ESR Study of Hydroxyl Alkoxyamine (HMPAP) in DMF and *tert*-Butylbenzene

Meizhen Yin,* Tilo Krause, Wolf D. Habicher

Dresden University of Technology, Institute of Organic Chemistry, Mommsenstrasse 13, D-01062 Dresden, Germany

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ABSTRACT: Hydroxyl alkoxyamine (HMPAP) in DMF and in *tert*-butylbenzene with oxygen as a scavenger was studied with electron spin resonance spectroscopy. From kinetics studies performed at 120°C, it was found that the rate constant of C—O bond homolysis was smaller in DMF than in *tert*-butylbenzene. The difference in the behavior could be related to the formation of an activated six-membered intermediate formed through intramolecular H-bonding in *tert*-butylbenzene and the disruption of H-bonding in the polar solvent DMF. This led to alteration of the equilibrium constant between the alkoxyamine and the corresponding nitroxide and C-centered radical in DMF and decreased initiating efficiency for the controlled/living radical polymerization using HMPAP as initiator. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 102: 4116–4120, 2006

Key words: ESR; initiator; radical polymerization; living polymerization

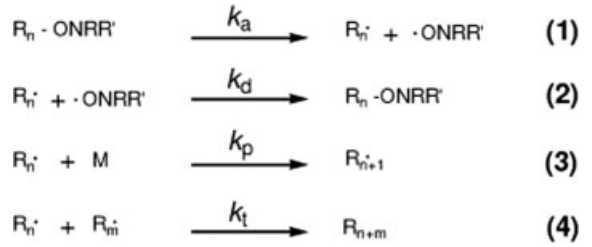
INTRODUCTION

Alkoxyamines have a relatively unstable C—O bond.[1,2] On heating, this bond readily cleaves homolytically to yield a carbon-centered radical species and a nitroxide, which is the prerequisite for alkoxyamines to act as radical initiators. Directly related to this homolysis is the process of trapping a carbon-centered radical with a nitroxide. It generally occurs via coupling of the two radical species to yield alkoxyamine as a covalent adduct. In this way, alkoxyamine homolysis can be considered a reversible process. The reversible homolytic C—O bond cleavage of alkoxyamines has led to the development of a living-radical polymerization technique.[3,4] For nitroxide-mediated living-radical polymerization, the so-called reversible activation of the dormant alkoxyamines needs to meet two basic requirements. First, alkoxyamine C—O bond homolysis needs to produce a carbon-centered radical that is able to undergo addition to a monomer (propagation). Second, nitroxide needs to be a persistent compound, which is only capable of trapping the carbon-centered radical via coupling. A schematic mechanism of the nitroxide-mediated radical polymerization is shown in Scheme 1 (the alkoxyamine, carbon-centered radical, and nitroxide are represented as R_n-ONRR′, R_n·, and R′RNO·, respectively).

The cleavage rate constants of the dormant chains into radicals (activation), k_a, and of the reverse coupling (deactivation), k_d, are crucial for the living-radical polymerization process (Scheme 1). The rate constant k_a and k_d influence the degree of livingness and control of the resulting polymer and the monomer conversion rate.[5] In successful living-radical polymerization, k_a has to be sufficiently large to ensure a reasonable conversion time and low polydispersity. However, k_a must not exceed a critical value, for which the controlling persistent radical effect breaks down, and the optimum values of k_a and k_d depend on the propagation constant (k_p) and the termination rate constant (k_t) of the different monomers.[5] As a rule, a k_a of at least 10^{-3} s^{-1} is desirable, and it would be helpful if k_a could be reasonably predicted on the basis of the alkoxyamine and nitroxide structures in order to avoid unnecessary synthetic and experimental work. In the absence of monomer, that is, when $n = 0$, no propagation occurs, and only reactions (**1**), (**2**), and (**4**) should occur. The dissociation rate constant, k_a, of alkoxyamines can be measured conveniently by quantitative electron spin resonance (ESR) spectroscopy from the appearance of the nitroxide radical using a specified scavenger for the transient radicals.[1,2,6–9] Studer[10] and S. Marque[6,7,11] reported their ESR measurements of a large number of homolysis constants of different alkoxyamines. Among the alkoxyamines, the alkoxyamine 2-hydroxymethyl-2-[(2-methyl-1-phenyl-propyl)-(1-phenyl-ethoxy)-amino]-propane-1,3-diol (**HMPAP**, **1**) was measured in an inert solvent *tert*-butylbenzene.

