kcal/mol of ring strain. The fact that **65** gives a 34% yield of ethylene shows that it fragments directly to **66**, which implies that **60** follows the same mechanism. Isomeric radical **68** gave no ethylene because β-scission would produce **69**, which is far less stabilized than **66** (see Table I and its associated discussion below).



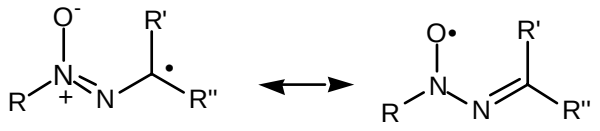

Proceeding to the next homolog, we find that thermolysis of **70** produces δ-azoxy radical **71**, which leads to products typical of perester thermolysis, namely, the alkane, alkene, and



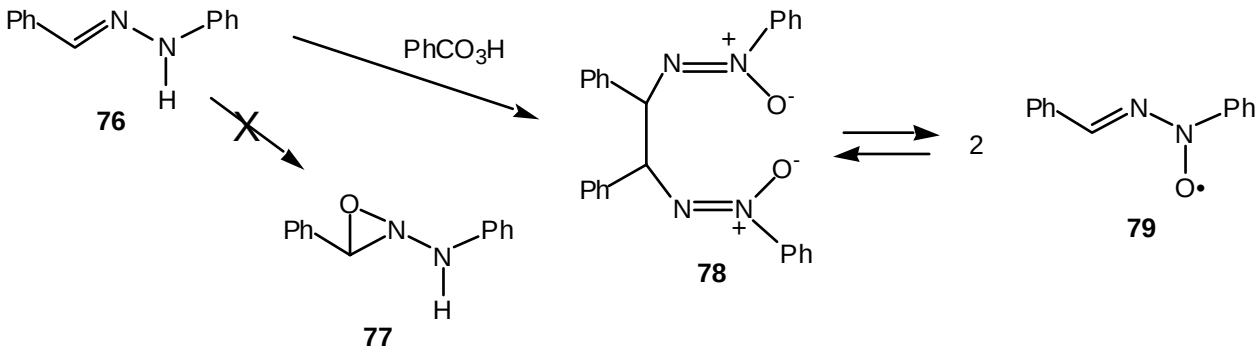

t-butyl ether from **71**. Although the major product was the carboxylic acid precursor of **70**, the presence of **74** was proven unambiguously, suggesting that **71** cyclizes to **72**, which then reopens to **73**.[73] Six-membered analogs of **72** were shown to be persistent by ESR at room temperature[59] but in our case, the gem dimethyl group, five-membered ring strain, and high temperature would all contribute to rapid opening of **72**.

## α-Azoxy radicals

Hydrazones can give a variety of products upon oxidation[1,74-78] but in this review, we will be concerned only with their conversion to α-azoxy radicals **75a**, alternately represented as

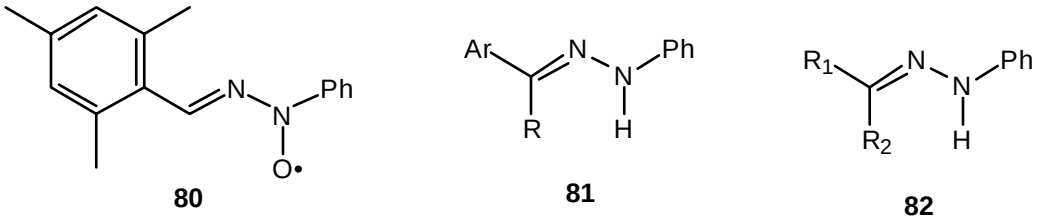



hydrazonyloxides **75b**. The chemistry of such radicals is less well understood than the topics covered above. Bergmann and coworkers reported in 1923 that oxidation of benzaldehyde N-phenylhydrazone **76** with perbenzoic acid led to the unlikely structure **77**.[79] After several more misassignments,[80-82] the correct structure of the "Bergmann oxide" was finally established as **78**.[83,84]

