The Barton Reaction: Can a More Tenable Pathway Be Hypothesized for the Formation of Nitrosoalkyl Derivatives?

Loris Grossi*[a]

Abstract: Herein, we report that in the formation of nitrosoalkyl derivatives during the photolysis of alkyl nitrites, the formation of the intermediate alkyl alkoxy nitroxide, due to the trapping of alkyl radicals by the starting nitrite, is the key step of the entire process. In fact, these nitroxides, detectable by EPR spectroscopy, decay to the final nitroso derivatives under thermodynamic control. In light of this, the Barton reaction mechanism has been reviewed. The nitrosoalkyl derivatives, or the hydroxamic acids when steroids are involved, have now to be considered as the ending products of the entire process and not, unless a very high concentration of NO is present in the medium, the result of a direct reaction of NO with the alkyl radical, as is commonly accepted.

Keywords: Barton reaction · EPR spectroscopy · radicals · reaction mechanisms · spin trapping

Introduction

The importance of the Barton reaction for synthetic purposes is the possibility of attacking inactivated hydrogen intramolecularly through a 1,5-hydrogen shift. In fact, since the early 1960s, it has been reported that alkoxyl radicals deriving from the photolysis of the corresponding alkyl nitrites, among several possible reactions, can undergo an internal rearrangement that leads to an alkyl radical. For the formation of the corresponding nitrosoalkyl derivative, or the hydroxamic acid in the synthesis of steroids, the key step commonly accepted is the encounter of the alkyl radical and NO. But, it is now well documented that alkyl nitrites can themselves act as efficient traps for alkyl radicals,[1–3] and thus a possible alternative and/or competitive mechanism accounting for the formation of the nitrosoalkyl derivatives is hypothesized.

Results and Discussion

In the photolysis of alkyl nitrites, the formation of dialkyl nitroxides, detectable by EPR spectroscopy, is usually described as shown in Equations (5) and (6)[2,3] (Scheme 1),

$$\text{RO-NO} \xrightarrow{h\nu} \text{RO}\cdot + \text{NO} \qquad (1)$$
$$\text{RO}\cdot + \text{NO} \longrightarrow \text{RO-NO} \qquad (2)$$
$$2\,\text{RO}\cdot \longrightarrow \text{disproportion products} \qquad (3)$$
$$\text{RO}\cdot \xrightarrow{\text{1,5-H shift}} \text{R}'\cdot \qquad (4)$$
$$\text{R}'\cdot + \text{NO} \longrightarrow \text{R}'\text{-NO} \qquad (5)$$
$$\text{R}'\text{-NO} + \text{R}'\cdot \longrightarrow \text{R}'\text{-N(O}\cdot\text{)-R}' \qquad (6)$$
$$\text{R}'\cdot + \text{RO-NO} \longrightarrow \text{RO-N(O}\cdot\text{)-R}' \qquad (7)$$
$$\text{RO-N(O}\cdot\text{)-R}' \longrightarrow \text{RO}\cdot + \text{R}'\text{-NO} \qquad (8)$$

Scheme 1. The commonly accepted Barton reaction mechanism, and action of alkyl nitrite as a spin trap.

with the key step of the process being the formation of the nitrosoalkyl derivative [Eq. (5)], which depends on the concentration of both the alkyl radical and the free NO.[4]

In the literature, several photochemical studies on both the chemical behavior of alkyl nitrites [Eq. (1)] and quantitative estimates of the primary quantum yield (a quite efficient process) in the gas phase have been reported.[5] In particular, the rapid re-formation of the nitrite from primary products [Eq. (2)] is stated to be important,[6] as proved by experiments conducted on RO–NO molecules in the presence of ^{15}NO,[7] which showed the formation of the corresponding RO–^{15}NO in a high yield. In contrast, studies on the quantum yield of the photolysis of alkyl nitrites in solution are not so plentiful.

As stressed before, as the nitrosoalkyl derivatives come from the interaction of free NO and alkyl radicals,[4] a high

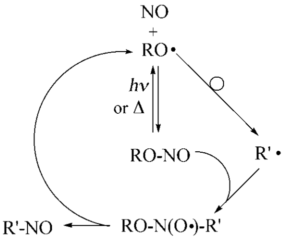
---

[a] Prof. L. Grossi
Dipartimento di Chimica Organica "A. Mangini"
Viale Risorgimento 4, 40136 Bologna (Italy)
Fax: (+39) 051-209-3654
E-mail: grossi@ms.fci.unibo.it

DOI: 10.1002/chem.200500079

concentration of both reactants should be present in the medium to account for the high yield usually reported. However, the low ultimate quantum yield[8,9] of the photolysis of alkyl nitrites in solution, for instance 0.25 for the *n*-pentyl nitrite and 0.08 for the *tert*-butyl nitrite, shows that, on the contrary, the concentration of both reactants is very small. In particular, the concentration of the free alkyl radical will depend on alternative competitive processes that both the parent alkoxyl radical, through intermolecular hydrogen abstraction from the solvent, and the alkyl radical itself, through the self-termination process, can undergo. In light of all of these considerations, Equation (5) might not represent an efficient route for the formation of nitrosoalkyl derivatives.