In connection with our work[12] nitroxide-mediated polymerization of multifunctional acryl- and methacryl derivatives using alkoxyamine **1** as a initiator was carried out in aqueous and polar solvents such as DMF; therefore, it is of interest to examine the rate constants of the C—O bond homolysis of alkoxy-

**Present address*: Max Planck Institute for Polymer Research, Ackermannweg 10, D-55128 Mainz.
Correspondence to: M. Yin (yinmz@yahoo.com).



Scheme 1 Schematic mechanism of dissociation of the nitroxide-capped alkoxyamine.

amine **1** in DMF. With this information we might be able to explain some of the polymerization results. For reasons of comparison, the thermal homolysis kinetics of alkoxyamine **1** in *tert*-butylbenzene was also investigated, and the solvent effect is discussed in this article.

EXPERIMENTAL

Reagents and solvents

2-Hydroxymethyl-2-[(2-methyl-1-phenyl-propyl)-(1-phenyl-ethoxy)-amino]-propane-1,3-diol (**HMPAP**, **1**) was synthesized according to the report of Harth et al.[13] *N,N′*-dimethylformamide (DMF) was purified by a standard procedure. *tert*-Butylbenzene (Fluka) was used as received.

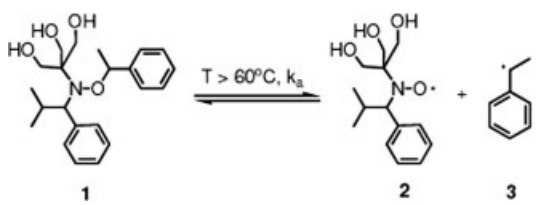
Analyses and measurements

ESR spectroscopic measurements were carried out on a Bruker EMX spectrometer. The nitroxide concentration was determined by double integration of the ESR signals, and the data were calibrated under identical conditions.

RESULTS AND DISCUSSION

Temperature limit of C—O bond homolysis of alkoxyamine 1

To check the temperature limit of the C—O bond homolysis, alkoxyamine **1** was dissolved in the inert solvent *tert*-butylbenzene and degassed with nitrogen for 20 min before ESR measurement. There were no signals of radicals detected by ESR at room temperature. After the solution was slowly heated to 60°C, the signal of nitroxide **2** appeared, which correctly reflected the beginning of the decomposition



Scheme 2 Thermal decomposition of the alkoxyamine 1.

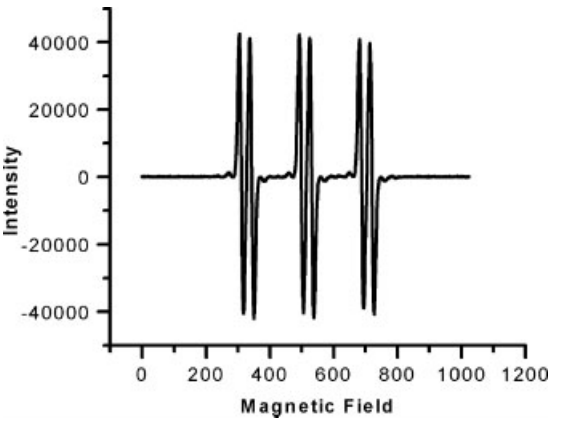


Figure 1 ESR spectrum of nitroxide 2 (1×10^{-3} mol/L in *tert*-butylbenzene).

