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Stability of twisted diarylnitroxides: Photochemical tests

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ABSTRACT

Photochemical stability and possible routes for photodegradation of twisted diarylnitroxides were determined. It was shown that quantum yields for twisted diarylnitroxides fall in the range typical for the best representatives of alkylnitroxides providing an additional support that twisting of the phenyl ring from the N-O conjugation plane constitutes an efficient route for increasing thermo and photo stability of the nitroxides.

Introduction

Stable nitroxide radicals are widely used in various areas: as redox mediators, radical traps, spin labels and probes, antioxidants, redox active electrode materials, etc. [1,2]. Wide spectrum of practical applications of nitroxides listed above requires new compounds with precisely adjusted properties, e.g., stability, redox-potential values, solubility, etc. Consequently, targeted structural design of molecules for certain application is of primary importance. Commonly used stable alkylnitroxides (the most popular is TEMPO – 2,2,6,6-tetramethylpiperidine-1-oxyl – and its derivatives) are not too sensitive to structural modification since electron transfer via σ – bonds is less efficient than via π-conjugation. From this point of view, diarylnitroxides are more preferable. However, arylnitroxides are commonly insufficiently stable. Contrary to the aliphatic compounds in which the spin density is located at the nitroxyl group, the spin density in arylnitroxides is delocalized over the *ortho*/*para* positions of aromatic rings [3,4]. Such delocalization provides additional reaction centers and initiates unwanted reaction channels thus decreasing stability.

Recently, new strategy for molecular design of stable diaryl nitroxides was suggested [5,6] and a broad series of new twisted diarylnitroxides containing a bulky substituent in the *ortho*-position in the phenyl ring was obtained. Principal idea of structural design was in removing one aryl moiety from the conjugation with the nitroxyl radical center (thus preventing spin density delocalization over the phenyl ring) whereas the other aryl ring should stay conjugated. This allows obtaining a smart tunable system with the increased stability (both thermodynamic and kinetic) not only of the radical species but of their oxidized and reduced forms as well [4]. New approach broadens the scope of available stable diarylnitroxyl radicals which are practically important.

The present paper is further development of this research. It is aimed at quantitative estimation of the photochemical stability of twisted arylnitroxides and their comparison with previously known relatively stable nitroxide radicals of diaryl and dialkyl type. Since some of twisted diarylnitroxides can stay for weeks in benzene solution in an open air without light protection at room temperature without any noticeable destruction, more harsh conditions were applied (laser light, wavelength 405 nm, intensity $5{\cdot}10^{-9}$ Einstein/s per sample) to get reliable quantitative data. The structure/stability relationship will be established for the radicals to demonstrate the role of twisting in their stabilization. Possible routes for photochemical degradation of diaryl nitroxides will be also discussed. It should be mentioned that photochemical degradation of dialkylnitroxides has been previously reported in a number of publications [7–11] whereas photochemical stability of diaryl derivatives has drawn little attention [12].

Results and discussion

For the investigation, a number of diarylnitroxides with bulky *tert*-butyl and trifluoromethyl substituents in the phenyl rings were chosen (Scheme 1) and synthesized. Radicals **1**–**5** were chosen to reveal an influence of the electronic nature of the substituents as well as their location on the stability and photoinduced degradation routes. Twisted nitroxides **1**–**3** will be compared with their planar counterparts **4** and **5**.

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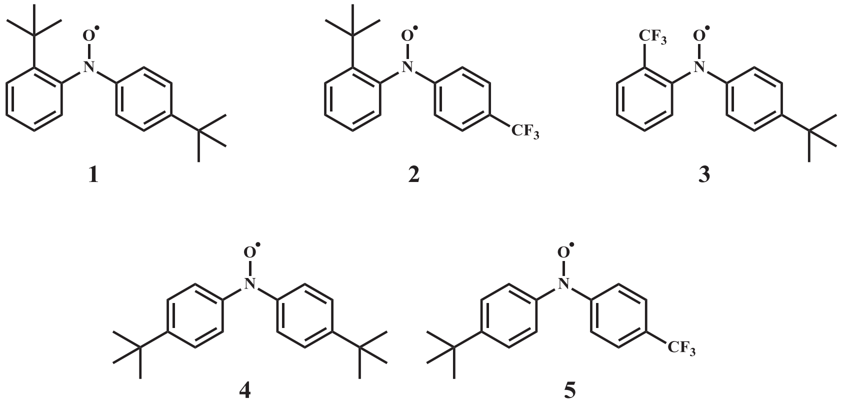


Scheme 1. The diarylnitroxides under investigation.

