ChemPlusChem

A Multidisciplinary Journal Centering on Chemistry



European Chemical Societies Publishing

Accepted Article

Title: The Kinetics of 1,3-Dipolar Cycloaddition of Vinyl Monomers to 2,2,5,5-Tetramethyl-3-imidazoline-3-oxides

Authors: Sergey A. Cherkasov, Anastasiya D. Semikina, Polina M. Kaletina, Yulia F. Polienko, Denis A. Morozov, Alexander M. Maksimov, Igor A. Kirilyuk, Elena G. Bagryanskaya, and Dmitriy Parkhomenko

This manuscript has been accepted after peer review and appears as an Accepted Article online prior to editing, proofing, and formal publication of the final Version of Record (VoR). This work is currently citable by using the Digital Object Identifier (DOI) given below. The VoR will be published online in Early View as soon as possible and may be different to this Accepted Article as a result of editing. Readers should obtain the VoR from the journal website shown below when it is published to ensure accuracy of information. The authors are responsible for the content of this Accepted Article.

To be cited as: ChemPlusChem 10.1002/cplu.202100266

Link to VoR: https://doi.org/10.1002/cplu.202100266

WILEY-VCH

The Kinetics of 1,3-Dipolar Cycloaddition of Vinyl Monomers to 2,2,5,5-Tetramethyl-3-imidazoline-3-oxides

Sergey A. Cherkasov^{a,b}, Anastasiya D. Semikina^{a,b}, Polina M. Kaletina^{a,b}, Yulia F. Polienko^a, Denis A. Morozov^a, Alexander M. Maksimov^a, Igor A. Kirilyuk^a, Elena G. Bagryanskaya^a, Dmitriy A. Parkhomenko^a*

[a] S.A. Cherkasov, A.D. Semikina, P.M. Kaletina, Dr. Yu.F. Polienko, Dr. D.A. Morozov, Dr. A.M. Maksimov, Dr. I.A. Kirilyuk, Prof. E.G. Bagryanskaya, Dr. D.A. Parkhomenko N.N. Vorozhtsov Novosibirsk Institute of Organic Chemistry SB RAS

- 9 Lavrentiev Ave., Novosibirsk 630090, Russia E-mail: parkhomenko@nioch.nsc.ru
- [b] S.A. Cherkasov, A.D. Semikina, P.M. Kaletina

Novosibirsk State University 1 Pirogova str., Novosibirsk 630090, Russia

Supporting information for this article is given via a link at the end of the document.

Abstract: In our previous work [Edeleva et al. Chem. Commun. 2019, 55, 190-193], we proposed a versatile approach to the activation of the homolysis of an aldonitrone group-containing alkoxyamine by 1,3-dipolar cycloaddition to a vinyl monomer. Both nitroxide- and alkoxyamine-containing aldonitrones were found to be capable of reacting with the activated alkenes. In the present study, the kinetics of these reactions with 11 different vinyl monomers were investigated using EPR and NMR spectroscopy, and apparent activation energies as well as pre-exponential factors were determined. The influence of monomer structure on the rate of the 1,3-dipolar cycloaddition is discussed. For the vinyl monomers typically used in nitroxide mediated polymerization (styrene, methyl methacrylate) the rate coefficient of cycloaddition to the nitroxide is around $k(353K) \sim 4.10^{-4} \text{ L mol}^{-1} \text{ s}^{-1}$, whereas for *n*-butyl acrylate and methyl vinyl ketone we observed the fastest cycloaddition reaction with $k(353K) = 8 \cdot 10^{-3}$ and $4 \cdot 10^{-2}$ L mol⁻¹ s⁻¹ respectively.

Introduction

Nitroxide-mediated polymerization (NMP) is a versatile method^{[1-} ^{11]} enabling the synthesis of narrowly dispersed polymers and copolymers with ordered architecture and composition. Since the pioneering studies of Solomon, [12-13] numerous researchers have contributed to further development of NMP with the aim of technological improvement for widespread use.^[9] The rate of alkoxyamine homolysis is the key factor that determines NMP success (e.g., the time needed for effective monomer conversion and polymer dispersity). A higher rate of alkoxyamine homolysis allows for polymerization at lower temperatures and the achievement of better control over the molar mass of the polymer. On the other hand, the synthesis of thermally unstable alkoxyamines poses problems with their storage and transportation, e.g., gradual decomposition needs to be prevented. A possible solution involves the development of alkoxyamines with a tunable decomposition rate. Thus, the current trends in NMP include designing approaches to changing the alkoxyamine homolysis rate using external factors.[14-17]

Several methods are presented in the literature and involve protonation, $^{[18-20]}$ complexation with metals, $^{[21-24]}$ or chemical *in*

situ transformation.^[25-26] Recently, we presented a new technique for the activation of alkoxyamine homolysis by 1,3-dipolar cycloaddition of a monomer to a cyclic aldonitrone-derived alkoxyamine of the 3-imidazoline-3-oxide series (Scheme 1).^[26]



Scheme 1. The 1,3-dipolar cycloaddition reaction of monomers with 2,2,5,5-tetramethyl-3-imidazoline-3-oxides.^[27]