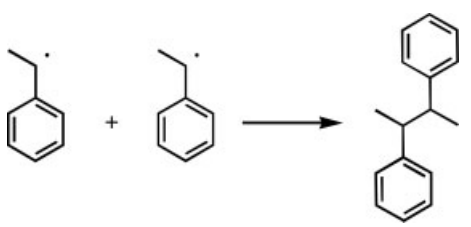
of alkoxyamine **1** (Scheme 2). A representative ESR spectrum of nitroxide **2** is shown in Figure 1.

As shown in Scheme 2, the decomposition of alkoxyamine **1** formed two radicals, the persistent nitroxide **2** and the more reactive styryl radical **3**.[7,13] To avoid a recombination of nitroxide **2** and styryl radical **3**, it was necessary to trap the reactive species **3** by a scavenger.[1,5,14]

The use of a commercially available galvinoxyl radical (2,6-di-*tert*butyl-4-(3,5-di-*tert*-butyl-4-oxocyclohexa-2,5-dien-1-ylidenmethyl)phenoxyl) as a scavenger for the transient radical has been reported previously,[6,14] but in our study the galvinoxyl radical did not lead to the desired trapping of the active carbon radical **3** at 120°C; instead, a fast decay of the signal of nitroxide **2** was observed. Therefore, oxygen was used to scavenge the styryl radical as previously described.[1,2,6,7] Because no signal of styryl radical **3** formed from the decomposition of alkoxyamine **1** could be detected during ESR measurement, it was concluded that active radical **3** was either instantaneously trapped by O_2 or dimerized to 2,3-diphenylbutane (Scheme 3).

Kinetics of C—O bond homolysis of alkoxyamine 1 in DMF

Harth et al. reported that alkoxyamine 1 is an efficient initiator for nitroxide-mediated polymerization of styrene and *n*-butyl acrylate.[13] In our laboratory similar results were obtained.[12,15] However, when



Scheme 3 Dimerization of styryl radical to 2,3-diphenylbutane.

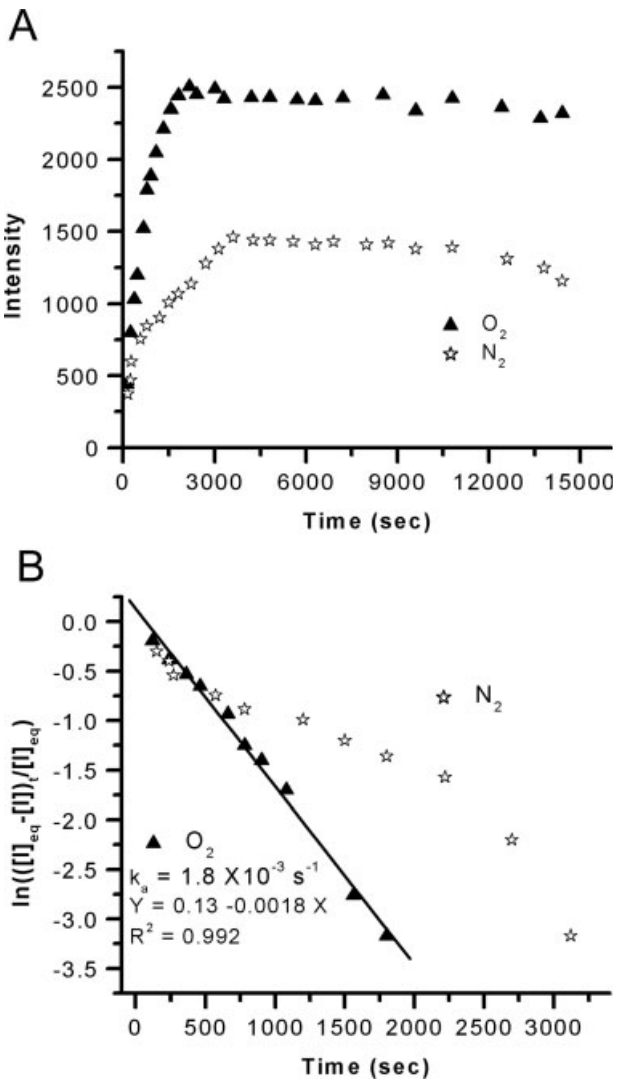


Figure 2 (a) Time dependence of nitroxide 2 signal intensities during thermolysis of alkoxyamine 1 in DMF with oxygen or with nitrogen at 120°C. (b) Plot of $\ln\{([I]_{eq} - [I]_t)/[I]_{eq}\}$ versus time in DMF with oxygen or with nitrogen at 120°C.