Previous studies conducted in this laboratory on the photolysis of alkyl nitrites[1,10] showed that this class of compounds is a very efficient and fast trap for alkyl radicals [Eq. (7)], leading to the formation of alkyl alkoxy nitroxides that can decay to nitrosoalkyl derivatives. Thus, for the formation of R–NO, an alternative mechanism involving the starting nitrite can be hypothesized (Scheme 2). To support this mechanism, an EPR study on the behavior of different alkyl nitrites to the photolysis was conducted.



Scheme 2. The new alternative mechanism for the Barton reaction.

The first alkyl nitrite under investigation was *sec*-butyl nitrite **4**. The resulting alkoxyl radical mainly decays through intramolecular processes, such as β scission and/or a 1,2-hydrogen shift,[11] or through a fast[6] recombination with NO. Furthermore, to suppress intermolecular processes like hydrogen abstraction, benzene was used as the solvent.

When a solution of **4** was made to flow continuously through a cell inside an EPR spectrometer cavity and was photolyzed at a temperature slightly above the freezing point of benzene, at least two alkyl alkoxy nitroxides, **5** and **6** (70 % and 20 %, respectively), were detected (Figure 1);[12] but, no dialkyl nitroxides, as usually predicted, were observed (Scheme 3).

However, conducting the experiments at a higher temperature, ≈15–20 °C, dialkyl nitroxide **7** was detected with a concomitant decrease of radical **6**; over time, only radicals **5** and **7** (70 % and 30 %, respectively) remained visible (Figure 2, Scheme 3).

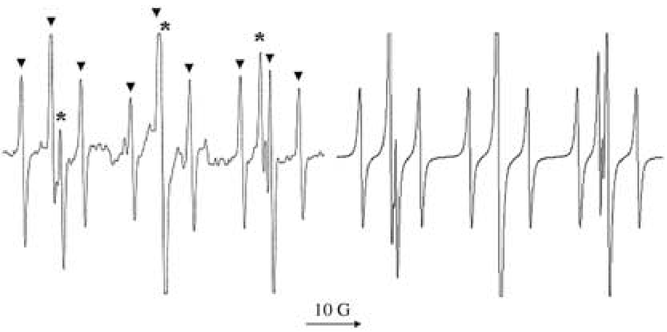
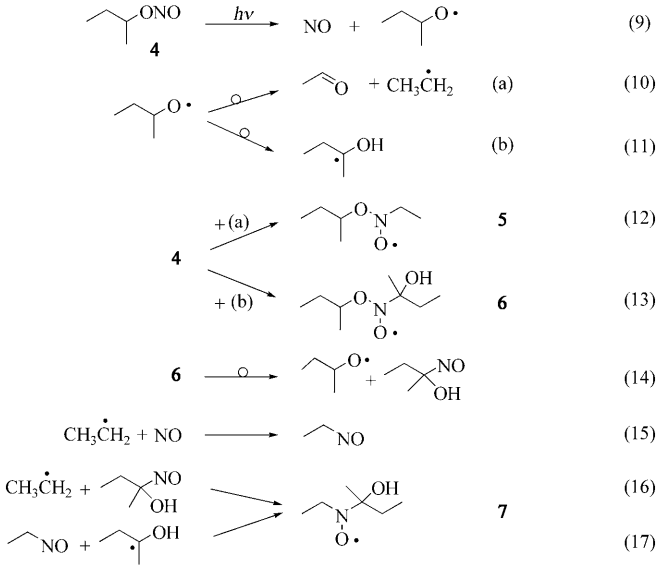


Figure 1. Left: EPR spectrum obtained at ≈5 °C by photolyzing a solution of **4** in benzene; ▼ = radical **5** and * = radical **6**. Right: Computer-simulated spectrum. The length of the arrow represents a magnetic field unit of 10 G.



Scheme 3. Reactions that can take place during the photolysis of nitrite **4**, accounting for the detected radical species.

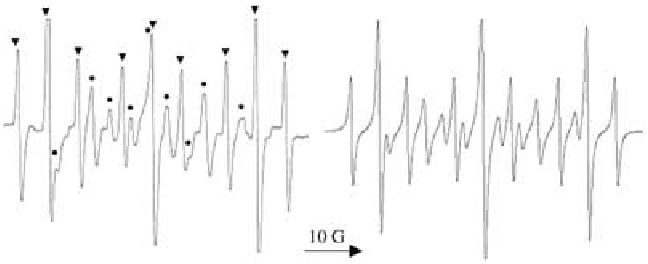
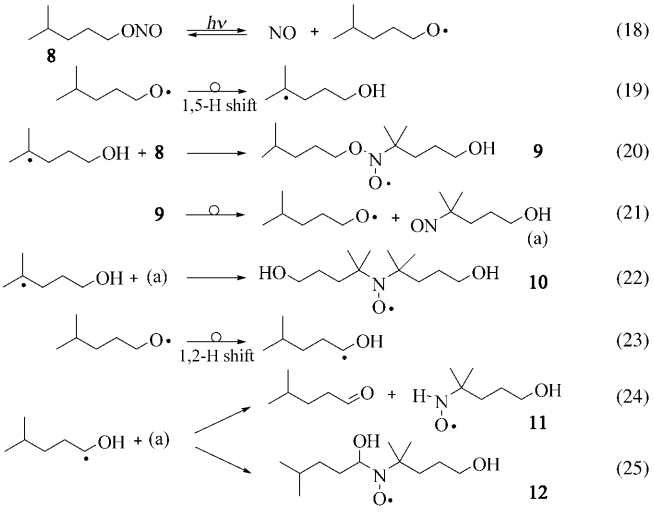