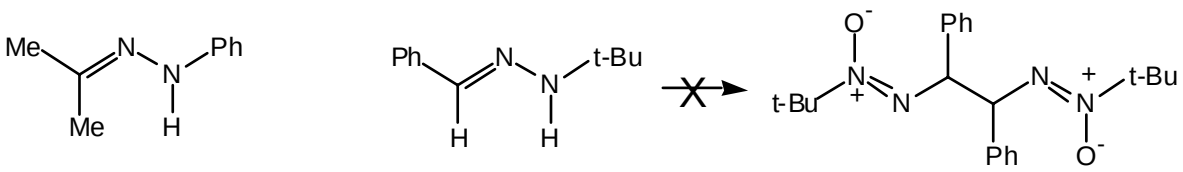



The activation energy for breaking the central C-C bond of **78** was a remarkably low 14 kcal/mol, indicating that α-azoxy radicals **79** are particularly stable. These radicals were observed by ESR in a hot toluene solution of **78**; in fact, the ESR spectra of many hydrazonyloxides have been analyzed in detail.[85,86] The elevated temperature caused no permanent change but the signals disappeared immediately on cooling as **79** reverted to **78**. Radicals **79** could also be trapped with nitrosobenzene or phenyl-t-butyl nitrone.[85]

Sterically hindered hydrazonyloxides such as **80** were much more persistent, as would be expected if their main reaction is indeed C-C dimerization to a structure like **78**. MCPBA oxidation of ketone hydrazones **81** yielded the hydrazonyloxide radicals as well, but they were stable for only a few hours in solution and no radical dimers could be isolated. When both R groups of the ketone were alkyl as in **82**, no radicals were seen by ESR unless at least one of the groups was especially sterically demanding.[85] Irradiation of **81** and **82** with t-Bu-OO-t-Bu, t-BuOOH and air gave the corresponding hydrazonyloxides but in low concentration and accompanied by secondary radical products.

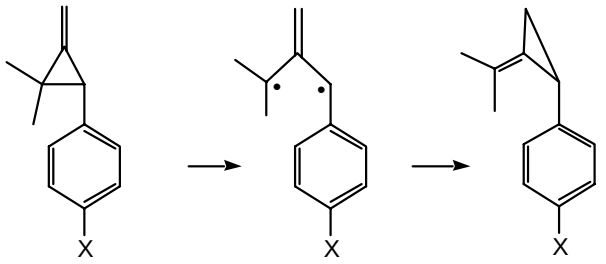



We attempted to oxidize acetone phenylhydrazone **83** with MCPBA in $CH_2Cl_2$ at –65 °C but the initially bright yellow solution turned to a brown sludge on warming to 0-10 °C. TLC showed a streak and NMR showed acetone to be the dominant product. In contrast to the successful oxidation of benzaldehyde N-methylhydrazone,[84,87] similar treatment of **84** gave a mixture of products, none of which was **85**. [61]



**83** **84** **85**

In order to evaluate the stabilization of aliphatic α-azoxy radicals, we and Xavier Creary studied the rearrangement rate of p-substituted phenylmethylenecyclopropanes **86**.[88] Substituents X accelerate the rearrangement, depending on their ability to stabilize biradical **87**.

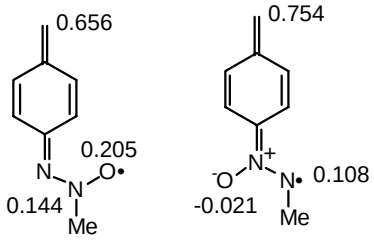


**86** **87** **88**

Table I. Relative Rearrangement Rates of Arylmethylenecyclopropanes

| X | $k_{rel}$ (80 °C) |
|---|---|
| H | 1.00 |
| t-Bu-N=N(O)- | 2.00 |
| $NO_2$ | 3.76 |
| $CH_2$=CH- | 4.67 |
| t-Bu-N=N- | 4.85 |
| $Me_2N$- | 7.88 |
| t-Bu-N(O)=N- | 9.45 |
| Ph-N=N- | 12.10 |
| t-Bu-N(O)=CH- | 13.50 |