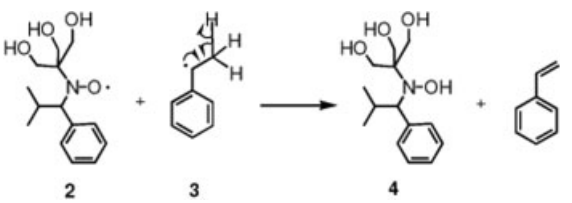
we investigated the polymerization of multifunctional acryl- and methacryl derivatives using alkoxyamine 1 as initiator, the results showed that it was a great challenge to accomplish precisely controlled radical polymerization of those functional monomers using alkoxyamine 1 as the initiator.[12] A possible explanation for this is that the initiation system did not work as well in an aqueous polymerization system (or polar surroundings), which is the type most suitable for these water-soluble functional monomers, as it did in organic solvents or in the bulk phase of a nonpolar monomer.[12]

To verify this, the thermal decomposition of alkoxyamine 1 was investigated in DMF because the polymerizations were performed in this polar solvent, and the released nitroxide was monitored by ESR experiments. A temperature of 120°C was selected, similar to the temperature used for polymerization. The solution was treated in two ways before ESR measurement: one solution was bubbled with air for 20 min, which means oxygen was used as a scavenger; and the other solution was bubbled with nitrogen for 20 min, as had been done in the polymerization process. The signal intensities of the nitroxide radical 2 during the thermolysis of alkoxyamine 1 in DMF with and without oxygen at 120°C were monitored, as shown in Figure 2(a).

As shown in Figure 2(a), both intensities of nitroxide 2 increased with time up to a maximum value. It took about 36 min (2160 s) for the solution with oxygen as a scavenger to reach the maximum value, whereas it took a longer time (60 min) for the solution degassed with nitrogen to reach the plateau value. It should be noted that in a controlled radical polymerization process, it is not favorable to need a long time to reach the maximum of decomposition of alkoxyamine. For the best control of the process, the time needed to form the primary radical should be short in comparison with the rates of the other polymerization steps. As can be seen from this experiment, when we used oxygen as a scavenger, the concentration of the nitroxide radical increased as well as the rate of homolysis. However, at the same time, the styryl radical was trapped. Thus, the presence of oxygen was not favorable for the progress of the polymerization. After the maximum value was reached, the signal intensities of nitroxide 2 did not decrease with time when the solution was bubbled with oxygen. However, a small decrease in the signal intensity of nitroxide could be observed when the time was extended in the case of the solution degassed with nitrogen, which could be related to a hydrogen transfer reaction (Scheme 4). Similar hydrogen transfer reactions in nitroxide-mediated radical polymerization have been reported previously.[16–18] The formation of hydroxylamine 4 was proved by LC-MS measurement in our lab.

The plot of $\ln\{([I]_{eq} - [I]_t)/[I]_{eq}\}$ versus time followed the expected first-order kinetics [Fig. 2(b), I = intensity of nitroxide signal] with oxygen as a scavenger, and the experimental cleavage rate constant of $k_a = 1.8 \times 10^{-3}\ s^{-1}$ was obtained using eq. (1)[6,7]:

$$\ln\left(\frac{[NO^{\bullet}]_{eq} - [NO^{\bullet}]_t}{[NO^{\bullet}]_{eq}}\right) = -k_a t \qquad (1)$$



Scheme 4 Hydrogen transfer reaction of the nitroxide radical 2 to give hydroxylamine 4.

where $[NO^{\bullet}]_t$ is the transient concentration of nitroxide and $[NO^{\bullet}]_{eq}$ is the equivalent concentration of nitroxide.

