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Hydroxy- and Silyloxy-Substituted TEMPO Derivatives for the Living Free-Radical Polymerization of Styrene and *n*-Butyl Acrylate: Synthesis, Kinetics, and Mechanistic Studies

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Abstract: The synthesis of new 2,2,6,6-tetramethylpiperidin-1-oxyl (TEMPO) styryl derivatives as mediators for the living free-radical polymerization is described. Two of the α-methyl groups at the 2- and 6-position of the parent TEMPO styryl alkoxyamine have been replaced by hydroxymethyl and silyloxymethyl groups. To further increase the steric hindrance around the alkoxyamine oxygen atom, the remaining two methyl groups have been substituted with larger ethyl groups. Styrene polymerizations using hydroxy-substituted TEMPO derivatives are fast, but are not well-controlled. As previously shown for other OH-substituted alkoxyamines, intramolecular H-bonding leads to an acceleration of the C−O bond homolysis and, hence, to an acceleration of the polymerization process. However, the OH groups also increase the alkoxyamine decomposition rate constant. The kinetics of the C−O bond homolysis have been determined using EPR spectroscopy. Decomposition studies have been conducted with the aid of ^{1}H NMR spectroscopy. In contrast to the OH-substituted alkoxyamines, highly hindered silyloxy-substituted TEMPO alkoxyamines turned out to be excellent mediator/initiators for the controlled styrene polymerization. Polystyrene with M_n of up to 80 000 g/mol and narrow polydispersities (PDI) has been prepared using the new alkoxyamines. Reactions have been conducted at 105 °C; however, even at 90 °C controlled but slow polymerizations can be achieved. Furthermore, and more importantly, poly(*n*-butyl acrylates) with narrow PDIs (<1.15) have been prepared at 105 °C with the new alkoxyamines. Controlled acrylate polymerization can be conducted at temperatures as low as 90 °C. The silylated alkoxyamines presented belong to the most efficient initiator/mediators for the controlled acrylate polymerization known to date. The effect of the addition of free nitroxide on the acrylate polymerization is discussed. Moreover, the synthesis of diblock copolymers with narrow PDIs is described.

Introduction

Nitroxide-mediated polymerizations (NMP),[1] atom transfer radical polymerizations (ATRP),[2] and RAFT polymerizations[3] provide polymers with polydispersities (PDI) below the theoretical limit for a conventional radical polymerization (1.5). The NMP process is controlled by the persistent radical effect (PRE)[4] and is based on the reversible formation of a dormant alkoxyamine from the corresponding nitroxide and the chain-growing polymer radical. The equilibrium in this controlled radical polymerization lies far on the side of the dormant alkoxyamine, ensuring a low concentration of free radicals during the polymerization. The equilibrium constant between the nitroxide-capped polymer and the free nitroxide and polymer radical, respectively, is of great importance in these processes.[4,5] We[6] and others[7,8] have shown that H-bonding in nitroxides leads to a stabilization of the nitroxide, and this in turn alters the equilibrium constant between the alkoxyamine and the corre-

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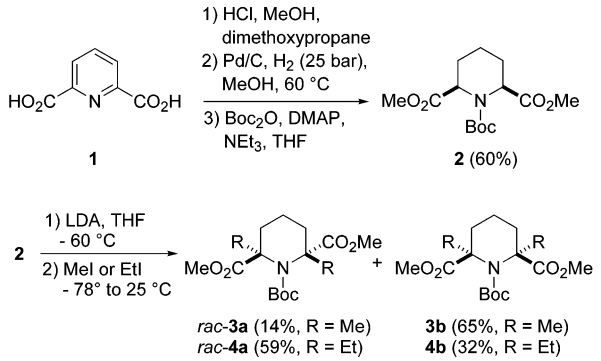
Scheme 1. Preparation of Hindered Piperidines via a Dianion Double-Alkylation Strategy



sponding nitroxide and C-centered radical. Nitroxides capable of forming intramolecular H-bonds have been shown to be very efficient mediators for the controlled/living radical polymerization of *n*-butyl acrylate.[8]

Herein we present results on the synthesis of new hydroxy- and silyloxy-substituted 2,2,6,6-tetramethylpiperidin-1-oxyl (TEMPO) derivatives. Their efficiency as mediators for the polymerization of styrene and *n*-butyl acrylate will be discussed. Furthermore, rate constants for the C−O bond homolysis of the new alkoxyamines derived from these nitroxides and decomposition studies of the new alkoxyamines will be presented.