The reaction of the 1,3-dipolar cycloaddition of vinyl monomers to 3-imidazoline-3-oxides was the subject of several studies more than 30 years ago.^[27-28] This reaction was shown to afford predominantly 2-substituted tetrahydroimidazo[1,5-b]isoxazoles (Scheme 1). Nonetheless, these papers provide neither the data on the rates of 1,3-dipolar cycloaddition nor a quantitative comparison of reactivity of different dipolarophiles. Furthermore, cost-effective implementation of NMP is based on model-guided process design, which requires a complete set of temperaturedependent rate constants of alkoxyamine homolysis as well as 1,3-dipolar cycloaddition to nitroxides and alkoxyamines.^[29-30]

In the present study, we performed kinetic measurements using a cost-effective approach, EPR spectroscopy. The kinetic data were processed, and the rate constants for the cycloaddition were determined for 11 monomers (see Chart 1). The use of the diverse monomers should elucidate the opportunities for the application of the 1,3-dipolar cycloaddition method to NMP. Aside from 10 commercially available monomers of different classes, we synthesized a perfluorinated monomer: 4perfluorotolyl vinyl sulfide (Chart 1). It should be noted that 4perfluorinated monomers and the corresponding (co-)polymers receive much attention nowadays due to their enhanced properties, e.g., hydrophobicity and ionizing-radiation resistance.[31-32]

During the polymerization, both nitroxide **1** and alkoxyamine **2** can react with vinyl monomers to form cycloadducts. Therefore, in addition, kinetics of the reaction of the corresponding

alkoxyamine, 2, with each of four highly active dipolarophiles (Scheme 1) were measured and compared with those of nitroxide **1**.



Chart 1. Structures of the monomers, nitroxide, and alkoxyamine that were subjected to the 1,3-dipolar cycloaddition reaction.

Results and Discussion

1,3-Dipolar cycloaddition of monomers to nitroxide 1

EPR spectroscopy is commonly used to investigate the kinetics and mechanisms of radical reactions. To monitor the evolution of a reagent and/or product concentration, which describes the kinetics of the reaction, EPR spectra of the reagents and products must be sufficiently different to be distinguished from each other.

The 1,3-dipolar cycloaddition of vinyl monomers to 1 does not meet the criterion of the sufficient difference in EPR spectra because the structures of the reagent and product are quite similar. The difference in the EPR spectra of 1 and of the cycloadduct is due to the nitrogen hyperfine coupling constant (a_N), and $\Delta a_N \approx 0.03$ mT for the reagent and product, while the width of the EPR line is fivefold greater and is ~0.15 mT.^[26] Thus. EPR spectra of the initial and formed nitroxides overlap, and only three EPR lines are observed with an apparent coupling constant $(a_{N,app})$ that changes during the reaction and depends on the ratio between the concentrations of the initial and formed nitroxide.

A model for EPR investigation of the reaction kinetics

To develop a method for determining the rate constant by means of the evolution of the apparent coupling constant (a_{N.app}), we performed the following model validation via a line shape analysis of a cumulative EPR spectrum. We selected two

nitroxides, N1 and N2, with identical g-factors (which determine the position of the central line) and identical linewidths but slightly different hyperfine coupling constants a_1 and a_2 ($\Delta a = a_2$ – a₁ << a₁, a₂).

In general, lines in EPR spectra have a Voigt profile, which is a convolution of Gaussian and Lorentzian profiles. For the sake of simplicity, we performed subsequent analyses assuming a Gaussian profile for the EPR spectrum lines. We defined the position of the central line in the EPR spectra as x = 0; therefore, the position of the high field line represents coupling constant a_N. The Gaussian profile is given by

$$f = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(x-a)^2}{2\sigma^2}}$$

J

where *a* is the mean, and σ is dispersion and in case of EPR is equal to lwpp/2, where lwpp is peak-to-peak line width.

Because in an EPR experiment, a derivative of absorption is obtained, the shape of the EPR line is described as

$$F' = -\frac{x-a}{\sqrt{2\pi\sigma^3}}e^{\frac{(x-a)^2}{2\sigma^2}}$$
(1)

The cumulative spectrum of two species N_1 and N_2 with molar fractions c and (1 - c) has the following line shape:

$$f'_{x} = cf'_{a_{1}} + (1-c)f'_{a_{2}} = -c\frac{x-a_{1}}{\sqrt{2\pi\sigma^{3}}}e^{-\frac{(x-a_{1})^{2}}{2\sigma^{2}}} - (1-c)\frac{x-a_{2}}{\sqrt{2\pi\sigma^{3}}}e^{-\frac{(x-a_{2})^{2}}{2\sigma^{2}}}$$
(2)

Assuming $\Delta a = a_2 - a_1 << \sigma$, eq. (2) can be rewritten as eq. (3), which gives the EPR line shape in case of a slight difference in the hyperfine coupling constants.