Figure 2. Left: EPR spectrum obtained at ≈15–20 °C by photolyzing a solution of **4** in benzene; ▼ = radical **5** and ● = radical **7**. Right: Computer-simulated spectrum. The length of the arrow represents a magnetic field unit of 10 G.

The detection of nitroxides **5** and **6** underlines the capability of alkyl nitrites to act as traps for alkyl radicals, whereas for the formation of nitroxide **7**, ambiguous evidence was available; in fact, both Equations (16) and (17) (Scheme 3) could account for its presence. Nevertheless, the decay of **6**, but not of **5**, shows that by raising the temperature Equation (14) predominates, and therefore 2-nitroso-2-butanol is the trap that accounts for the formation of **7** [Eq. (17)]. On the contrary, if nitrosoethyl was the spin trap [Eq. (16)], Equation (15) should take place; but, the fact that diethyl nitroxide was undetected, which should be easily formed, gives evidence against its involvement.[13,14]

The 4-methylpentyl nitrite **8**, whose resulting alkoxyl intermediate undergoes the Barton rearrangement, was the second substrate investigated. When a solution of **8** in benzene was made to flow through a cell inside the EPR spectrometer cavity and was photolyzed, at 5 °C, three radical species were detected: **9**, **10**, and **12** (15 %, 70 %, and 15 %, respectively; Scheme 4, Figure 3).



Scheme 4. Reactions that can take place during the photolysis of nitrite **8**, accounting for the detected radical species.

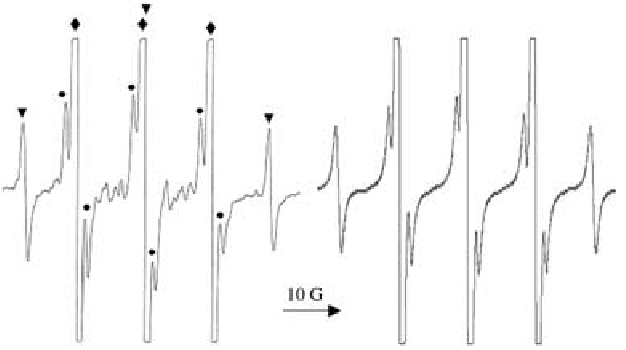


Figure 3. Left: EPR spectrum obtained at ≈5 °C by photolyzing a solution of **8** in benzene; ▼ = radical **9**, ◆ = radical **10**, and ● = radical **12**. Right: Computer-simulated spectrum. The length of the arrow represents a magnetic field unit of 10 G.

The formation of alkyl alkoxy nitroxide **9** supports, once again, the role of alkyl nitrite as a spin trap, whilst to account for dialkyl nitroxide **12**, a 1,2-hydrogen shift of the intermediate alkoxyl radical[11] [Eq. (23)] followed by the trapping of the new alkyl radical [Eq. (25)] has to occur.

Concerning di-*tert*-alkyl nitroxide **10**, the preponderant species, the usually accepted mechanism could, in principle, account for its presence. On the contrary, following our hypothesis, a fast decay[15,16] of **9** to the corresponding 4-methyl-4-nitroso-1-pentanol should occur [Eq. (21)], due to low thermodynamic stability. This claim could be validated by conducting experiments at lower temperatures; in fact, an increase in the thermodynamic stability of **9** should be shown. Tests were then carried out in acetonitrile at −47 °C. The EPR spectra showed the formation of nitroxides **9**, **10**, and **11** (35 %, 45 %, and 20 %, respectively; Figure 4).

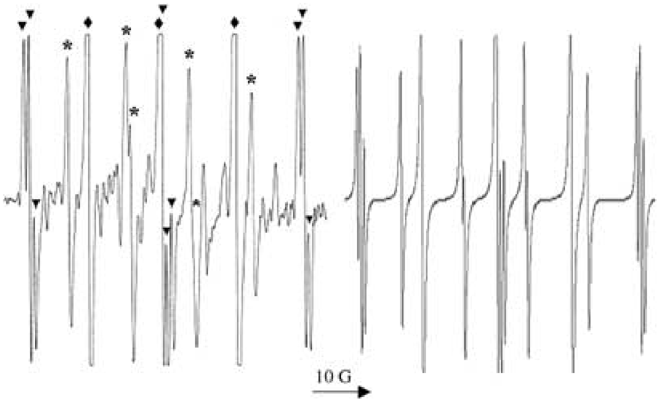


Figure 4. Left: EPR spectrum obtained at −47 °C by photolyzing a solution of **8** in acetonitrile; ▼ = radical **9**—the hyperfine splitting due to the hydrogen atoms in the γ position (-CH_2–O-) are now manifest—◆ = radical **10**, and * = radical **11**. Right: Computer-simulated spectrum. The length of the arrow represents a magnetic field unit of 10 G.