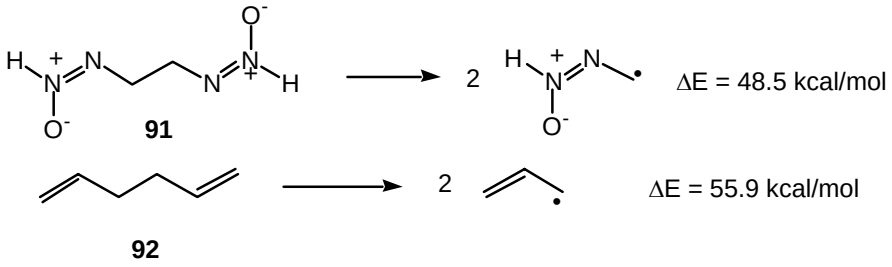
Selected values of $k_{rel}$ (80 °C) are shown in Table I. The much smaller rate enhancement of proximal azoxy ($k_{rel}$ = 2.00) compared to distal azoxy ($k_{rel}$ = 9.45) is in excellent accord with ethylene loss from **65** but not **68**. Furthermore, theoretical calculations showed that the spin density on the substituent is much greater and that on the benzylic position is much smaller for distal azoxybenzyl radical **89** than for the proximal analog **90**. Distal azoxy is among the most effective radical stabilizing groups but is not as strong as nitrone ($k_{rel}$ = 13.5). Obviously, both of



**89** **90**

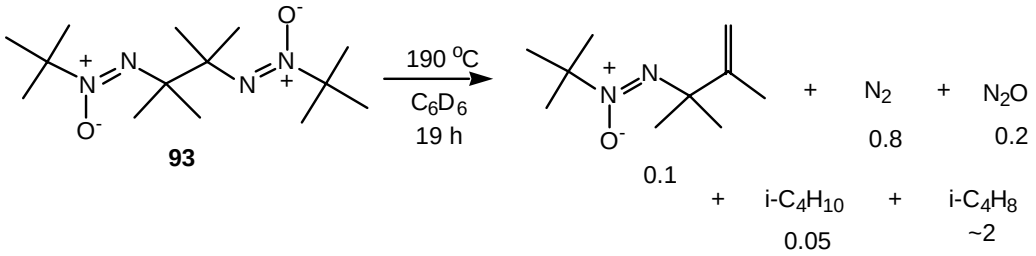
these groups benefit from nitroxyl resonance forms such as **75b**. The $k_{rel}$ values in Table I correlated nicely with B3LYP calculated energy changes for the isodesmic reaction of substituted benzylic radicals with toluene.

Theoretical calculations also indicate a large stabilization energy for aliphatic α-azoxy radicals. Dissociation of **91** was calculated at the QCISD/6-311++G**//B3LYP/6-31G* level to be 7.4 kcal/mol less endothermic than the analogous process in 1,5-hexadiene **92**.[57]



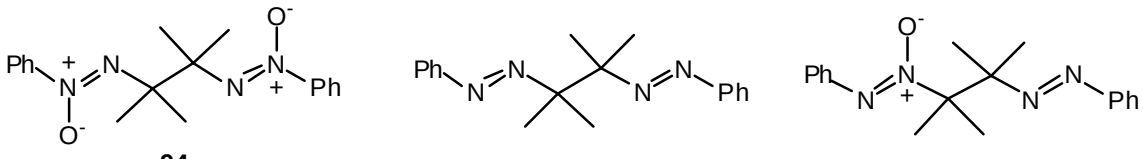

**91** **92**

The facile dissociation of **78**, the large stabilizing effect of the distal azoxy group on **87**, and the calculations on **91** stand in contrast to the behavior of bisazoxyalkane **93**. Although thermolysis of **93** might be expected to cleave the central C-C bond, this compound is nearly as stable as azoxy-t-butane **3** and it gives the same kind of products, presumably by the Cope amine oxide elimination (product yields shown below are moles/mole). The $\Delta G^{\ddagger}$ for C-C cleavage must exceed that for the elimination reaction, $\Delta G^{\ddagger}$ (190 °C) = 36.8 kcal/mol.