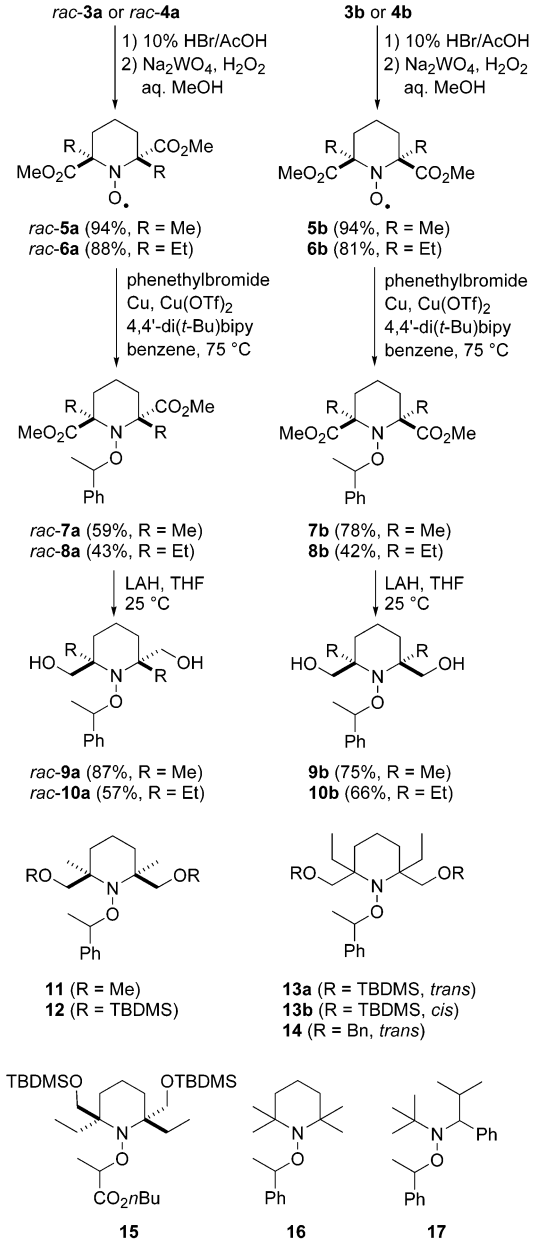
Results and Discussion

Preparation of the Alkoxyamines. Esterification of diacid **1**, reduction, and subsequent Boc protection afforded meso-diester **2** (60%, Scheme 1).[9] Double alkylation of **2** provided *trans*-**3a** (14%) and *cis*-**3b** (65%).[10] Ethylated compounds **4a**,**b** were prepared in analogy.

N-Deprotection (HBr/AcOH) followed by oxidation (Na_2WO_4, H_2O_2) afforded the nitroxides **5a**,**b**[10] and **6a**,**b** in excellent yields (Scheme 2). Alkoxyamine synthesis according to a literature procedure[11] provided **7a**, **7b**, **8a**, and **8b** in moderate to good yields. The alkoxyamines **7a** and **8a** were obtained as a 1:1 mixture of inseparable diastereoisomers. $LiAlH_4$ reduction gave diols **9a**,**b** and **10a**,**b**. The diols were protected using standard procedures (→ **11**−**14**). The known[1c] alkoxyamines **16** and **17** were included in this study for comparison. The relative configuration of all new alkoxyamines could unambiguously be assigned on the basis of X-ray analysis of **9b** and **10b**.[12]

Polymerization of Styrene. The initial polymerizations were conducted in sealed tubes using 1 mol % of the alkoxyamine initiator at 125 °C and were stopped after 6 h. The conversion

Scheme 2. Preparation of the Various Alkoxyamines Studied



was determined gravimetrically. If conversion exceeded 95% after 6 h, polymerizations were repeated and were stopped after 1.5 to 3 h. The PDI and the molecular weight of the polymers were analyzed using size exclusion chromatography (SEC). The results are summarized in Table 1.

Polymerizations using the diesters **7a**,**b** were not controlled (PDI > 1.5, entries 1 and 2). The alkoxyamines **8a**,**b** provided higher conversions; however, control was still not satisfactory (entries 3 and 4). With trans-diol initiator **9a**, a conversion of 74% was achieved in just 1.5 h; however, the measured polydispersity was rather broad (1.25, entry 5). The reaction with cis-diol **9b** was slower, but a narrow PDI was obtained (1.14, entry 6). The ethyl-substituted trans-diol **10a** provided a fast, but not well-controlled polymerization (entry 7).[13] The best result was obtained with the cis-ethyl-substituted diol **10b**, where reaction occurred fast and controlled (entry 11). Unfortunately,

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(12) Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Center as private communication no. CCDC-217340 (**9b**) and CCDC-217341 (**10b**) (Klaus Harms, 2003). Copies of the data can be obtained free of charge on application to CCDC, 112 Union Road, Cambridge CB21EZ, U.K. (fax: (+44) 1233 336−033; e-mail: deposit@ccdc.cam.ac.uk).

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Table 1. Polymerization of Styrene Using Alkoxyamines **7**−**14**, **16**, and **17** as Mediator/Initiators under Different Conditions

entry	alkoxyamine (mol %)	time (h)	temp (°C)	$M_{n,exp}$ (g/mol)	$M_{n,th}$ (g/mol)	PDI	conversion (%)	entry	alkoxyamine (mol %)	time (h)	temp (°C)	$M_{n,exp}$ (g/mol)	$M_{n,th}$ (g/mol)	PDI	conversion (%)
1	**7a** (1%)	6	125	4600	4500	1.64	43	17	**13a** (1%)	2	125	7300	6600	1.12	63
2	**7b** (1%)	6	125	7100	6000	1.57	58	18	**13a** (0.4%)	3	125	18200	16400	1.13	63
3	**8a** (1%)	6	125	6300	6400	1.32	61	19	**13a** (0.2%)	3	125	36000	30200	1.17	58
4	**8b** (1%)	6	125	6100	7400	1.22	71	20	**13a** (0.1%)	3	125	48200	47900	1.20	46
5	**9a** (1%)	1.5	125	10300	7700	1.25	74	21	**13a** (1%)	15	105	9500	8900	1.12	85
6	**9b** (1%)	3	125	6500	7000	1.14	67	22	**13a** (0.4%)	20	105	20300	18700	1.11	72
7	**10a** (1%)	2	125	10100	9900	1.29	95	23	**13a** (0.1%)	21	105	78200	70500	1.20	68
8	**10a** (0.4%)	2	125	15400	18200	1.24	70	24	**13a** (0.4%)	48	90	17800	13800	1.10	53
9	**10a** (0.2%)	2	125	37000	21100	1.24	62	25	**13b** (1%)	2	125	9200	6800	1.12	65
10	**10a** (0.1%)	2	125	46000	44700	1.36	43	26	**13b** (0.1%)	21	105	67400	69800	1.22	67
11	**10b** (1%)	3	125	5900	7100	1.13	68	27	**13a**,**b** (0.1%)	21	105	69900	68700	1.21	66
12	**10b** (0.4%)	3	125	14100	16400	1.16	63	28	**14** (1%)	2	125	8100	6500	1.11	62
13	**10b** (0.2%)	3	125	27100	26100	1.22	50	29	**14** (0.4%)	20	105	22100	19000	1.17	73
14	**10b** (0.1%)	3	125	57000	48200	1.32	46	30	**16** (1%)	6	125	1800	2000	1.30	19
15	**11** (1%)	6	125	4800	5200	1.19	50	31	**17** (1%)	6	125	5000	6600	1.16	63
16	**12** (1%)	6	125	7100	7200	1.19	69	32	**17** (1%)	15	105	6400	5300	1.17	51