$$f_{z}' \approx -c \frac{x - a_{1}}{\sqrt{2\pi\sigma^{3}}} e^{\frac{(x - a_{1})^{2}}{2\sigma^{2}}} - (1 - c) \frac{x - a_{2}}{\sqrt{2\pi\sigma^{3}}} e^{\frac{(x - a_{1})^{2}}{2\sigma^{2}}} =$$

$$= -\frac{x - ca_{1} - (1 - c)a_{2}}{\sqrt{2\pi\sigma^{3}}} e^{\frac{(x - a_{1})^{2}}{2\sigma^{2}}} = -\frac{x - a_{2} + c\Delta a}{\sqrt{2\pi\sigma^{3}}} e^{\frac{(x - a_{1})^{2}}{2\sigma^{2}}} =$$

$$= -\frac{x - a_{app}}{\sqrt{2\pi\sigma^{3}}} e^{\frac{(x - a_{1})^{2}}{2\sigma^{3}}}$$
where

$$a_{ann}(t) = a_2 - c(t)\Delta d$$

Equation (4) shows that the evolution of the apparent hyperfine coupling constant represents the kinetics of the reaction if Δa_N $<< \sigma$. To validate eq. (4), we assume a unimolecular reaction of nitroxide N₁ transformation into N₂ with rate coefficient k_1 : $N_1 \xrightarrow{k_1} N_2$ (5)

$$N_1 \rightarrow$$

If the initial concentration of N_1 is C_0 , then the evolution of the nitroxides' concentrations can be expressed as

 $[N_1] = C_0 \exp(-k_1 t), [N_2] = C_0 (1 - \exp(-k_1 t))$ (6) Integral intensity of the EPR lines is proportional to concentrations of the radicals. Accordingly, the cumulative spectrum can be calculated as the sum of individual spectra weighted by the concentrations:

$$S(t) = [N_1] \times S_1 + [N_2] \times S_2$$

For the validation of the above-mentioned assumption, we calculated cumulative EPR spectra S(t) (eq. (7)) by means of the EasySpin toolbox^[33] for the N₁ transformation reaction with the following parameters: $g_1 = g_2 = 2$, $a_{N1} = 1.4$ mT, $a_{N2} = 1.43$ mT, and Gaussian line broadening with different lwpp values (0.05, 0.1, 0.15, and 0.3 mT). Rate coefficient k_1 was set to 3 \times $10^{-3}s^{-1}$, which is in the typical range of reported rate coefficients, and the initial concentration of N1 was set to 1 M for simplicity.

(3)

(4)

(7)

10.1002/cplu.202100266

WILEY-VCH



Figure 1. (Left) The calculated dependence of $a_{N,app}$ on time during the transformation of N₁ (a_{N1} = 1.40 mT) to N₂ (a_{N2} = 1.43) with rate coefficient $k_1 = 3 \times 10^{-3} s^{-1}$ for various lwpp values; black: lwpp = 0.05 mT, red: lwpp = 0.1 mT, and magenta: lwpp = 0.3 mT. (Right) The calculated EPR spectrum of nitroxide N₁; arrows show the determination of $a_{N,app}$.

We determined apparent coupling constant $a_{N,app}$ over time as a distance between low-field and center-field lines. In the course of the reaction, $a_{N,app}$ changed from 1.40 to 1.43 mT owing to the transformation of N₁ to N₂.

The calculation results for various lwpp values are presented in Figure 1. The solid curve in Figure 1 was obtained using eq. (4). If the difference in hyperfine coupling constants of N₁ and N₂ (Δa_N) is nearly equal to lwpp (black symbols, Figure 1), then the evolution of $a_{N,app}$ only poorly reproduces the reaction kinetics. By contrast, if lwpp > $3\Delta a_N$, then $a_{N,app}$ as a function of time describes the reaction kinetics adequately.

For the data-processing procedure, we fitted the function obtained at $a_{N,app}(t)$ for different lwpp values using the following exponential equation:

$$a_{N,app}(t) = a_{N2} - \Delta a_N e^{-\lambda t}$$
(8)

Table 1 presents the rate constant k_{obs} determined in the models with various lwpp values. As readers can see in Table 1, the accuracy of the rate constant determination increases with the increasing lwpp value. For lwpp > 0.15 mT, which is typical for nitroxides, the obtained *k* effectively reproduces the model value of 3×10^{-3} s⁻¹ with 1–2% error.

Although the Gaussian profile allows us to present the abovementioned approach in the simplest way, broad EPR lines of the Gaussian shape can rarely be seen in experiments. We performed the same numerical analysis – as presented above for the Gaussian profile – on other broadening types commonly seen in experiments: Lorentzian, Voight, and overmodulation of a narrow line (see Supporting Information [SI] for details). As indicated in Table 1, regardless of the broadening type used, the obtained k effectively reproduces the model value starting from a peak-to-peak line width of 0.1 mT.