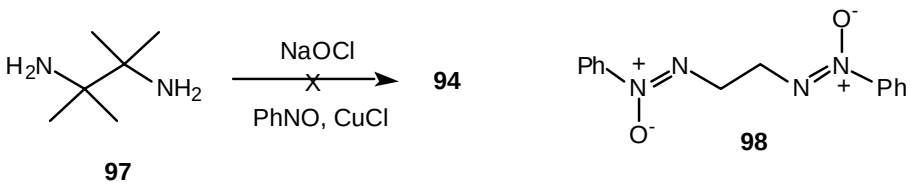

**93**

In view of the stability of **93**, it would be interesting to determine the contribution of each set of phenyl groups, terminal and internal, to the lability of **78**, whose activation energy is at least 22 kcal/mol lower than that of **93**. Compound **94** would be useful because it possesses the gem-dimethyl groups of **93** and the terminal phenyl groups of **78**. Attempts to oxidize **95**[89] with one equivalent of MCPBA gave mainly **96** with lesser amounts of the isomeric mono



**94** **95** **96**

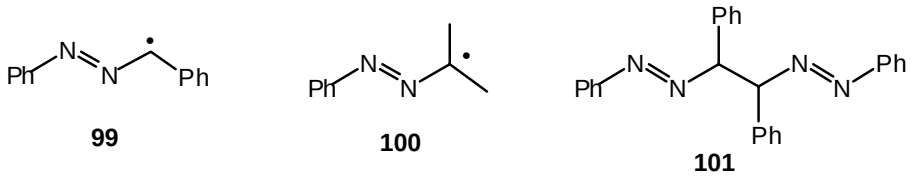
azoxyazoalkane plus two of the three bisazoxyalkanes, the absent one being **94**. Likewise, application of Kovacic's method[28] to 2,3-diamino-2,3-dimethylbutane **97** did not yield **94**. Since both methods failed, it is possible that **94** is thermally labile but that unlike **79**, the




**97** **98**

hydrazonyloxide radicals undergo some irreversible reaction like disproportionation. One can estimate the stability of **94** by two approaches, which, however, give much different answers.

The first approach is based on the known, very stable bisazoxy compound **98**.[90] With no added scavenger, the thermolysis half-life of **98** at 185 °C is 29 min and the complex product mixture includes aniline and biphenyl. Addition of thiophenol reduces the yield of biphenyl, increases the yield of aniline, and enhances the thermolysis rate by ~25%.[73] If the reaction being measured is irreversible C-C bond homolysis, its $\Delta G^{\ddagger}$ (185 °C) is 34.3 kcal/mol. This value is far above the 14 kcal/mol for **78**, implying a very large radical stabilizing role for the internal phenyl groups. Interestingly, this behavior is opposite that of hydrazonyl radicals, where the resonance energy of **99** (18.4 kcal/mol) exceeded that of **100** (15.3 kcal/mol) by only 2.9

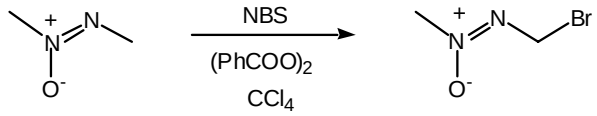



**99** **100** **101**

kcal/mol.[89] In order to estimate of $\Delta G^{\ddagger}$ of **94**, we assume that addition of four methyl groups to **98** should lower its $\Delta G^{\ddagger}$ by about 5.5 kcal/mol, the known torsional strain energy of **95**.[89] Therefore $\Delta G^{\ddagger}$ for **94** should be 28.8 kcal/mol, making it an easily handled compound. However, it is possible that C-C homolysis of **98** is highly reversible, even in the presence of thiophenol, so that 34.3 kcal/mol is a maximum for $\Delta G^{\ddagger}$. In that case, the estimated $\Delta G^{\ddagger}$ for **94** is also a maximum.