it turned out that **10a** and **10b** are not perfectly suited for the controlled preparation of high molecular weight polystyrene. For both alkoxyamines, an increased PDI (1.3 to 1.4) was obtained for polymers with M_n values above 30 000 g/mol (entries 8−10, 12−14). We speculated that the OH groups lead to decreased nitroxide, alkoxyamine stability (stability studies will be discussed below), or both. Therefore, we studied reactions with O-protected derivatives of alkoxyamines **9b**, **10a**, and **10b** (→ **11**, **12**, **13a**,**b**). Polymerization of styrene with bis(methyl ether) **11** occurred slower as compared to **9b**, bearing two free hydroxyl groups (compare entry 11 with 15). Furthermore, PDI slightly increased. The TBDMS-prototected alkoxyamine **12** is more efficient than **11** (entry 16), and the ethyl-congener **13a** turned out to be a highly efficient initiator/mediator (63%, 2 h, PDI = 1.12, entry 17). A similar result was obtained for the cis-derivative **13b** (entry 25).

To document the efficiency of **13a**,**b**, polymerizations were repeated with established alkoxyamines for comparison. Using styryl TEMPO **16**, we obtained a conversion of only 19% with a PDI of 1.30 under the same conditions (Table 1, entry 30). With the well-known Hawker-Braslau alkoxyamine **17**,[14a] a slower polymerization and a slightly higher PDI were achieved (entries 31 and 32).

13a can be used for the preparation of high molecular weight polystyrenes at 125 °C (Table 1, entries 18−20). At 105 °C, even better results were obtained (M_n up to 78 200 g/mol with PDI below 1.20, entries 21−23). The diastereoisomer **13b** is also a very efficient initiator/mediator (entry 26). Polymerization using a mixture of the *trans*-**13a** and *cis*-**13b** (64:36 mixture) provided the same result (entry 27). *It is important to note that it is not necessary to separate the cis- and trans-compounds during synthesis. Therefore, the most demanding task in large-scale alkoxyamine synthesis, namely the chromatographic separation of **4a** and **4b**, is not necessary!* Bis(benzyl ether) **14** works as well as TBDMS ether **13a**, showing that the Si group has no special influence (entries 28 and 29). Thus, the "expensive" TBDMS groups can be replaced by benzyl groups without losing initiator/mediator efficiency. Furthermore, we found that controlled styrene polymerization with **13a** can be conducted at temperatures as low as 90 °C (entry 24, 53%, PDI = 1.10).

To prove the controlled/living character of the **13a**-mediated styrene polymerization, we determined the monomer consumption as a function of time, and we analyzed the molecular weight as a function of monomer conversion (Figure 1). The linear increase of $\ln([M]_0/[M])$ vs time and linear increase of molecular weight vs conversion as well as the decrease of PDI at increasing conversion prove the controlled character of the polymerization.

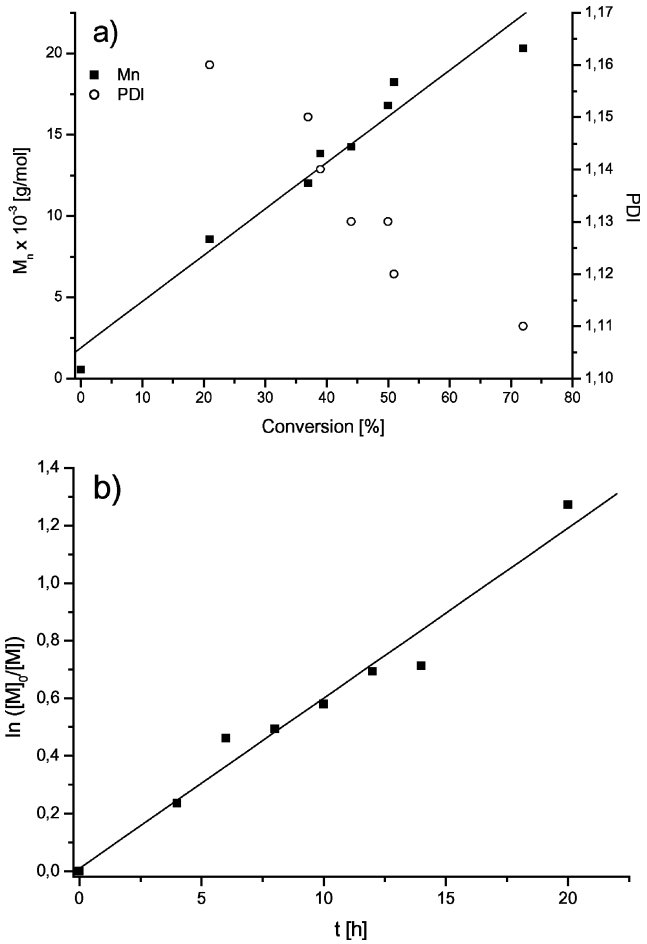


Figure 1. (a) Molecular weight and PDI vs monomer conversion. (b) Monomer consumption vs time (styrene, 105 °C, 0.4 mol % **13a**).