The marked increase of alkyl alkoxy nitroxide **9** (35 % vs 15 %) confirmed its enhanced stability at lower temperatures,[17,18] whilst the concomitant decrease of **10** (45 % vs 70 %) led to the hypothesis that **9** is the parent compound of 4-methyl-4-nitroso-1-pentanol [Eq. (21)], and in turn the precursor of **10** [Eq. (22)]. This behavior implies that the process is reversible. Thus, by raising the temperature again, an increase of **10** along with a concomitant reduction of **9** could be detected. Experiments carried out at −35 °C confirmed this, clearly supporting our assertion. As for nitroxide **11**, the oxidation reaction [Eq. (24)] accounts for it (Figure 5), as reported in the literature,[19] .

At this stage, the study of substrates whose corresponding alkoxyl radicals can lead to a single alkyl radical seemed to be decisive. In fact, the formation of a single alkyl alkoxy nitroxide could make the mechanism leading to the nitroso derivatives easier to understand. The 1-methylcyclopentyl nitrite **13** could fulfil this requirement; the corresponding alkoxyl radical undergoes a rapid β-scission process to lead to a single alkyl radical (Scheme 5).

A solution of **13** in isooctane was then investigated at −50 °C; the EPR spectrum showed the formation of nitroxides **14** and **15** (80 % and 20 %, respectively; Figure 6a). Nitroxide **14** confirmed the role of alkyl nitrite as a spin trap,

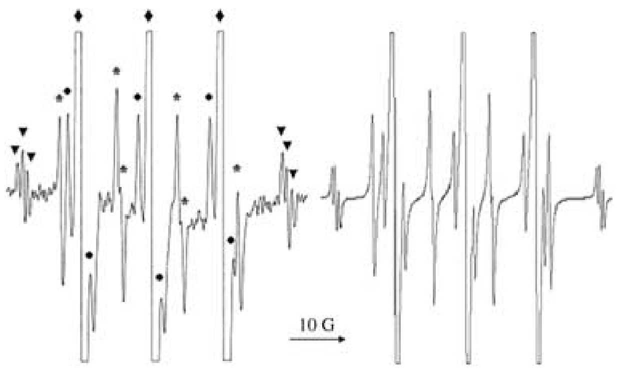
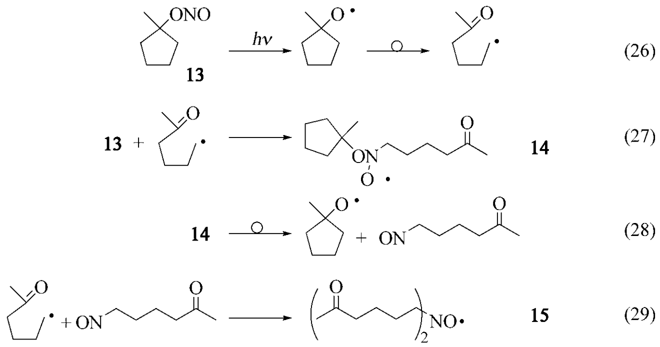


Figure 5. Left: EPR spectrum obtained at −35 °C by photolyzing a solution of **8** in acetonitrile; ▼ = radical **9**—the central group is masked by radical **10**—◆ = radical **10**, * = radical **11**, and ● = radical **12**. Right: Computer-simulated spectrum. The length of the arrow represents a magnetic field unit of 10 G.



Scheme 5. Reactions that can take place during the photolysis of nitrite **13**, accounting for the detected radical species.

whilst for nitroxide **15** we needed to prove the mechanism of its formation. The evidence obtained with previous substrates indicated that by conducting experiments at different temperatures we could verify if any relationship existed between the two. So, tests were conducted at higher temperatures, in particular at −30 °C (Figure 6b) and at room temperature (Figure 6c). The increase of dialkyl nitroxide **15** at the expense of the alkyl alkoxy nitroxide **14** was evidenced. This result strongly supported our hypothesis, that is, the dependence of the stability of alkyl alkoxy nitroxides[18] on temperature, and the role of these species as precursors of the dialkyl nitroxides through the formation of the intermediate nitrosoalkyl derivatives [Eqs. (27)–(29)].

The latter experiment strengthened the idea that the substrates that are able to lead exclusively to a single and unequivocal radical intermediate were those able to give definitive proof for the mechanism of formation of the nitrosoalkyl intermediate. So, we thought it was necessary to confirm this result by investigating similar substrates. For this purpose, 4-pentenyl nitrite **16** was taken into consideration. In fact, the corresponding 4-pentenyloxyl intermediate can undergo a fast rearrangement to the 2-tetrahydrofurylmethyl radical, the sole ending radical species, through a 5-*exo-trig* intramolecular ring closure.