 Table 1. The output of the model for the determination of the apparent rate

 constant for chemical reaction (5) depending on peak-to-peak line width (used as input) for different line-broadening types

hump (mT)	<i>k</i> _{obs} , [10 ⁻³ s ⁻¹]				
iwpp, [mi1]	Gaussian	Lorentzian	Voight	Overmodulation	
0.05	3.52	3.62	3.62	3.6	
0.1	3.13	3.18	3.16	3.07	
0.15	3.06	3.08	3.07	2.98	
0.3	3.01	3.03	3.02	2.99	

Experimental determination of a temperature-dependent kinetic rate constant

The typical kinetic plots obtained after the processing of the experimental data by the above-mentioned procedure are presented in Figure 2, and all the results are summarized in Table 2. The kinetic data obtained by EPR were processed according to eq. (8). Activation energies and pre-exponential factors were obtained via the Arrhenius equation for the rate coefficient:

$$k(t) = A e^{\overline{RT}}$$
(9)

Εc

10.1002/cplu.202100266

WILEY-VCH



Figure 2. Kinetics of the evolution of the apparent hyperfine constant (symbols) and the fit to eq. (8) (solid curves) at different temperatures (see the figure for the values) for the reaction of 1,3-dipolar cycloaddition of 1-vinyl imidazole to nitroxide (left) and Arrhenius plots of this reaction for all the studied monomers (right).

The obtained activation energies of the 1,3-cycloaddition reaction of nitroxide are in the ~47-70 kJ/mol range, in good agreement with the data presented in the literature for cyclic aldonitrones.^[34-35] The rate of 1,3-dipolar cycloaddition is often related to electron-acceptor properties of a substituent in a vinylic group of olefins.[36-39] We selected the temperature of 353K, which is typical for an NMP process, and compared the rate constants of the cycloaddition to nitroxide. As one can see in Table 2, the fastest monomers in the context of the 1,3-dipolar cycloaddition to nitroxide are those that have a strong electron acceptor in the vinyl moiety, e.g., a carbonyl or nitrile group. This is true for methyl vinyl ketone, n-butyl acrylate, Nisopropylacrylamide (NIPAM), and acrylonitrile. The much lower rate constant of methyl methacrylate in comparison with n-butyl acrylate is due to the methyl substituent instead of hydrogen at the α position toward the acrylate group; this substituent causes greater steric hindrance of the reactive center. The ether group is much more electron-donating (according to the resonance effect) than electron-withdrawing on an inductive one; therefore, n-butyl vinyl ether and vinyl acetate yielded lower rates of the 1,3-dipolar cycloaddition reaction. Besides, aromatic groups are characterized by an electron-donating resonance effect, which was reflected in a lower reaction rate in the cases of styrene, 4vinylpyridine, 1-vinylimidazole, and 4-perfluorotolyl vinyl sulfide. It should be noted that for a fluorine-substituted monomer, the highest rate of 1,3-dipolar cycloaddition was observed in comparison with other aromatic π -conjugated monomers. This fact further confirms the assumption that electron acceptor properties of a substituent in a vinylic group of a monomer determine its rate of 1,3-dipolar cycloaddition to aldonitronecontaining compounds.

1,3-Dipolar cycloaddition to alkoxyamine 2

¹H NMR measurement of the 1,3-dipolar cycloaddition rate constant toward alkoxyamine **2** was performed for the monomers with the highest rate of cycloaddition to nitroxide, namely methyl vinyl ketone, *n*-butyl acrylate, acrylonitrile, and NIPAM. To avoid possible thermal decomposition of the alkoxyamine, all experiments were carried out at 328 K (see SI, section 5).

Table 2. Activation energies and pre-exponential factors for the 1,3-dipolar cycloaddition reaction of different monomers to 1 and 2 as well as the *k* value at 353 and 328 K.

		2			
Monomer	<i>E</i> a, [kJ/mol]	<i>A</i> , [10 ⁵ M ⁻¹ s ⁻¹]	<i>k</i> _{353К} , ^[а] [10 ⁻⁴ М ⁻¹ s ⁻¹]	<i>k</i> _{328K} , ^[b] [10 ⁻⁴ M ⁻¹ s ⁻¹]	<i>k</i> _{328K} , ^[a] [10 ⁻⁴ M ⁻¹ s ⁻¹]
methyl vinyl ketone	47	2.8	400	110	96
n-butyl acrylate	55	12	80	19	19
NIPAM	63	47	30	5.4	5.3
acrylonitrile	53	1.6	23	5.5	7.3
4-perfluorotolyl vinyl sulfide	59	3.3	6.6	1.5	-
4-vinylpyridine	63	12	5.9	1.2	-
methyl methacrylate	59	3.1	5.4	1.1	-
styrene	68	32	2.9	0.47	-
<i>n</i> -butyl vinyl ether	65	12	2.5	0.49	-
1-vinylimidazole	69	29	1.6	0.27	-
vinyl acetate	62	1.7	1.1	0.22	-

[a] Measured experimentally; [b] calculated using Arrhenius parameters.

The reaction of **2** with *n*-butyl acrylate, acrylonitrile, or NIPAM was conducted with an excess of the monomer, so that the consumption of **2** obeyed pseudo-first-order kinetics (Figure 3b). Due to the high cycloaddition rate observed for methyl vinyl ketone, the reaction of the latter with **2** was carried out at a 1:1 monomer-to-alkoxyamine ratio. In this case, reagent consumption conformed to second-order kinetics (Figure 3c). The obtained rate constants (Table 2) are close to those for the analogous reaction with the corresponding nitroxide, **1**.