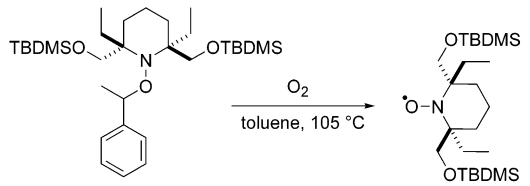
Polymerization of *n*-Butyl Acrylate. We then studied the *n*-butyl acrylate polymerization using **13a**,**b** and **10a**. To date, NMP of acrylates is still a challenge.[1c] Polymerizations were performed in neat *n*-butyl acrylate as described in the Supporting

Table 2. Polymerization of *n*-Butyl Acrylate Using Alkoxyamines **10a**, **13a**,**b**, and **17** as Mediator/Initiators under Different Conditions

entry	alkoxyamine (mol %)	nitroxide **18a** (mol %)	time (h)	temp (°C)	$M_{n,exp}$ (g/mol)	$M_{n,th}$ (g/mol)	PDI	conversion (%)
1	**10a** (0.2%)		6	125	43900	57000	1.79	90
2	**10a** (0.2%)		16	105	71700	47500	1.27	74
3	**13a** (0.4%)		15	125	37100	28900	1.55	90
4	**13a** (1%)		24	105	13300	9200	1.20	72
5	**13a** (1%)	0.05%	24	105	6000	4100	1.12	32
6	**13a** (1%)	0.04%	24	105	8200	5500	1.13	43
7	**13a** (1%)	0.02%	24	105	10100	6700	1.14	52
8	**13a** (1%)	0.01%	24	105	11500	8100	1.15	63
9	**13a** (1%)	0.008%	24	105	11800	8100	1.16	63
10	**13a** (1%)	0.006%	24	105	12300	8300	1.17	65
11	**13a** (1%)	0.004%	24	105	12600	8500	1.19	66
12	**13a** (0.4%)		24	105	31600	21500	1.23	67
13	**13a** (0.4%)	0.02%	42	105	29100	22100	1.13	69
14	**13a** (0.1%)	0.005%	42	105	64700	57700	1.22	45
15	**13a** (1%)		64	90	25000	18300	1.29	57
16	**13a** (1%)	0.01%	96	90	17300	12600	1.16	39
17	**13b** (1%)	0.01%	24	105	11000	8300	1.16	65
18	**13a**,**b** (1%)	0.01%	24	105	11800	8500	1.15	67
19	**17** (1%)	0.05%[a]	6	125	9500	6200	1.21	48

[a] The nitroxide derived from alkoxyamine **17** was used. For the preparation of the nitroxide, see ref 14a.

Scheme 3. Synthesis of Nitroxide **18a** via Thermolysis of Alkoxyamine **13a**



13a **18a** (89%)

Information. Diol **10a** was not able to control the polymerization at 105 and 125 °C (Table 2, entries 1 and 2). At 125 °C the **13a**-mediated acrylate polymerization was also not controlled (entry 3). However, at 105 °C we obtained poly(*n*-butyl acrylate) with a narrow PDI (entries 4 and 12). The dormant polymeric alkoxyamine derived from **13a** is obviously not sufficiently stable at 125 °C; however, at 105 °C activity and stability for efficiently controlled acrylate polymerization is high enough.

All the reported successfully controlled nitroxide-mediated acrylate polymerizations have been conducted in the presence of 5 mol % free nitroxide (with respect to the alkoxyamine).[14] Therefore, we repeated the polymerization in the presence of nitroxide **18a** which was readily prepared via thermolysis of **13a** in the presence of oxygen (Scheme 3). Polymerization was slower, but PDI further decreased (Table 2, entry 5). We were also able to prepare *n*-butyl acrylate with a M_n of 64 700 g/mol in a controlled manner (entries 13 and 14). As for the styrene polymerizations, the diastereoisomer **13b** shows similar activity than **13a** (entry 17). A mixture of **13a**,**b** (64:36 mixture) provided the same result (entry 18). Controlled polymerization can even be conducted at 90 °C (entries 15 and 16). *It is important to note that **13a**,**b** belong to the most efficient initiator/mediators for the controlled acrylate polymerization known to date*.[1c,14,15] To the best of our knowledge, poly(*n*-butyl acrylate) with polydispersities around 1.1 prepared via NMP have so far only been reported for noncyclic alkoxyamines.[1c,14,15] To underline the efficiency of the new initiators, we repeated the acrylate polymerization under the same conditions using one of the best alkoxyamines (→ **17**) known to date. At 125 °C **17** provided worse results under our conditions (entry 19). Moreover, polymerizations at 105 °C were not reproducible using **17**. Controlled NMP of acrylates is not possible using TEMPO initiator **16**.