However, no linear relationship was found when the solution was degassed with nitrogen [Fig. 2(b)]. Therefore, it was not possible to calculate the cleavage rate constant, k_a, under similar conditions in the polymerization process. However, by comparison of the plots in Figure 2(b) it can be assumed that k_a was not larger than the value of $k_a = 1.8 \times 10^{-3}$ s^{-1} under oxygen conditions.

Kinetics of C—O bond homolysis of alkoxyamine 1 in *tert*-butylbenzene

The ESR data of alkoxyamine 1 in *tert*-butylbenzene was previously reported by Marque et al.[7] To compare their results with ours, the kinetic experiment was also conducted in *tert*-butylbenzene at 120°C with oxygen as a scavenger for the styryl radical. The time dependence of nitroxide 2 concentration during the thermolysis of alkoxyamine 1 in *tert*-butylbenzene is given in Figure 3(a).

The experimental cleavage rate constant, $k_a = 4.7 \times 10^{-3}$ s^{-1}, obtained using eq. (1) [Fig. 3(b)], was a little smaller but comparable to that reported in the literature ($k_a = 5.6 \times 10^{-3}$ s^{-1}, $T = 115$°C–124°C).[7] The activation energy, E_a, of the cleavage of the C—O bond was calculated on the basis of eq. (2)

$$k_a = Ae^{-E_a/RT} \tag{2}$$

where $A = 2.4 \times 10^{14}$ s^{-1} was used to give rise to a value of 125.6 kJ/mol, which was in good agreement with the previously reported value of 125.1 kJ/mol,[7] meaning that in principle our measurement conditions were optimized.

For reasons of comparison, the thermal decomposition of alkoxyamine 1 was also investigated in *tert*-butylbenzene with nitrogen at 120°C. A similar phenomenon was observed. After the maximum value was reached, the signal intensities of nitroxide 2 decreased with time when the solution was bubbled with nitrogen [Fig. 3(a)]. Furthermore, the experimental cleavage rate constant, $k_a = 3.1 \times 10^{-3}$ s^{-1}, was slightly smaller than that when the solution was bubbled with oxygen [Fig. 3(b)].

Because it was not possible to obtain the cleavage rate constant, k_a, in DMF under nitrogen conditions, the effectiveness of alkoxyamine 1 in DMF and in *tert*-butylbenzene was only compared for the solution with oxygen as a scavenger. A comparison with the thermal homolysis of alkoxyamine 1 in DMF [Fig. 2(a)] shows that in *tert*-butylbenzene the time (1200 s) to reach the maximum was shorter [Fig. 3(a)]. That means the alkoxyamine 1 homolyzed faster in *tert*-butylbenzene than in DMF. Further evidence of this came from the comparison of the cleavage rate constant of alkoxyamine 1 in DMF and in *tert*-butylbenzene. The decomposition rate constant of alkoxyamine 1 in DMF [$k_a = 1.8 \times 10^{-3}$ s^{-1}; Fig. 2(b)] was smaller than that in *tert*-butylbenzene [$k_a = 4.7 \times 10^{-3}$ s^{-1}; Fig. 3(b)]. As mentioned previously, satisfactory living-radical polymerization apparently requires a rate constant, k_a, of about 10^{-3} s^{-1} for the dissociation of the intermediate polymeric alkoxyamine. Both the rate constant of C—O bond homolysis in *tert*-butylbenzene and that in DMF matched this theoretical value at 120°C. Of course, having a high degree of control of polymerization depends on other conditions, which were described in the Introduction section. Here, we only discuss the solvent effect in the initiation system.