Radicals **1**–**5** are stable in crystal form; they stay for months in an open air without any noticeable destruction. As concerns the radicals' life time in solution, preliminary estimation using spin counting method showed that the sample of 2-^{t}Bu,4′-CF_3-diphenyl nitroxide stayed for more than two weeks in benzene solution in an open air at room temperature without protection of the light and exhibited the amount of radical species which was almost 100% of the starting value. Encouraged with this result, we performed more detailed quantitative research on photochemical stability of radicals **1**–**5** in toluene solution. Toluene seems to be an optimal solvent for estimating the inherent stability of the radicals toward decomposition since it is not prone to initiate secondary radical transformations.

To determine the quantum yields of photochemical decomposition of radicals **1**–**5**, the irradiation with near-UV laser light (wavelength 405 nm, intensity $5{\cdot}10^{-9}$ Einstein/s per sample) was carried out. The following kinetic model of photochemical radical decomposition was used:

$$\frac{dN}{dt} = I_0(1 - 10^{-A(t)})\varphi$$

where N is the number of radical molecules, I_0 is light intensity, φ is the quantum yield of the reaction, $A(t)$ is absorbance of the solution at the irradiation wavelength, which was calculated by Bouguer–Lambert–Beer's law$A(t) = \frac{\varepsilon_{405} l}{V} \cdot N(t)$,where ε_{405} is extinction coefficient on the irradiation wavelength, l is the optical path length of irradiating light, and V is the sample volume.

In equation given above the value $I_0(1 - 10^{-A(t)})$ is the number of photons absorbed by radical molecules per unit time, and the expression $\Delta(t) = \int_0^t I_0(1 - 10^{-A(\tau)})d\tau$ represents the absorbed irradiation dose. According to equation, the slope of the curves of $N(t)$ against $\Delta(t)$ gives the quantum yield of photochemical decomposition of the radicals [13].

The quantum yields of photochemical decomposition of radicals **1**–**5** measured as described above are given in Table 1. This table also lists extinction coefficients ε of the radicals at the irradiation wavelength, and the product $\varepsilon \cdot \varphi$, which is proportional to the apparent rate constant of photochemical reaction in the limit of low absorbance. Some literature data obtained for other types of nitroxides are also given in Table 1 for comparison. If the data in toluene were not available in literature, the results measured in other hydrocarbons (benzene or pentane) were taken. These solvents are close in polarity and do not provoke radical transformations, similar to toluene. Thus, one can expect that such comparison will not lead to any uncertainty in the conclusions.

As follows from the data presented in Table 1, twisted diarylnitroxides **1** and **2** are significantly more stable under laser irradiation than planar di-*para*-substituted analogues, in spite of a vacant *para*-position in one ring. Interestingly, electronic nature of substituents does not affect photodegradation efficiency (entries 1, 2 in Table 1) whereas the dihedral angle turned out to be a crucial point. One can see that nitroxide **3** is destabilized as compared to 4,4′-disubstituted compounds, contrary to twisted nitroxides **1** and **2**. The reason is much smaller dihedral angle which does not block the conjugation with NO moiety completely (52.2° in case of **3** vs. 69.8° and 67.4° for **2** and **1**) due to less bulky trifluoromethyl group in the *ortho* position. This provides a certain spin

Table 1
Quantum yields of decay of radicals 1–5 (toluene, 298 K, 405 nm, intensity $5{\cdot}10^{-9}$ Einstein/s per sample) and some literature data for comparison.