WILEY-VCH



Figure 3. NMR spectra of a mixture of NIPAM and **2** before (bottom) and after (top) the cycloaddition reaction (a), and the kinetics of 1,3-dipolar cycloaddition of *n*-butyl acrylate (black), acrylonitrile (red), NIPAM (blue) (b), or methyl vinyl ketone (c) to **2** at 328 K (solid curves: approximation; inset: linearization).

It should be noted that although one could expect an aldonitrone proton signal (e) (see Figure 3a) to be the best option for monitoring the 1,3-dipolar cycloaddition kinetics, it overlapped in most cases with the signals of vinylic protons. For example, the NMR spectra of the reaction mixture of 2 and NIPAM before and after 300 min of incubation at 328 K are displayed in Figure 3a. On the other hand, growing signals e' and a' of the forming cycloadduct have a low signal-to-noise ratio because their multiplet structures yield low-quality kinetic curves with high uncertainty of approximation. Fortunately, the proton of the phenylacetic moiety (j) was found to be sensitive to the reaction despite being far outside of the reaction center. Recently, it was demonstrated that this proton is located at 5.23-5.25 ppm for a styrene cycloadduct but at 5.13-5.14 ppm for the initial alkoxyamine (see SI in ref. [26]). Consequently, for the measurements of reaction kinetics we chose the line at 5.1 ppm.

Conclusion

A detailed study of 1,3-dipolar cycloaddition reactions of 11 different vinyl monomers to 3-imidazoline-3-oxide-1-oxyl was conducted by EPR spectroscopy. An effective approach was developed for the measurement of the rate constants in the case of similar values of hyperfine coupling constants between the initial and newly formed nitroxides and was applied to the studied systems. It was shown that the rate constants of the 1,3-dipolar cycloaddition to the nitroxide vary within one order of magnitude depending on the structure of the monomers. It was found that the rate constants for the 1,3-dipolar cycloaddition to an alkoxyamine at 328 K are close to the ones for the addition to the nitroxide. Methyl vinyl ketone manifested the highest rates of cycloaddition to both the alkoxyamine and nitroxide. All the above-mentioned details of the mechanism should help to further optimize the NMP of various monomers.

Experimental Section

Chemicals

The following substances were used as received: toluene (Reachem, 99.9%), NIPAM (Sigma-Aldrich, 99%), *n*-butyl acrylate (Sigma-Aldrich, 99%), *n*-butyl vinyl ether (Sigma-Aldrich, 98%), methyl methacrylate (Acros Organics, 99%), acrylonitrile (Sigma-Aldrich, 99%), vinyl acetate (Sigma-Aldrich, 99%), and 1-vinylimidazole (Sigma-Aldrich, 99%). Styrene (Sigma-Aldrich, 99%) and 4-vinylpyridine (Acros Organics, 95%) were additionally purified by distillation. Nitroxide **1** was synthesized as described in ref. [40], and alkoxyamine **2** was obtained according to ref. [26]. Monomer **3** was synthesized as described below.

Measurements of EPR kinetics of 1,3-dipolar cycloaddition of a monomer to 1 $\,$

A sample of a reaction mixture containing the nitroxide and a monomer in toluene in a glass capillary was placed in an oil or water thermostat preheated to a desired temperature and was incubated for selected periods (2–60 min depending on the conversion rate). The concentration of the nitroxide was 0.02 mM, and the concentration of monomers was 1 M except for *n*-butyl acrylate and methyl vinyl ketone (0.5 and 0.1 M, respectively). EPR spectra were recorded on a Bruker Elexsys E540 spectrometer at room temperature for various incubation periods. The parameters of EPR measurements were as follows: mw frequency = 9.87

ChemPlusChem

ARTICLE

GHz, mw power = 2 mW, modulation amplitude = 0.3 mT, the number of points = 1024, conversion time = 20 ms, and sweep width = 6 mT.

NMR measurement of the kinetics for the 1,3-dipolar cycloaddition of monomers to alkoxyamine 2

A pseudo-two-dimensional ¹H NMR spectrum was recorded using a Bruker Avance 200 spectrometer equipped with a BVT 3300 temperature control unit. The first axis was ¹H NMR spectra, and the second axis was time. The concentration of **2** was 30 mM, and the concentration of a monomer was 0.4 M, except for methyl vinyl ketone (30 mM). Toluene-d₈ served as a solvent (0.525 mL, δ H 2.13 ppm). All experiments were conducted at 328 K. Kinetic data were obtained as a dependency of signal integral intensity on time. For measurement purposes, the resonance of α -H of the ester group was selected (δ = 5.1 ppm) due to the absence of overlapping signals. Recently, it was reported that this signal changes its position during the reaction under study (see SI in ref. [26]). This signal is also affected by the homolysis reaction, but at 328 K, homolysis is negligible.