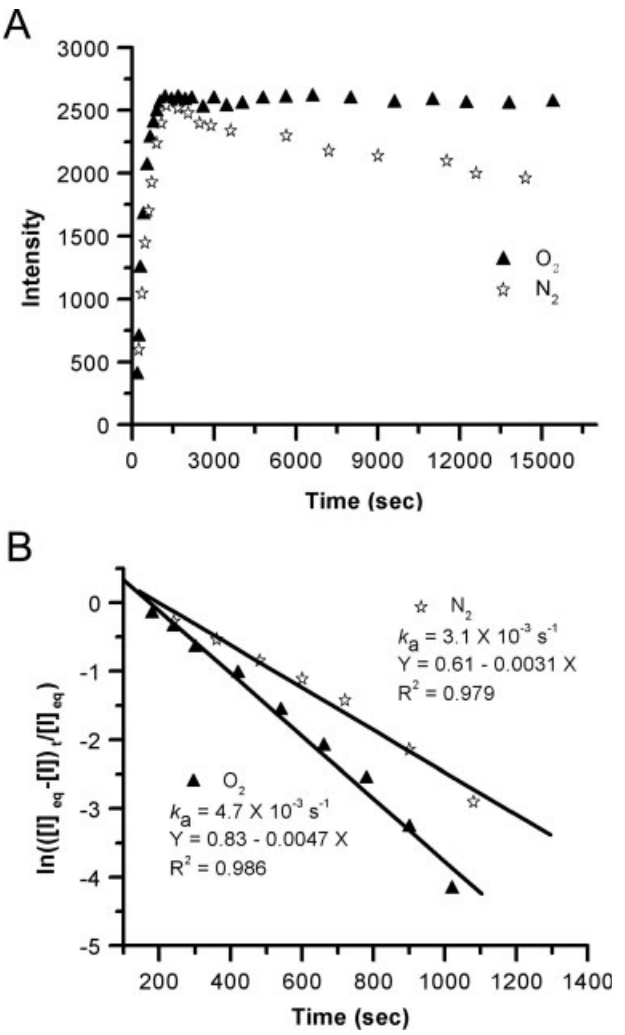


Figure 3 (a) Signal intensities of the nitroxide radical 2 versus time during thermolysis of alkoxyamine 1 in *tert*-butylbenzene with oxygen or with nitrogen at 120°C. (b) Plot of $\ln\{([I]_{eq} - [I]_t)/[I]_{eq}\}$ versus time in *tert*-butylbenzene with oxygen or with nitrogen at 120°C.

Studer[7] and others[13,19,20] have shown that H-bonding in nitroxide leads to stabilization of the nitroxide,

and this in turn alters the equilibrium constant between the alkoxyamine and the corresponding nitroxide and C-centered radical. With a polar solvent like DMF, the formation of a six-membered intermediate by intramolecular H-bonds is disturbed because the polar solvent DMF builds up a shell around the polar atoms. Therefore, the equilibrium constant between the alkoxyamine and the corresponding nitroxide and C-centered radical in DMF might be different from that in an apolar solvent like *tert*-butylbenzene. The smaller cleavage rate constant of alkoxyamine 1 in DMF offered an indirect evidence of this. This could also be the reason why alkoxyamine 1 was a very efficient mediator for the controlled/living-radical polymerization of nonpolar monomers like styrene and *n*-butyl acrylate[13]; however, it was not as suitable as an initiator for the polymerization of polar monomers in aqueous or polar solvents.[12]

CONCLUSIONS

The cleavage of the hydroxyl alkoxyamine (HMPAP, 1) was studied by ESR in *tert*-butylbenzene as an nonpolar solvent and in DMF as a polar solvent. The intention of performing this comparison was to explain the difference in the effectiveness of this alkoxyamine in controlling radical polymerization of polar and nonpolar monomers. The longer time needed to homolyze and the smaller cleavage rate constant of the thermal decomposition of alkoxyamine 1 in DMF, compared to that in *tert*-butylbenzene, might explain the low control of polymerization of multifunctional acryl- and methacryl derivatives using alkoxyamine 1 as initiator in a polar solvent like DMF.

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