The first experiment was carried out on a solution of 4-penten-1-ol in slightly aerated acetonitrile, in the presence of *t*BuONO: under these conditions **16** is formed by *trans*-nitrosation[20] [Eq. (30), Scheme 6].

When this solution was made to flow through a cell inside the EPR spectrometer cavity and was photolyzed, at −30 °C, the spectrum showed the presence of nitroxide **17** exclusively (Figure 7). The detection of only this nitroxide enables us to stress several points of our hypothesis. Because the cyclization of the 4-pentenyloxyl radical is a process characterized by a high reaction rate[21] [Eq. (34)], it is possible to consider the 2-tetrahydrofurylmethyl radical as the exclusive ending radical species of the photolysis of 4-pentenyl nitrite,

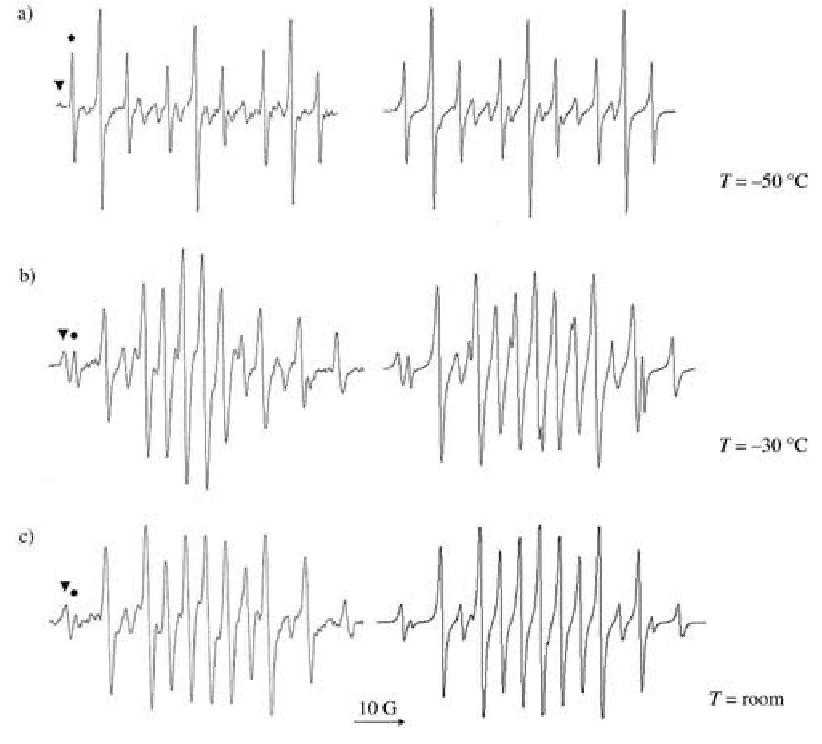
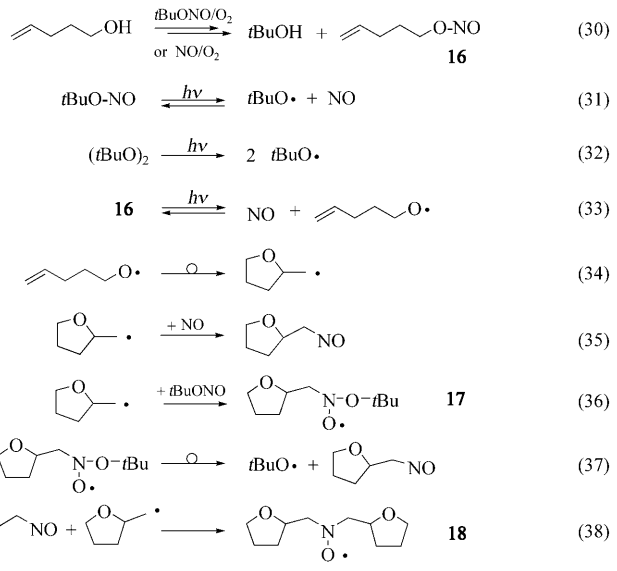


Figure 6. Left: ESR spectra obtained by photolyzing a solution of **13** in isooctane: a) at −50 °C; b) at −30 °C; c) at room temperature. The relative concentration of the radical species, **14** (▼) and **15** (●), increases in favor of **15** by increasing the temperature. Right: Computer-simulated spectra. The length of the arrow represents a magnetic field unit of 10 G.



Scheme 6. Reactions that can take place during the photolysis of nitrite **16**, generated in different ways.