The effect of additional nitroxide on the conversion and on the PDI has been theoretically analyzed by Fukuda[14d] and Fischer.[14f] At large additional nitroxide concentrations, the conversion can be described using eq 1 ($[Y]_0$ = concentration of added free nitroxide; K = equilibrium constant between active and dormant chains ($K = k_d/k_c$); k_c = rate constant for the cross-coupling of the C-centered radical with the nitroxide; k_d = dissociation rate constant for the C−O bond homolysis; k_p = propagation rate constant; $[I]_0$ = initial alkoxyamine concentration). At lower nitroxide concentrations, however, the conversion has to be described using eq 2, as suggested by Fukuda (k_t = termination rate constant).[14d]

$$\ln([M]_0/[M]) = k_p K([I]_0/[Y]_0)t \quad (1)$$

$$\ln([M]_0/[M]) = (k_p/2k_t K[I]_0)\{(3k_t K^2[I]_0^2 t + [Y]_0^3)^{2/3} - [Y]_0^2\} \quad (2)$$

According to eq 2, to increase the conversion the amount of added nitroxide has to be decreased. Indeed, in our experiments a lowering of the free nitroxide concentration from 0.04 mol % to 0.004 mol % resulted in an increase of the conversion (from 43 to 65%, Table 2, entries 6−11). As expected from the theoretical work, PDI slightly decreased along with the increase of the nitroxide concentration (from 1.13 to 1.19). However, even at the lowest nitroxide concentration tested, polymerization

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(15) Sterically highly hindered 4-oxo-TEMPO-derived alkoxyamines for the controlled/living radical polymerization of *n*-butyl acrylate providing polyacrylates with PDIs below 1.15: Wetter, C.; Gierlich, J.; Knoop, C.; Müller, C.; Schulte, T.; Studer, A. *Chem.−Eur. J.*, in press.

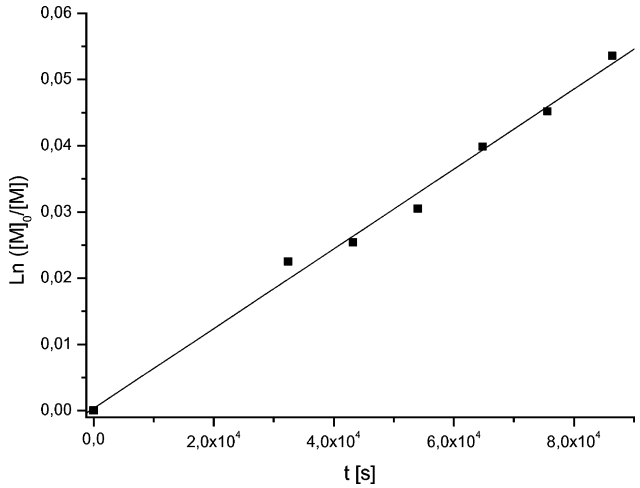

Figure 2. $\ln([M]_0/[M])$ as a function of time for the determination of K according to eq 1 (bulk polymerization at 105 °C using 1 mol % **13a** and 0.5 mol % of **18a**, $k_p = 7.1 \times 10^4$ M^{-1} s^{-1}).[14e]

was still well-controlled. The best result in terms of conversion and narrow PDI was obtained using 1 mol % nitroxide **18a** with respect to alkoxyamine **13a**.

Lacroix-Desmazes used eq 1 to determine the equilibrium rate constant K for the DEPN system (DEPN = *N*-*tert*-butyl-*N*-(1-diethylphosphono-2,2-dimethylpropyl) nitroxide).[14e] The $\ln([M]_0/[M])$ was plotted as a function of time at high concentration of added nitroxide. K was directly obtained from the slope (1.6×10^{-11} M at 105 °C). In analogy, we determined K for the *n*-butyl acrylate polymerization mediated by **18a** at 105 °C (Figure 2). A value of 4.2×10^{-12} M was extracted. This is in the same range as the K value obtained for the DEPN system, which is among the best noncyclic mediators known to date for the acrylate polymerization.[14e] From the K value and the experimentally determined k_d for the homolysis of **15** (3.1×10^{-4} s^{-1} at 105 °C, vide infra), k_c was readily calculated ($k_c = 1.4 \times 10^8$ M^{-1} s^{-1}).

Block Copolymerizations. We then investigated the formation of diblock copolymers using alkoxyamine **13a**. To this end, polystyrene or poly(*n*-butyl acrylate) prepared with alkoxyamine **13a** was used as a macroinitiator for the controlled styrene and acrylate polymerization. Poly(*n*-butyl acrylate)-*block*-(polystyrene) with a M_n of 45 000 g/mol and a narrow PDI (1.16) was obtained at 105 °C using a poly(*n*-butyl acrylate) macroinitiator (0.2 mol %, M_n = 10 800 g/mol, PDI = 1.13, 15 h, 54%). (Polystyrene)-*block*-poly(*n*-butyl acrylate) could be prepared using a polystyrene macroinitiator (0.2 mol %, M_n = 9500 g/mol, PDI = 1.12) at 105 °C for 24 h; however, conversion remained low (18%). The block copolymer was formed with a narrow PDI (PDI = 1.18, M_n = 23 000 g/mol). Problems in the formation of (polystyrene)-*block*-poly(*n*-butyl acrylate) using polystyrene macroinitiators have previously been reported for noncyclic alkoxyamines.[14a] In addition, we used a polystyrene macroinitiator (0.2 mol %, M_n = 9500 g/mol, PDI = 1.12) for the neat styrene polymerization (15 h, 105 °C, 56% conversion). Polystyrene with a narrow PDI (1.17) and increased M_n was obtained (M_n = 38 300 g/mol), documenting the living character of **13a**-mediated styrene polymerizations.