Synthesis

The synthesis of 4-perfluorotolyl vinyl sulfide [1-(ethenylsulfanyl)-2,3,5,6-tetrafluoro-4-(trifluoromethyl)benzene] was performed in two steps with isolation and characterization of an intermediate product,

1-[(2-bromoethyl)sulfanyl]-2,3,5,6-tetrafluoro-4-(trifluoromethyl)benzene, to ensure high purity of the target compound. Both the intermediate and target compounds were characterized via ¹H, ¹³C, and ¹⁹F NMR. The NMR spectra were recorded on Bruker AV-300 [300.13 (¹H) MHz, 282.40 (¹⁹F) MHz] or Bruker DRX-500 [125.76 (¹³C) MHz] spectrometers for solutions of the samples in CDCl₃. NMR coupling constants (J) were measured in Hertz. IR spectra were recorded by means of a Bruker Vector 22 spectrophotometer from films for liquid samples. UV spectra were obtained on a Hewlett Packard 8453 spectrophotometer. Molecular mass and elemental composition were determined from high-resolution mass spectra acquired on a Thermo Electron Corporation DFS instrument (ionizing electron energy: 70 eV).



Scheme 2. The synthesis of 4-perfluorotolyl vinyl sulfide, which served as a monomer.

1-[(2-Bromoethyl)sulfanyl]-2,3,5,6-tetrafluoro-4-(trifluoromethyl)benz ene (3)

To a solution of trifluoromethyl-tetrafluorobenzenethiol (52.86 g, 211.34 mmol) in acetonitrile (200 mL), a solution of sodium methoxide (4.2 mol/L) in methanol (55 mL) was added. The resulting thiolate solution was added with stirring to a mixture of 1,2-dibromoethane (665.83 g, 3544.25 mmol) and acetonitrile (290 mL). The resulting mixture was stirred at room temperature for 3 h and then incubated overnight. Dry HBr was passed through the reaction mass to neutralize the excess of sodium methoxide. The NaBr precipitate was filtered off, and the excess of 1.2-dibromoethane was distilled off from the filtrate, first under normal pressure and then in vacuum (in a water-jet pump). For the indicated reagents' quantities, the amount of distilled-off bromoethane was 520 g. The residue, 66.61 g, was then distilled in vacuum (3–4 mmHg) to obtain 51.51 g (68%) of the target compound.

Colorless liquid, b.p 100–103°C/3 mmHg. ¹H NMR (300.13 MHz, CDCl₃): δ H = 3.51–3.43 (m, 2H; CH₂), 3.43–3.35 (m, 2H; CH₂) ppm. ¹³C NMR

(125.76 MHz, CDCl₃): δC = 147.1 (dm, $^{1}J_{CF}$ = 247 Hz; C-(2,6)), 144.3 (ddm, $^{1}J_{CF}$ = 262, $^{2}J_{CF}$ = 18 Hz; C-(3,5)), 120.8 (q, $^{1}J_{CF}$ = 275 Hz; CF₃), 119.0 (t, $^{2}J_{CF}$ = 20 Hz; C-(1)), 109.6 (qtd, $^{2}J_{CF}$ = 35 Hz, $^{2}J_{CF}$ = 13 Hz, $^{3}J_{CF}$ \approx 4 Hz; C-(4)), 35.8 (t, $^{4}J_{CF}$ = 3 Hz; C_a), 29.5 (d, $^{5}J_{CF}$ \approx 1.5 Hz; C_β). ^{19}F NMR (282.36 MHz, CDCl₃, C₆F₆ (δ = -162.9)): δF -57.5 (t, $^{4}J_{FF}$ = 22, 3F; CF₃), -132.7 to -132.9 (m, 2F; F-(2,6)), -140.4 to -140.9 (m, 2F; F-(3,5)) ppm. IR (film, v_{max}, cm⁻¹): 2972(vw) (CH), 1645(s) (ArF), 1608(w), 1479(vs) (ArF), 1429(m), 1398(m), 1329(vs) (CF3), 1259(m), 1184(s), 1149(s) (CF3), 1059(w), 982(vs) (CF), 949(m), 831(s) (C-S), 715(s) (C-S), 624(m), (CBr) 571(vw), 509(vw), 478(vw), 441(vw). UV (hexane, λ_{max} , nm (log ϵ)): 224 (3.75), 276 (3.88).MS (70 eV) m/z calcd for CgH4BFF7S: C 30.27; H 1.13; Br 22.38; F 37.24; S 8.98; found: C 30.06; H 1.11; Br 22.08; F 37.78; S 8.75.

1-(Ethenylsulfanyl)-2,3,5,6-tetrafluoro-4-(trifluoromethyl)benzene (4perfluorotolyl vinyl sulfide)

To a solution of 1-[(2-bromoethyl)sulfanyl]-2,3,5,6-tetrafluoro-4-(trifluoromethyl)benzene (4.45 g, 12.46 mmol) in dioxane (40 mL), 9.40 g of a 40% aqueous NaOH solution (94.00 mmol) was added. Into the resulting two-phase system, 2.01 g (9.56 mmol) of tetraethylammonium bromide was introduced with stirring. The resultant mixture was next stirred at 50°C, with monitoring of the reaction progress via ¹⁹F NMR until the starting compound fully reacted. The reaction ended in 48 h. After cooling to room temperature, the product mixture was poured into 400 mL of water and allowed to settle. The bottom organic layer was separated and placed in 11 mL of ca. 10% HCI, shaken, and allowed to settle again. In this way, 2.97 g (86%) of the crude target product was isolated. The resulting product was dried over CaCl₂ and then sublimated in the presence of hydroquinone at 80-82°C under a pressure of 0.5 mmHg. Thus, 2.41 g of the pure target compound was obtained.