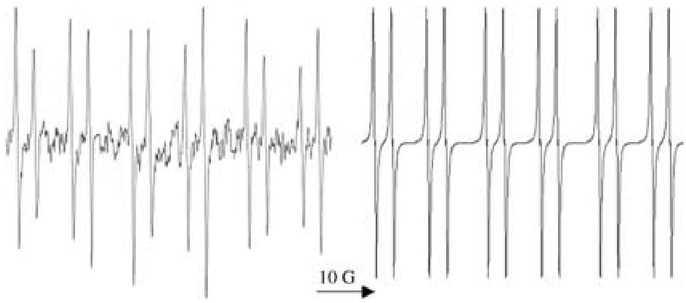


Figure 7. Left: EPR spectrum of radical **17** detected at −30 °C by photolyzing a solution of **16** in slightly aerated acetonitrile with 4-penten-1-ol and *t*BuONO. Right: Computer-simulated spectrum. The length of the arrow represents a magnetic field unit of 10 G.

and therefore the quantum yield of the process is ≈1. Meanwhile, the fact that di-2-tetrahydrofurylmethyl nitroxide **18** was undetected, which should be derived from the direct involvement of the likely 2-tetrahydrofurylmethyl nitroso derivative, led us to the conclusion that the trapping of alkyl radicals by NO [Eq. (35)] is less efficient than that by an alkyl nitrite, and in particular, than that by a *tert*-alkyl nitrite [Eq. (36)]. Lastly, the sole detection of **17**, with no dialkyl nitroxides (usually reported to be the main radical species) confirmed the high stability of the alkyl *tert*-alkoxy nitroxides at low temperatures.

A second experiment was conducted on a solution of 4-penten-1-ol in slightly aerated acetonitrile and *tert*-butylperoxide, through which pure NO gas was bubbled. Under these conditions, 4-pentenyl nitrite **16** was formed by reaction of the alcohol with the NO/O_2 mixture[22] [Eq. (30)]. When this solution was made to flow through a cell inside the EPR spectrometer cavity and was photolyzed, at −47 °C, the spectrum showed the formation of nitroxides **17** and **18**, almost in equal amounts.

This result definitely proves that the recombination reaction between an alkoxyl radical and NO, the reverse of Equation (31), occurs,[6,23] and that the corresponding nitrite, *t*BuONO in this case, acts efficiently as a trap for alkyl radicals [Eq. (36)]. However, the detection of nitroxide **18** seems in contrast to the result obtained in the previous experiment. In particular, the high thermodynamic stability of **17** at low temperatures could not account for the formation of the 2-tetrahydrofurylmethyl nitroso derivative [Eq. (37)], precursor of **18**, at least in that amount. But, the high quantity of NO now present in the medium (pure NO gas added) most probably leads to the direct formation of the 2-tetrahydrofurylmethyl nitroso derivative [Eq. (35)] and then **18** [Eq. (38)].

To validate the latter hypothesis, that is, the direct formation of a nitrosoalkyl derivative only when a high concentration of NO is available [Eq. (5)], an experiment was carried out with 4-penten-1-ol dissolved in acetonitrile, slightly aerated, through which pure NO gas was bubbled. Under these conditions nitrite **16** was formed by interaction of the corresponding alcohol and the NO/O_2 mixture [Eq. (30)].[22] When this solution was investigated at −47 °C, the EPR spectrum showed the presence of nitroxide **18** exclusively (Figure 8).

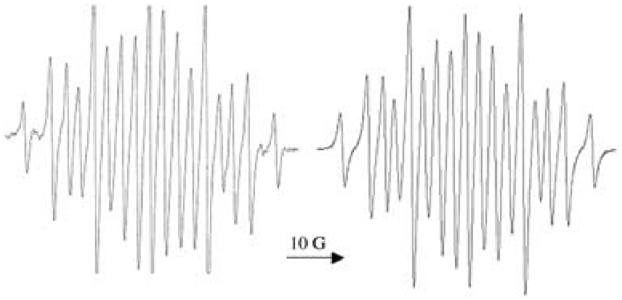


Figure 8. Left: EPR spectrum of radical **18** detected at −47 °C by photolyzing a solution of **16** in slightly aerated acetonitrile with 4-penten-1-ol and NO. Right: Computer-simulated spectrum. The length of the arrow represents a magnetic field unit of 10 G.

The coupling of NO with the 2-tetrahydrofurylmethyl radical, the sole ending radical species,[24] is now the most likely reaction [Eq. (35)], and then 2-(nitrosomethyl)tetrahydrofuran the precursor of nitroxide **18** [Eq. (38)].

Conclusion

The behavior of several alkyl nitrites during photolysis was studied in different solvents and at different temperatures. All the results led to the conclusion that the starting alkyl nitrite, acting as a spin trap[26] of alkyl radicals deriving from possible reactions that the intermediate alkoxyl radical can undergo, has a crucial role in the entire process. In particular, it has been proved that the intermediate alkyl alkoxy nitroxides have to be considered the precursors of the nitrosoalkyl derivatives, the main ending products. Actually, these species must be seen as the final products of the entire process, and not, unless a very high concentration of NO is present in the medium, the result of a direct reaction of alkyl radical intermediates with NO, which is in contrast to the commonly accepted mechanism of the Barton reaction. Furthermore, it has been clearly shown that the formation of the dialkyl nitroxides, which predominate at high temperatures, and the alkyl alkoxy nitroxides, which predominate at low temperatures, is under thermodynamic control.

Experimental Section

Materials: Nitrites were synthesized from the corresponding alcohols following the standard procedures reported in the literature,[22,25] and distilled under vacuum before use. The acetonitrile used was of 99.9+% purity.