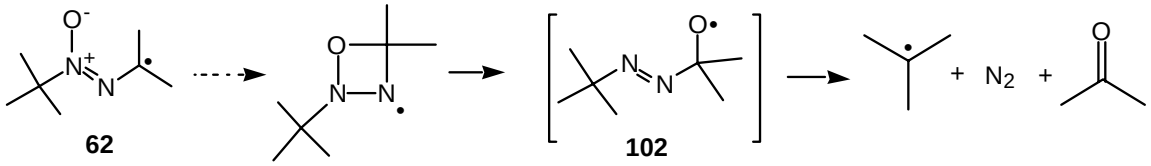
The second estimate of $\Delta G^{\ddagger}$ for **94** is based on the $\Delta G^{\ddagger}$'s of **101** (27.3 kcal/mol) and **95** (32.2 kcal/mol). If we ignore $\Delta S^{\ddagger}$ and add the 4.9 kcal/mol difference between these figures to the 14 kcal/mol $E_a$ of **78**, we obtain for **94** $E_a$ = 18.9 kcal/mol. It is therefore possible that our failure to prepare **94** is due to thermal lability. Whether this is true or not, there are inconsistencies in the thermal stability of hydrazonyloxide dimers that call for clarification by careful kinetic studies of both the new cases and of known compounds.

While generation of aryl substituted α-azoxy radicals like **79** is not difficult,[84,85] almost nothing is known about their aliphatic counterparts. One reaction that presumably gives such a radical is β-scission of **60** but in this case we were unable to isolate any product attributable to **62**. Although we have found no published ESR spectra of purely aliphatic hydrazonyl oxides, such radicals must exist because free radical bromination of azoxyalkanes (e.g. **20**) gives the expected substitution products.[91,92]



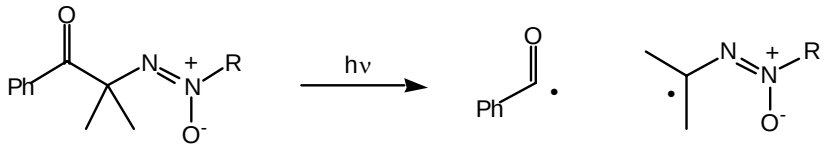

**20**

It is conceivable that α-azoxy radicals cyclize and then fragment at elevated temperatures, analogous to **33**→**42**. Although fragmentation of the alkoxy radical **102** would be rapid,[93] the cyclization shown below is calculated to be endothermic by 32 kcal/mol.[57]




**62** **102**

Attempts to prepare azo and perester precursors that would generate **62** under mild conditions met with failure. Recently however, we synthesized azoxyketones **103a,b** which are expected to give α-azoxy radicals by irradiation at room temperature.[94] The outcome of these experiments will be reported in the near future.[95]




**103a** R = t-Bu
**103b** R = Ph

## Conclusions

In stark contrast to azoalkanes, azoxy compounds rarely form radicals on heating or irradiation. Furthermore, they are unreactive to alkyl radical attack unless the reaction is intramolecular. For example, β-carbon centered radicals cyclize to azoxy nitrogen or oxygen and produce short-lived aminyl nitroxides that reopen or hydrazyl radicals that undergo fragmentation. The azoxy group is a powerful stabilizer of an adjacent radical center but the chemistry of α-azoxy radicals (hydrazonyloxides) and their dimers is not fully understood.

## Acknowledgments

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