	Substituents in the phenyl rings	Solvent	Irradiation wavelength λ, nm	Quantum yield, φ	Extinction coefficient, ε, $M^{-1}{\cdot}cm^{-1}$	$\varepsilon \cdot \varphi$, $M^{-1}{\cdot}cm^{-1}$	Reference
1	2,4′-di ^{t}Bu	toluene	405	$4{\cdot}10^{-3}$	650	2.6	present work
2	2-^{t}Bu,4′-CF_3	toluene	405	$5.5{\cdot}10^{-3}$	400	2.2	present work
3	2-CF_3,4′-^{t}Bu	toluene	405	$1.3{\cdot}10^{-2}$	1350	17.55	present work
4	4,4′-di-^{t}Bu	toluene	405	$8{\cdot}10^{-3}$	1200	9.6	present work
5	4-^{t}Bu,4′-CF_3	toluene	405	$8{\cdot}10^{-3}$	1350	10.8	present work
6	4,4′- OCH_3	benzene	436	$8{\cdot}10^{-3}$	∼1000	8	[12]
7	TEMPO	heptane	436	$<6{\cdot}10^{-4}$	∼10	$<6{\cdot}10^{-3}$	[8]
		CCl_4	365	$4.8{\cdot}10^{-1}$	–*	–	
8	di-*tert*-butyl-nitroxide	pentane	254	$2.1{\cdot}10^{-1}$	∼2500	525	[7]
9	nitronyl nitroxide	benzene	578	$9.8{\cdot}10^{-3}$	–*	–	[14]
			313	$1.3{\cdot}10^{-2}$	–*	–	
10	2,2,5,5-tetramethyl-4-phenyl-3-imidazoline-1-oxyl**	toluene	365	$1.6{\cdot}10^{-1}$	55	8.8	[9]

[*] Data on extinction coefficient were not provided in the corresponding reference.

density in the vacant *para* position which is the main destabilizing factor for this type of compounds.

Noteworthy, photodegradation ability (the $\varepsilon \cdot \varphi$ value) of radicals **1** and **2** is better than that for some often used stable nitroxides, e.g., di-*tert*-butyl-nitroxide or 2,2,5,5-tetramethyl-4-phenyl-3-imidazoline-1-oxyl (entries 8, 10 in Table 1). The $\varepsilon \cdot \varphi$ value for nitronyl nitroxide was not reported whereas comparison of quantum yields (φ) measured for diarylnitroxides **1, 2** and nitronyl nitroxide indicates that the former have the advantage of the latter. Thus, though TEMPO is still the champion in photochemical stability among nitroxide radicals, comparison with other widely used representatives of alkylnitroxides emphasizes perspectives of twisted diarylnitroxides **1** and **2**.

Elucidation of possible routes for photodegradation of nitroxide radicals is an important issue since it provides information for targeted structural design of stable compounds. It should be noted that literature data on the mechanism of photodegradation of nitroxides excited in the n–π^* transition are scanty. It has been shown that these radicals can dissociate via C—N bond breaking [11]. Di-*para* -anisidylnitroxide radicals in both liquid and solid phases were suggested to undergo isomerization into the corresponding aminyl radicals [12]. The other possible routes are photoreduction and photo elimination of nitric oxide [7,9,8]. The principal TEMPO decay reaction is H-atom abstraction from the solvent [8].

To determine the main reaction channels for photochemical transformations of the radicals **1**–**5,** radical **4** was chosen as a model compound. The 9 mmol·L^{-1} solution of **4** in toluene evacuated to 10^{-3} Torr was exposed to the laser irradiation in optical quartz cuvette for 330 min until less than 50% of the starting compound were destroyed. The process was interrupted at an early stage since we were interested in the investigation of primary products and tried to minimize the impact of secondary transformations of radical species. ESI-HRMS analysis of the reaction mixture obtained after irradiation of **4** was performed. It revealed the presence of four main compounds (*a-d* in Scheme 2) as well as two minor products (*e, f*) which are evidently attributed to the secondary reactions with the solvent. Formation of *tert*-butyl substituted carbasol-*N*-oxyl (a, the major product), N-4-*tert*-butylphenyl-5,10-dihydrophenazine (c) and 5,10-dihydrophenazine-*N*-oxyl (b) indicates that diaryl nitroxides are much less prone to dissociative C-N bond breaking as compared to their dialkyl counterparts [7,11] though a certain amount of *tert*-butylphenylamine (*d*) was formed.