Colorless liquid. ¹H NMR (300.13 MHz, CDCl₃): δ H = 6.44 (ddt, ³J_{HH} = 16.5, ³J_{HH} = 9.4, ⁵J_{HF} = 1.3, 1H; H_α), 5.51 (d, ³J_{HH} = 9.4, 1H; H_{cls}), 5.48 (d, ³J_{HH} = 16.5, 1H; H_{trans}). ¹³C NMR (125.76 MHz, CDCl₃): δ C = 146.5 (dm, ¹J_{CF} = 248 Hz; C-(2,6)), 144.4 (ddm, ¹J_{CF} = 262, ²J_{CF} = 17 Hz; C-(3,5)), 126.9 (t, ⁴J_{CF} = 3 Hz; C_α), 121.0 (q, ¹J_{CF} = 274 Hz; CF₃), 119.2 (s; C_β), 119.0 (t, ²J_{CF} = 19 Hz; C-(1)), 109.6 (qt, ²J_{CF} = 35 Hz, ²J_{CF} = 13 Hz; C-(4)) ppm. ¹⁹F NMR (282.36 MHz, CDCl₃, C₆F₆ (δ = -162.9)): δ F -57.5 (t, ⁴J_{FF} = 22, 3F; CF₃), -133.0 to -33.2 (m, 2F; F-(2,6)), -140.8 to -141.2 (m, 2F; F-(3,5)) ppm. IR (film, v_{max}, cm⁻¹): 2879(vw) (CH), 1645(s) (ArF), 1593(s) (C=C), 1483(vs) (ArF), 1400(m), 1329(vs) (CF₃), 1269(w), 831(s) (C-S), 716(s) (C-S), 660(w), 588(w), 548(vw), 484(vw), 436(vw). UV (CHCl₃, λ_{max} , nm (log ϵ)): 285 (4.48). MS (70 ev) m/z calcd for C₉H₃F₇S: 275.9838; found: 275.9837.

Acknowledgements

The kinetics measurements were supported by the Russian Science Foundation (grant No. 20-73-00350). The synthesis of nitroxide **1** and alkoxyamine **2** was performed under the financial support of the Ministry of Science and Higher Education of the Russian Federation (grant No. 14.W03.31.0034). The authors are grateful to the Multi-Access Chemical Service Center SB RAS for analysis and characterization of 4-perfluorotolyl vinyl sulfide and **3**.

Keywords: alkoxyamine •1,3-dipolar cycloaddition • kinetics • nitroxide • nitroxide-mediated polymerization

K. Matyjaszewski, *Curr. Opin. Solid State Mater. Sci.* **1996**, *1*, 769-776.
 C. J. Hawker, A. W. Bosman, E. Harth, *Chem. Rev.* **2001**, *101*, 3661-3688.