Kinetics of the C−O Bond Homolysis: EPR Experiments. The kinetic experiments were conducted in *tert*-butylbenzene at 407 K. Oxygen was used to scavenge the styryl radical, and the concentration of the released nitroxide was measured by EPR spectroscopy, as previously described.[5e,h,6,17] The experimental cleavage rate constant k_d was calculated using eq 3 (conversions up to 30%). The activation energy E_a was estimated from the rate constants using $A = 2.4 \times 10^{14}$ s^{-1}.[6]

$$\ln\left(\frac{[\text{nitroxide}]_\infty - [\text{nitroxide}]_t}{[\text{nitroxide}]_\infty}\right) = -k_d t \qquad (3)$$

As expected from the polymerization results described above, the smallest k_d values were obtained for the bis(esters) **7** and **8** (Table 3, entries 1−4). In agreement with the H-bonding concept,[6−8] larger rate constants were measured for alkoxyamines bearing free hydroxyl groups (**9**, **10**, entries 5−8). For the methyl and the ethyl series, the cis/trans-isomers showed similar rate constants. As expected for steric reasons, the ethyl-substituted alkoxyamines homolyze faster than the corresponding methyl compounds (compare entries 5 and 6 with 7 and 8). The importance of steric effects on the rate of the C−O bond cleavage has previously been discussed.[5h,6,13,15] In agreement with the polymerizations, large rate constants were measured for the silyloxy alkoxyamines **13a** and **13b** (entries 11 and 12). Probably, steric effects overcompensate the importance of H-bonding upon switching from **10a**,**b** to **13a**,**b**. Furthermore, there is no special Si effect: the bis(benzyl ether) **14** homolyzes as fast as the corresponding Si-substituted alkoxyamines **13** (compare entries 11 and 12 with 13). As comparison, for the Hawker-Braslau alkoxyamine **17** a higher E_a was measured for the homolysis under the same conditions (127.1 kJ/mol).[5h]

From the EPR experiments we could obtain important information on the stability of the various nitroxides (Figure 3). The EPR data of the new nitroxides were directly obtained from the kinetic experiments and are summarized in Table 3. For an alkoxyamine leading to a stable nitroxide, 90−95% of nitroxide was liberated during the EPR experiment. However, in EPR experiments on alkoxyamines leading to unstable nitroxides the concentration of the released nitroxide did not exceed 50% of the initial alkoxyamine concentration. As example, results of EPR experiments on the homolysis of the hydroxy-substituted alkoxyamine **10b** and the corresponding silyl-protected congener **13b** are presented in Figure 4. The concentration of liberated nitroxide **18b** derived from bis(silyl ether) **13b** reached the maximum after 175 s (about 93% nitroxide liberated). No decomposition of **18b** was noticed during the following 1250 s. However, a different picture was observed for the hydroxy derivative **10b**. The maximum concentration of **20b** (35%) was reached after 120 s.[18] After 120 s, the nitroxide concentration steadily decreased and then

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(17) (a) Kovtun, G. A.; Aleksandrov, A. L.; Golubev, V. A. *Bull. Acad. Chim. USSR, Div. Chem.* **1974**, *10*, 2115−2121. (b) Howard, J. A.; Tait, J. C. *J. Org. Chem.* **1978**, *43*, 4279−4283. (c) Grattan, D. W.; Carlsson, D. J.; Howard, J. A.; Wiles, D. M. *Can. J. Chem.* **1979**, *57*, 2834−2842.
(18) For the most efficient alkoxyamines, the nitroxide is liberated within the first 250 s. Our experimental setup allows us to reach the target temperature of the EPR sample in about 90 s, as independently determined. Therefore, for the systems fast homolyzing our k_d, E_a may be at the lower limit. To address this problem, we determined E_a for alkoxyamine **13a** at 378 and 363 K where temperature adjustment is not an issue. In fact, similar E_a's were calculated using 2.4×10^{14} s^{-1} as the *Arrhenius* factor (E_a (407 K) = 122.2 kJ/mol, E_a (378 K) = 122.4 kJ/mol, E_a (363 K) = 121.9 kJ/mol), indicating that the error is small using our experimental setup, even for the most efficient alkoxyamines. We thank a reviewer for drawing our attention to this problem.

Table 3. Results of the Kinetic Experiments and Decomposition Studies and EPR Data ($g = 2.006$, k_d and $k_{dec,nitroxide}$ Were Determined at 407 K; $k_{dec,alkoxyamine}$ Was Determined at 398 K)