EPR experiments: The solutions containing the reactants ($10–50\times10^{-3}$ M) were purged with gaseous N_2 for at least 45 min before use. The mixtures were then made to flow continuously (flow rate 2.0–3.5 $\mathrm{mL\,min^{-1}}$) through a flat quartz cell (0.3 mm width) inside an EPR spectrometer cavity, and were directly irradiated with a 500 W high-pressure mercury lamp. An EPR spectrometer equipped with a variable-temperature control system was used. Relative radical concentrations and hyperfine-splitting assignments were obtained by means of computer simulations. Table 1 shows the hyperfine coupling constants of the detected radical species.

Table 1. Hyperfine coupling (hfc) constants (*a*, in gauss; no. nuclei) of the detected radical species.

	a_N	a_{H_α}	a_{H_β}[a]	$a_{H_{\beta'}}$[a]	a_{H_γ}	*g* factor[b]
2	24.75		6.50 (2H)			2.0052
3	13.75		6.87 (4H)			2.0057
5	28.50		7.75 (2H)			2.0052
6	26.60					2.0052
7	15.40		10.50 (2H)			2.0057
9	28.25				1.00 [(2H)-CH_2]	2.0052
10	15.10					2.0057
11	13.00	12.12				2.0057
12	15.00		4.25			2.0057
14	26.63		7.62 (2H)			2.0052
15	14.75		10.13 (4H)			2.0057
17	25.25		4.00	12.00	0.375	2.0052
18	14.25		7.00 (2H)	11.20 (2H)		2.0057

[a] The hfc of H_β can be attributed to $H_{\beta'}$ and vice versa. [b] The *g* factors ±0.0002 were calculated by comparison with the *g* factor of the DPPH (2.0037±0.0002).

Acknowledgements

This work was financially supported by the Ministry of the University and Scientific and Technological Research (MURST), Rome (funds 60% and 40%), and by the University of Bologna (funds for selected research topics A.A. 2003).

---

[1] a) L. Grossi, S. Strazzari, *Chem. Commun.* **1997**, 917; b) L. Grossi, S. Strazzari, B. C. Gilbert, A. C. Whitwood, *J. Org. Chem.* **1998**, *63*, 8366; c) E. Gimenez-Arnau, L. Haberkorn, L. Grossi, J. P. Lepoittevin, *Tetrahedron* **2002**, *58*, 5535–5545.

[2] a) D. H. R. Barton, J. M. Beaton, I. E. Geller, M. M. Pechet, *J. Am. Chem. Soc.* **1960**, *82*, 2640–2641; b) C. H. Robinson, O. Gnoj, A. Mitchell, R. Wayne, E. Townley, P. Kabasakalian, E. P. Oliveto, D. H. R. Barton, *J. Am. Chem. Soc.* **1961**, *83*, 1771–1772; c) P. Kabasakalian, E. R. Townley, M. D. Yudis, *J. Am. Chem. Soc.* **1962**, *84*, 2716–2718.

[3] C. Lagercrantz, S. Forshult, *Nature* **1968**, *218*, 1247.

[4] a) M. I. Christie, J. S. Frost, *J. Chem. Soc.* **1964**, 468–473; b) E. J. Burrell, Jr., *J. Phys. Chem.* **1966**, *66*, 401–404.

[5] a) A. Mackor, Th. J. de Boer, *Recl. Trav. Chim. Pays-Bas* **1970**, *89*, 151–158; b) A. Mackor, Th. J. de Boer, *Recl. Trav. Chim. Pays-Bas* **1970**, *89*, 159–163; c) A. Mackor, Th. J. de Boer, *Recl. Trav. Chim. Pays-Bas* **1970**, *89*, 164–168.

[6] a) J. Heicklen in *Advances in Photochemistry*, *Vol. 14* (Eds.: J. N. Pitts, Jr., G. S. Hammond, W. A. Noyes, Jr.), Wiley-Interscience, New York **1988**, pp. 177–272; b) W. Deng, C. Wang, D. R. Katz, G. R. Gawinski, A. J. Davis, T. S. Dibble, *Chem. Phys. Lett.* **2000**, *330*, 541–546; c) M. J. Frost, W. M. Smith, *J. Chem. Soc. Faraday Trans.* **1990**, *86*, 1757–1762.

[7] a) P. Morabito, J. Heicklen, *Bull. Chem. Soc. Jpn.* **1987**, *60*, 2641–2650; b) P. Morabito, J. Heicklen, *J. Phys. Chem.* **1985**, *89*, 2914–2916; c) G. R. McMillan, *J. Phys. Chem.* **1963**, *67*, 931–932.

[8] P. Morabito, J. Heicklen, *Int. J. Chem. Kinet.* **1985**, *17*, 535–546.

[9] P. Kabasakalian, E. R. Townley, M. D. Yudis, *J. Am. Chem. Soc.* **1962**, *84*, 2718–2722.

[10] E. Gimenez-Arnau, L. Haberkorn, L. Grossi, J. P. Lepoittevin, *Tetrahedron* **2002**, *58*, 5535–5545.

