T.V.Magdesieva, O.A.Levitskiy *Russ. Chem. Rev.*, 2018, **87** (7) 707 – 725

DOI: 10.1070/RCR4769

Molecular design of stable diarylnitroxides

Tatiana V. Magdesieva, Oleg A. Levitskiy

Department of Chemistry, M.V.Lomonosov Moscow State University
Leninskie Gory 1, stroenie 3, 199991 Moscow, Russian Federation

The review is devoted to diarylnitroxides, which constitute an important type of organic radicals. These compounds are much less investigated than their alkyl counterparts. Meanwhile, they are of great interest, since they provide extensive opportunities for targeted structural modification and control of electronic properties of a molecule for a particular practical application. The existing trends of molecular design of stable diarylnitroxides and general approaches to their synthesis are discussed. Structural details and spin density distribution in diarylnitroxides are considered. Factors determining the stability of both the diarylnitroxide radicals and their oxidized and reduced forms and the redox properties of this class of organic radicals are addressed.

The bibliography includes 128 references.

Contents

1. Introduction

The interest in stable organic radicals, among which are nitroxides, is caused by the diversity of their properties and broad range of practical applications.[1–9] Nitroxide radicals are used as radical traps,[4] spin labels,[10, 11] antioxidants and biomimetics,[12–16] chain propagation initiators and mediators in living radical polymerization processes,[3, 17] molecular magnets[18] and so on. Owing to their ability to be converted to stable oxidized and reduced states (oxoammonium cations upon oxidation and aminoxyl anions upon reduction) and fast electrochemical transformations, nitroxides are of interest as redox-active materials for organic energy storage devices. Testing of alkylnitroxides as cathode materials for lithium ion and organic radical batteries[19, 20] has been actively performed since the beginning of the 21st century (for details, see below). Good prospects for their use in uninterruptible power supply devices[21] and in flow batteries[8] were demonstrated. In recent years, publications describing testing mixed aryl alkyl derivatives as redox-active electrode materials have started to appear (see, for example, Refs 22 – 24). The application of nitroxide radicals as mediators for metal – air[25, 26] and solar batteries[27 – 31] are known. Nitroxides are widely used in fine organic synthesis as catalysts[32 – 36] or mediators of oxidation reactions [*e.g.*, oxidation of alcohols[37] with NaOCl,[38, 39] oxone,[40] I_2,[41] iodine(III) compounds,[39, 42] O_2 (Refs 43 – 45) and so on]. This is far from covering all applications for this class of compounds.

The foregoing refers, mainly, to alkylnitroxides, among which TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl) is the most well known and widely studied radical. Unlike alkyl derivatives, diarylnitroxides are much less studied, although potential of their use may be rather extensive. This situation is largely due to the fact that the stability of diarylnitroxides is restricted by a number of structural features and, as long as these features are unknown, the use of even well elaborated synthetic methods smoothly giving alkyl derivatives does not meet with success. For this reason, only a small number of stable diarylnitroxide radicals were known until recently and this class of compounds did not receive an adequate attention.

The development of modern technology brings to the forefront the problem of targeted synthesis of com-

---

T.V.Magdesieva. Doctor of Chemical Sciences, Professor of the Organic Chemistry Division at the Department of Chemistry of the MSU.
Telephone: + 7(495)939 – 3065, e-mail: tvm@org.chem.msu.ru
Current research interests: organic electrochemistry, catalysis, electrocatalysis, molecular redox systems.
O.A.Levitskiy. Candidate of Chemical Sciences, Junior Researcher at the same Division.
Telephone: + 7(495)939 – 3065, e-mail: levicoleg@mail.ru
Current research interests: organic electrochemistry, electrosynthesis, quantum chemical calculations.

Received 27 July 2017
Translation: Z.P.Svitanko

pounds with specified properties. The structural modification of organic compounds can serve for tuning of their physicochemical properties (for example, the standard electrochemical potentials, solubility, *etc.*) in a definite way. Functionalization of an aromatic ring by introducing various substituents is a problem that has been adequately solved owing to a large number of synthetic approaches known to date. Apart from the synthetic accessibility and diversity of aromatic compounds, it is also important that the transfer of electronic effects to the reaction centre occurs far more efficiently through an aromatic ring than through a system of σ-bonds; therefore, functionalization of diarylnitroxides allows one to change the properties of compounds over a much broader range than a similar functionalization of the alkyl chain. This is supported by numerous literature examples, some of which are presented in this review (see below). Targeted design of arylnitroxide compounds may be based on not only traditional variation of the donor-acceptor properties and the number and positions of substituents in the aromatic ring, but also on the change in the degree of conjugation between the nitrogen atom and the aryl moiety.

The above implies good prospects for using diarylnitroxides to obtain materials with desired properties. The purpose of this review is to analyze in detail the possible grounds for the instability of diarylnitroxides and the difficulties associated with their synthesis and to discuss the basic principles that are to be taken into account for the structural design of stable diarylnitroxides. As shown by recent investigations,[46, 47] understanding of the problem and its causes makes it possible to develop efficient principles for the molecular design of diarylnitroxides and to considerably extend the range of available stable radicals of this type. This paves the way to novel functional materials.