entry	alkoxyamine	k_d (s^{-1})	E_a (kJ/mol)[a]	$k_{dec,\ alkoxyamine}$ (s^{-1})	nitroxide	$k_{dec,nitroxide}$ ($M^{-1}\ s^{-1}$)[b]	a_N (G)
1	**7a**	2.7×10^{-4}	138.5	3.6×10^{-6}	**5a**	stable	14.01
2	**7b**	6.6×10^{-4}	135.5	3.5×10^{-6}	**5b**	stable	14.01
3	**8a**	6.4×10^{-4}	135.6	7.1×10^{-6}	**6a**	stable	13.44
4	**8b**	9.9×10^{-4}	134.1	1.5×10^{-5}	**6b**	stable	13.58
5	**9a**	1.8×10^{-3}	132.1	4.0×10^{-5}	**19a**	25	14.87
6	**9b**	2.3×10^{-3}	131.3	1.7×10^{-5}	**19b**	60	14.66
7	**10a**	6.1×10^{-3}	128.0	8.2×10^{-5}	**20a**	110	15.23
8	**10b**	5.5×10^{-3}	128.4	8.9×10^{-5}	**20b**	135	15.30
9	**11**	1.3×10^{-3}	133.3	4.7×10^{-6}	**21**	stable	15.30
10	**12**	2.1×10^{-3}	131.6	3.8×10^{-6}	**22**	stable	15.16
11	**13a**	3.5×10^{-2}	122.2	1.9×10^{-5}	**18a**	stable	14.37
12	**13b**	2.1×10^{-2}	123.8	1.5×10^{-5}	**18b**	stable	14.16
13	**14**	1.9×10^{-2}	124.2	1.2×10^{-5}	**23**	stable	14.30
14	**15**	3.9×10^{-3}	129.5	1.9×10^{-5}	**18a**	stable	14.37

[a] E_a was calculated using $A = 2.4 \times 10^{14}\ s^{-1}$. [b] Stable indicates no significant decomposition of the nitroxide during the EPR experiment.

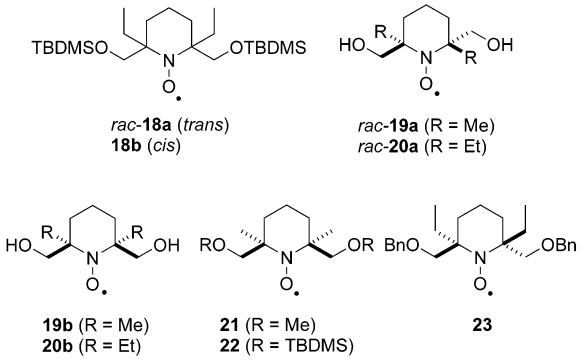


Figure 3. Several nitroxides studied.

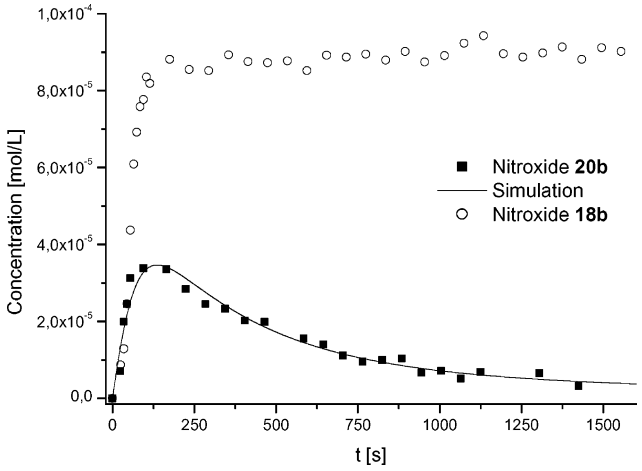
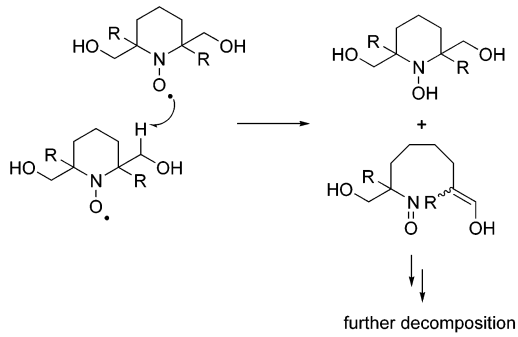


Figure 4. Evolution of the experimentally determined nitroxide concentration during homolysis of alkoxyamines **10b** and **13b** at 407 K. The line presents the concentration profile simulated using $5.5 \times 10^{-3}\ s^{-1}$ as rate constant for the initial C−O bond homolysis and 135 $M^{-1}\ s^{-1}$ as the rate constant for the bimolecular decomposition.

leveled off after 450 s. Similar nitroxide concentration profiles were obtained for the HO-substituted alkoxyamines **9a**,**b** and **10a**, indicating decomposition of the nitroxide during the EPR experiment (see the Supporting Information). We believe that the rate-determining step of the nitroxide decomposition is a bimolecular process, as suggested in Scheme 4.[19] On the basis

Scheme 4. Suggested Mechanism for the Decomposition of the HO-Functionalized Nitroxides.



of these considerations, the evolution of the nitroxide concentration during the EPR experiment can be described by the kinetic eq 4 ([Y] = nitroxide concentration; [I] = alkoxyamine concentration; k_d = rate constant for the C−O bond homolysis; $k_{dec,nitroxide}$ = rate constant for the bimolecular nitroxide decomposition).

$$d[Y]/dt = k_d[I] - 2k_{dec,nitroxide}[Y]^2 \qquad (4)$$

With the experimentally determined k_d, we simulated the evolution of the nitroxide concentration using Powersim, a program for modeling nonlinear dynamics.[20] The nitroxide concentration evolution ([**20b**]) for the homolysis experiment of **10b** could be perfectly modeled using the experimentally determined rate constant of $5.5 \times 10^{-3}\ s^{-1}$ for the initial C−O bond homolysis and 135 $M^{-1}\ s^{-1}$ as a rate constant for the bimolecular nitroxide decomposition (Figure 4, Table 3, entry 8).[21] In analogy, the rate constants for the decomposition of nitroxides **19a**,**b** and **20a** were estimated. For **19a** and **20a**, a nearly perfect fit of the experimental data was obtained with the simulation, whereas for **19b** the experimental data could not be ideally described using eq 4 (see the Supporting Information). To our knowledge, this is the first report where nitroxide decomposition rate constants and alkoxyamine C−O bond homolysis rate constants have been extracted from a single experiment.