[11] B. C. Gilbert, R. G. G. Holmes, H. A. H. Laue, R. O. C. Norman, *J. Chem. Soc. Perkin Trans. 2* **1975**, 1047–1052.

[12] A third radical species is evident in the spectrum; however, even though its structure could not be identified, the spectroscopic parameter would ascribe it to an alkyl alkoxy nitroxide-type.

[13] D. F. Bowman, T. Gillian, K. U. Ingold, *J. Am. Chem. Soc.* **1971**, *93*, 6555–6561.

[14] Actually, primary nitrosoalkyl compounds can tautomerize to the corresponding oximes, which easily donate an H atom to lead to an iminoxyl radical RCH=NO(•), a persistent σ radical detectable by EPR spectroscopy; whereas, no evidence of this species was obtained in any of the experiments in which primary nitrosoalkyls were involved.

[15] a) D. F. Bowman, J. L. Brokenshire, T. Gillian, K. U. Ingold, *J. Am. Chem. Soc.* **1971**, *93*, 6551–6555; b) M. J. Perkins, P. Ward, *J. Chem. Soc. B* **1970**, 395–400; c) M. J. Perkins in "Spin Trapping", *Advances in Physical Organic Chemistry*, *Vol. 17* (Eds.: V. Gold, D. Bethell), Academic Press, London, **1980**, pp. 1–64.

[16] In principle, alkyl alkoxy nitroxides could undergo two different β cleavages, one involving the N−OR bond (which we believe), and one involving the N−CR′ bond, the reverse of the trapping reaction. But, no dissociative bond energies (DBEs) for these processes are reported to support either of the two. However, our hypothesis is in agreement with the data reported by Ingold and Perkins concerning the *tert*-butoxy *tert*-butyl nitroxide: it is described as being unstable and decomposing to a *tert*-butoxyl radical and 2-methyl-2-nitrosopropane;[15a] the N−OR bond is the weakest of the two;[15b] kinetic data[15c] strongly stress that the fragmentation of *tert*-butoxy-*tert*-butyl nitroxides to give *tert*-butoxyl radicals is more rapid than that which gives *tert*-butyl radicals, by a factor of 100 (at 40 °C).

[17] a) A. Mackor, Th. A. J. W. Wajer, Th. J. de Boer, *Tetrahedron Lett.* **1967**, 386–390; b) A. Mackor, Th. A. J. W. Wajer, Th. J. de Boer, *Tetrahedron* **1968**, *24*, 1623–1631.

[18] In ref. [17a], it is reported that "a second radical has spin density on a nitrogen atom of ~25–30 G, and its EPR signal is predominant over that of the ordinary dialkyl nitroxide at temperature below −40 °C." In ref. [17b] it is reported that "the photolysis of the *t*BuONO in toluene would lead to the *tert*-butoxy benzyl nitroxide and dibenzyl nitroxide; but, at −40 °C the alkoxy alkyl nitroxide is formed exclusively." Actually, it is interesting to note that these au-

thors had already noted the same behavior that we report, but could not account for it.

[19] E. G. Janzen, D. E. Nutter, E. R. Davis, B. J. Blackburn, J. L. Poyer, P. B. McCay, *Can. J. Chem.* **1978**, *56*, 2237–2242.

[20] M. P. Doyle, J. W. Terpstra, R. A. Pickering, D. M. Le Poire, *J. Org. Chem.* **1983**, *48*, 3379–3382.

[21] J. Hartung, F. Gallou, *J. Org. Chem.* **1995**, *60*, 6706–6711.

[22] L. Grossi, S. Strazzari, *J. Org. Chem.* **1999**, *64*, 8076–8079.

[23] The recombination reaction between an alkoxyl radical and NO was also proved by conducting an experiment with a solution of di-*tert*-butyl peroxide in deoxygenated methanol, through which pure NO gas was bubbled. At low temperature, the nitroxide $HOCH_2N(O^{\bullet})$-O*t*Bu was detectable and to account for it, the intermediacy of the *t*BuONO has to be assumed.

[24] The high rate of cyclization[21] of the intermediate 4-pentenyloxyl radical led us to the conclusion that the reverse reaction of Equation (35) is negligible, thus supporting an ultimate quantum yield of ≈1 for nitrite **16**.

[25] W. A. Noyes, *Organic Syntheses*, *Vol. III*, Wiley, New York, **1943**, pp. 108–109.

[26] In light of the previous results, when conducting experiments with pure **16** the only nitroxide predicted would be **18**. However, when a solution of **16** in deaerated acetonitrile was made to flow through the cell inside the EPR spectrometer cavity and was photolyzed, at −37 °C, in addition to **18** (>95 %) a small amount (<%5) of 2-tetrahydrofurylmethyl-4-buten-1-oxy nitroxide ($a_N = 27.00$, $a_{H\beta} = 4.50$, $a_{H\beta'} = 10.75$ G) was also evident. This proves, once again, the efficiency of alkyl nitrite as a spin trap.

Received: January 24, 2005