The products composition indicates that photo conversion of **4** follows a complex mechanism including the parallel routes. The structures given in Scheme 2 clearly indicate that the “weak point” of the molecule are the *ortho*-positions in the phenyl rings which bear significant spin density leading to 2,2’—C—C coupling between the rings and facilitating the attack of the aminyl radicals. Interestingly, carbazole and phenazine derivatives are also formed in electrooxidation of diaryl amines [15].

To be sure that the products given in Scheme 2 do correspond to photoreactivity of nitroxide 4, the same experiment was repeated but irradiation was stopped at an earlier stage as compared to the previous case (10% instead of 50% of destroyed molecules). ESI-HRMS analysis of the reaction mixture gave the same three products (a,b,c), which were also dominant at 50% conversion.

Thus, analysis of photochemical stability of diarylnitroxides (the quantum yields) and examination of possible routes for their photodegradation provide an additional support that twisting of the phenyl ring from the N-O conjugation plane constitutes an efficient route for increasing thermo and photo stability of the nitroxides.

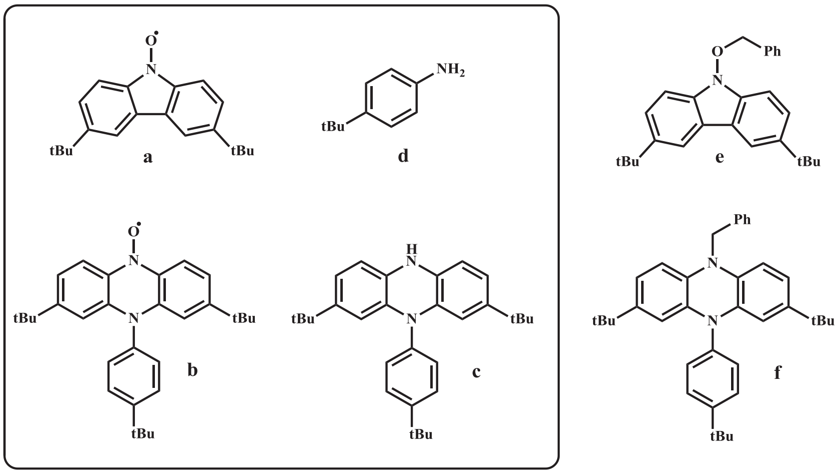
Experimental

Diaryl nitroxyl free radicals under investigation were synthesized and purified as described in [6]. Toluene was purified by refluxing over sodium followed by distillation.

For photochemical investigations, the solutions of radicals in toluene with concentrations $2 \div 5 \cdot 10^{-4}$ M were used. The solution (ca. 70 µL) was placed in a cylindrical cuvette with 3 mm inner diameter made of optical quartz. Prior to irradiation, the solution was evacuated to 10^{-3} Torr by pump-freeze-pump procedure, then the cuvette was filled with dry argon and sealed. The solution in the cuvette was placed in EPR cavity. The solution was irradiated along the axis of the cuvette using diode laser with 405 nm wavelength. EPR spectra were recorded at sequential times of irradiation and the quantity of radicals in the cuvette was measured.

Irradiating light intensity was determined in a separate experiment using ferrioxalate actinometry [16,17] and was found to be $5 \cdot 10^{-9}$ Einstein/s per sample. The optical absorbance spectra of the radical solutions in 1 cm quartz cuvettes were recorded using Shimazu UV2401-PC spectrometer to determine the extinction coefficients.

Quantum yield of radical photodecomposition was determined from the slope of the dependence of number of nitroxide radicals versus absorbed irradiation dose, as described in the previous Section.



Scheme 2. The products of photolysis of radical **4**.

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