(19) The decomposition of 4-oxo-TEMPO also occurs via a bimolecular process: (a) Murayama, T.; Yosshika, T. *Bull. Chem. Soc. Jpn.* **1969**, *42*, 2307−2309. (b) Rozantsev, E. G.; Sholle, V. D. *Synthesis* **1971**, 401−414. (c) Han, C. H.; Drache, M.; Baethge, H.; Schmidt-Naake, G. *Macromol. Chem. Phys.* **1999**, *200*, 1779−1783.

(20) Powersim Software Home Page. http://www.powersim.com (Nov 2003).

(21) The kinetic experiment with alkoxyamine **10b** was repeated using different concentrations (1×10^{-4}, 1.25×10^{-4}, 1.5×10^{-4}, and 2×10^{-4} M). Similar nitroxide decomposition rate constants were extracted from these experiments.

From these EPR experiments we suggest that the OH-bearing nitroxides decompose via a self-reaction (bimolecular process) and are therefore not sufficiently stable for NMP. Two questions remain to be answered: Why do OH groups accelerate the self-reaction and why are the O-protected alkoxyamines stable? We believe that intermolecular H-bonding between two nitroxides leads to a preorganization which in turn accelerates the decomposition. Indeed, in the X-ray structure of the cis-alkoxyamines **9b** and **10b** intermolecular H-bonding can be identified.[12]

Thermal Stability of the Alkoxyamines. The thermal decomposition of a polymeric alkoxyamine leading to a terminally unsaturated polymer and the corresponding hydroxylamine is an important side reaction in NMP. This process can occur via a β-hydrogen atom transfer from the transient polymer radical to the nitroxide or via a nonradical direct ionic elimination.[7c,22] We studied the thermal decomposition of the various alkoxyamines to provide styrene and the corresponding hydroxylamine. The alkoxyamine was dissolved in a NMR tube in perdeutero *p*-xylene (0.03 to 0.06 M). The degassed sample was heated to 398 K within the cavity of a 500 MHz ^{1}H NMR spectrometer, and the decomposition was followed by monitoring the decrease of the alkoxyamine signals as well as the increase of the styrene resonances. The signal of the benzylic H atom at around 4.7 was used to estimate the alkoxyamine concentration. Similar experiments have previously been described.[7c,22,23] Spectra were recorded every 5 min. The decomposition rate constants ($k_{dec,alkoxyamine}$) for the various alkoxyamines were determined using eq 5 ([S] = styrene concentration; [A] = alkoxyamine concentration) and are summarized in Table 3.[7c]

$$\ln([S]/[A] + 1) = k_{dec,alkoxyamine}\, t \qquad (5)$$

Smallest $k_{dec,alkoxyamine}$ values were measured for the ester-functionalized alkoxyamines (Table 3, entries 1−4). As expected from the EPR experiments, significantly faster decompositions were obtained for the hydroxy-modified TEMPO derivatives **9a**,**b** and **10a**,**b**. In the ethyl series, both isomers decomposed at similar rates; however, for the methyl-substituted alkoxyamines **9a**,**b** the trans-isomer is about 2 times less stable than the cis-isomer (entries 5−8). This agrees with the styrene polymerization results where the cis-isomer **9b** provided better results than the trans-alkoxyamine **9a**. The ethyl-substituted alkoxyamines decompose 2−5 times faster than the methyl compounds. Thus, the introduction of hydroxy functions and sterically demanding ethyl groups leads to the desired larger C−O bond homolysis rate constants; however, the stability of the alkoxyamines simultaneously decreases. The moderate stability of the alkoxyamine **10b** explains why polymerizations leading to polymers with molecular weights above 40 000 are not well-controlled. *For an ideal alkoxyamine initiator/mediator homolysis should be fast, and at the same time decomposition must be slow*. This is difficult to achieve because assuming that part of the decomposition occurs via disproportionation, the decomposition rate constant must correlate with the homolysis rate constant. However, for our Si-substituted alkoxyamines **13a**,**b**, homolysis is about 3 times faster and decomposition is about 5 times slower than for the corresponding hydroxy derivatives **10a**,**b**. This explains why **13a**,**b** are so efficient for NMP. The bis(benzyl ether) **14** decomposes with a similar rate constant as the TBDMS-protected alkoxyamines (entry 13), again showing that the Si-substituent has no special effect on the kinetics of the corresponding alkoxyamine.

Conclusions

We developed a straightforward synthesis for the preparation of a series of new bulky TEMPO styryl derivatives bearing α-hydroxymethyl, α-silyloxymethyl, or ethyl groups instead of methyl groups at positions 2 and 6. The silyloxy-substituted TEMPO derivatives have been shown to be highly efficient mediators for the controlled/living polymerization of styrene and *n*-butyl acrylate. Diblock copolymers with narrow PDIs have successfully been prepared with the silylated alkoxyamines. We have shown that controlled polymerization can be conducted at 90 °C. The new alkoxyamines belong to the most efficient initiator/mediators for the controlled acrylate polymerization known to date.[1c,14,15] Kinetic EPR experiments and ^{1}H NMR alkoxyamine decomposition studies have been applied to explain the polymerization results.

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Supporting Information Available: Experimental procedures and analytical data of all new compounds (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(23) The thermal stability experiments are not really a mimic of NMP conditions since no monomer is present. Decomposition during polymerization is therefore far slower.