ChemPlusChem

ARTICLE

WILEY-VCH

- A. Studer, Chem. Soc. Rev. 2004, 033, 267-273. W. A. Braunecker, K. Matyjaszewski, Prog. Polym. Sci. 2007, 32, 93-[4] 146.
- B. Charleux, J. Nicolas, Polymer 2007, 48, 5813-5833 [5]
- R. B. Grubbs, *Polymer Reviews* 2011, *51*, 104-137. L. Tebben, A. Studer, *Angew. Chem. Int. Ed.* 2011, *50*, 5034-5068. [6] [7]
- P. Astolfi, L. Greci, P. Stipa, C. Rizzoli, C. Ysacco, M. Rollet, L. Autissier, A. Tardy, Y. Guillaneuf, D. Gigmes, *Polymer Chemistry* **2013**, [8] 4, 3694-3704.
- [9] J. Nicolas, Y. Guillaneuf, C. Lefay, D. Bertin, D. Gigmes, B. Charleux, Prog. Polym. Sci. 2013, 38, 63-235
- A. Tardy, V. Delplace, D. Siri, C. Lefay, S. Harrisson, B. de Fatima [10] Albergaria Pereira, L. Charles, D. Gigmes, J. Nicolas, Y. Guillaneuf, Polymer Chemistry 2013, 4, 4776-4787.
- X. Pan, M. A. Tasdelen, J. Laun, T. Junkers, Y. Yagci, K. Matyjaszewski, *Prog. Polym. Sci.* **2016**, 62, 73-125. D. H. Solomon, E. Rizzardo, P. Cacioli, in *US Patent*, **1986**. [11]
- [12]
- [13] C. Johnson, G. Moad, D. Solomon, T. Spurling, D. Vearing, Aust. J. Chem. 1990, 43, 1215-1230.
- S. Marque, The Journal of organic chemistry 2003, 68, 7582-7590. [14]
- [15] D. Bertin, D. Gigmes, S. R. Marque, P. Tordo, Macromolecules 2005, 38. 2638-2650.
- [16] H. Fischer, A. Kramer, S. R. Marque, P. Nesvadba, Macromolecules 2005, 38, 9974-9984.
- [17] G. Audran, R. Bikanga, P. Brémond, J.-P. Joly, S. R. A. Marque, P. Nkolo, The Journal of Organic Chemistry 2017, 82, 5702-5709.
- P. Bremond, S. R. A. Marque, Chem. Commun. 2011, 47, 4291-4293. [18] M. V. Edeleva, I. A. Kirilyuk, I. F. Zhurko, D. A. Parkhomenko, Y. P [19] Tsentalovich, E. G. Bagryanskaya, The Journal of organic chemistry 2011, 76, 5558-5573.
- P. Brémond, A. Koïta, S. R. A. Marque, V. Pesce, V. Roubaud, D. Siri, [20] Org. Lett. 2012, 14, 358-361.
- [21] G. Audran, E. Bagryanskaya, I. Bagryanskaya, P. Brémond, M. Edeleva, S. R. Marque, D. Parkhomenko, E. Tretyakov, S. Zhivetyeva, *Inorganic Chemistry Frontiers* **2016**, 3, 1464-1472.
- G. Audran, E. Bagryanskaya, I. Bagryanskaya, M. Edeleva, S. R. Marque, D. Parkhomenko, E. Tretyakov, S. Zhivetyeva, *ChemistrySelect* **2017**, *2*, 3584-3593. [22]
- G. Audran, E. G. Bagryanskaya, I. Y. Bagryanskaya, M. Edeleva, P. Kaletina, S. R. A. Marque, D. Parkhomenko, E. V. Tretyakov, S. I. Zhivetyeva, *Inorg. Chem. Commun.* **2018**, *91*, 5-7. [23]
- G. Audran, E. Bagryanskaya, I. Bagryanskaya, M. Edeleva, J.-P. Joly, [24]
- G. Audran, E. Bagi yansaya, T. Bagi yansaya, M. Edeleva, C.T. Soly,
 S. R. A. Marque, A. Iurchenkova, P. Kaletina, S. Cherkasov, T. T. Hai,
 E. Tretyakov, S. Zhivetyeva, *RSC Advances* 2019, 9, 25776-25789.
 G. Audran, L. Bosco, P. Brémond, N. Jugniot, S. R. A. Marque, P. Massot, P. Mellet, T. Moussounda Moussounda Koumba, E. Parzy, A. Rivot, E. Thiaudière, P. Voisin, C. Wedl, T. Yamasaki, *Organic* [25] Chemistry Frontiers 2019, 6, 3663-3672
- [26] M. Edeleva, D. Morozov, D. Parkhomenko, Y. Polienko, A. lurchenkova, I. Kirilyuk, E. Bagryanskaya, Chem. Commun. 2019, 55, 190-193.
- T. A. Berezina, V. A. Reznikov, V. I. Mamatyuk, P. A. Butakov, Y. V [27] Gatilov, I. Y. Bagryanskaya, L. B. Volodarsky, Russ. Chem. Bull. 1994, 43. 838-843.
- V. Martin, L. Volodarskii, M. Voinov, T. Berezina, T. Lelvukh, Bulletin of [28] the Academy of Sciences of the USSR, Division of chemical science **1988**, 37, 1677-1683.
- [29] L. Bentein, D. R. D'hooge, M.-F. Reyniers, G. B. Marin, Macromol.
- Theory Simul. 2011, 20, 238-265.
 S. K. Fierens, D. R. D'hooge, P. H. M. Van Steenberge, M.-F. Reyniers, G. B. Marin, *Chem. Eng. J.* 2015, 278, 407-420.
 F. Boschet, B. Ameduri, *Chem. Rev.* 2014, 114, 927-980.
 V. K. Tiwari, P. K. Kulriya, D. K. Avasthi, P. Maiti, ACS Applied [30]
- [31]
- [32] Materials & Interfaces 2009, 1, 311-318.
- [33] S. Stoll, A. Schweiger, J. Magn. Reson. 2006, 178, 42-55.
- A. Alsbaiee, S. A. Ali, Tetrahedron 2008, 64, 6635-6644. [34]
- [35]
- S.-J. Li, D.-C. Fang, *PCCP* **2016**, *18*, 30815-30823. N. A. Bokach, M. L. Kuznetsov, V. Y. Kukushkin, *Coord. Chem. Rev.* [36] 2011, 255, 2946-2967.
- S. V. Chapyshev, U. Bergsträßer, M. Regitz, Chemistry of Heterocyclic Compounds 1996, 32, 59-64. [37]
- J. Geittner, R. Huisgen, R. Sustmann, Tetrahedron Lett. 1977, 18, 881-[38] 884
- Y. D. Samuilov, A. I. Konovalov, Russian Chemical Reviews 1984, 53, [39] 332-342.
- J. F. Polienko, T. Schanding, M. A. Voinov, I. A. Grigor'ev, Synth. Commun. 2006, 36, 2763-2768. [40]

WILEY-VCH

Entry for the Table of Contents



Kinetics of 1,3-dipolar cycloaddition of various vinyl monomers to an aldonitrone-containing nitroxide and alkoxyamine were studied at different temperatures by EPR and NMR spectroscopy. Among 11 studied monomers, the rate coefficient of the cycloaddition for methyl vinyl ketone is the highest.