Note that it is necessary to distinguish between ‘design’ and ’method of synthesis’. There are good, repeatedly verified methods of synthesis that allow preparation and characterization of diarylnitroxides (there are quite a few such publications), but the product may prove unsuitable for the subsequent practical use because of low stability of the radical or its redox form. Primary attention in the review is paid to compounds that are not only stable in the neutral state, but can form stable oxidized and reduced forms (oxoammonium cations upon oxidation and aminoxyl anions upon reduction). The latter is especially important, because none of the dialkylnitroxides known to date have stable reduced forms: aminoxyl anions are rapidly protonated or undergo other chemical reactions.[48] This precludes the use of dialkylnitroxides as, for example, ambipolar redox-active materials in energy storage and conversion devices, which are demanded in the context of modern chemistry of sustainable development.[49]

Thus, the goal of the review is to demonstrate new opportunities opened up by application of stable diarylnitroxide radicals as the basis for modern materials (first of all, molecular magnets and redox-active materials for electrochemical energy storage devices). Section 2 is devoted to analysis of the key principles of molecular design of stable diarylnitroxides. Section 3 describes general approaches to the synthesis of compounds of this class. Since EPR spectroscopy is the main and the most informative method for studying the structure and properties of organic radicals, Section 3 of the review gives a detailed comparative analysis of the key EPR characteristics of diarylnitroxides of various types, reflecting their structural features. These data can be utilized to determine the spin density distribution in the molecule and vividly illustrate the efficiency of principles of targeted molecular design considered in Section 2. The final Sections address the redox properties of diarylnitroxides and their relationship with the molecular structure. First of all, this refers to redox potentials and stability of oxidized and reduced forms, because these are key parameters determining the possibility and expediency of application of these compounds in various fields. For comparison, characteristics for TEMPO and some mixed arylalkylnitroxides are given. These data clearly illustrate the higher sensitivity of aryl derivatives to structural modification compared with the alkyl counterparts and demonstrate good prospects for the use of reasonably designed diarylnitroxides as redox-active electrode materials.

The presented information will be useful for specialists dealing with stable organic radicals and will give a new impetus to the development of this highly significant and promising field of chemistry. It is necessary to emphasize that the interest in diarylnitroxides that arouse in recent years does not at all mean that the potential of widely used alkyl derivatives is exhausted. Studies in this field are in progress and will be continued, as indicated by the large number of publications and reviews on this subject (see, for example, Refs 1 – 9); therefore, their detailed discussion is beyond the scope of this review. Conversely, publications dealing with aryl derivatives are scattered.

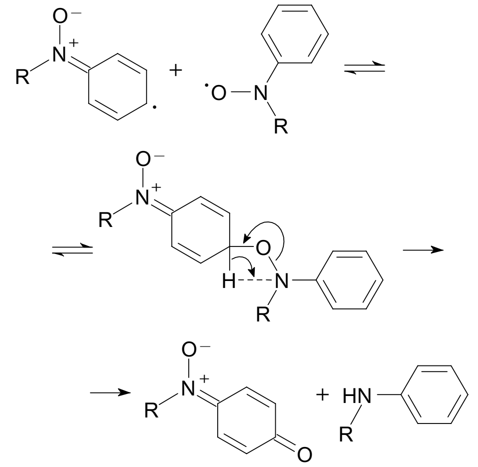
2. Stability of diarylnitroxide radicals: what is the problem?

The presence of the aromatic ring conjugated with the nitroxide moiety makes diarylnitroxide radical highly sensitive to the introduction of substituents of various nature into the benzene ring. This allows one to change the redox properties of the molecule over a broad range of potentials. However, it is not that simple. As is often the case, drawbacks and benefits are two sides of the same coin. The presence of the $\pi(\mathrm{Ar}) - \pi(\mathrm{NO})$ interaction leads to spin density delocalization over the benzene ring, which induces quite a number of secondary chemical reactions involving the ring (*e.g.*, proneness to dimerization at the *para*-position and other processes, giving rise to quinoid structures). This considerably reduces the stability of diarylnitroxides. Furthermore, traditional synthetic approaches to these compounds are complicated in the case of diarylnitroxides by a number of side processes, which decrease the yield of the target products.

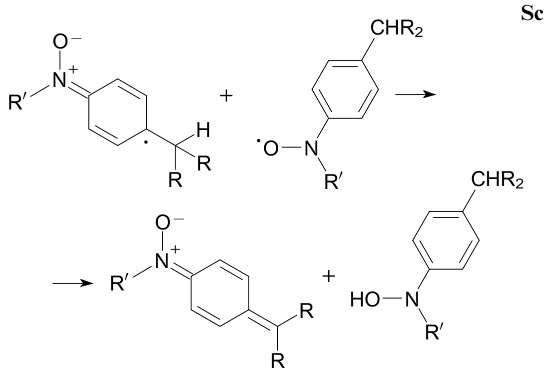
Therefore, the structural design of diarylnitroxides should be aimed, first of all, at the fabrication of a stable molecule the properties of which could be subsequently modified by traditional methods.

The parent compound for this class, the diphenylnitroxide radical, was first synthesized almost 100 years ago;[50, 51] however, the compound proved to be unstable.

Scheme 1



Scheme 2



Even in the early studies, it was noted that stabilization of the diphenylnitroxide radical requires introduction of an 'inert' substituent into the *para*-position.[52] This hinders the possible attack by the nitroxide centre of one molecule on the *para*-position of the aromatic ring of another molecule, which bears a certain spin density owing to the conjugation with the nitroxide group.[53] The subsequent irreversible step affords diarylamine and a quinoid molecule (Scheme 1).

Indeed, bis(4,4′-anisyl)nitroxide[54] proved to be substantially more stable than diphenylnitroxide. However, the methyl-substituted derivative is markedly inferior in stability even to unsubstituted diphenylnitroxide. The reason is that diarylnitroxides are not stabilized by any substituents in the *para*-position, but only by *para*-substituents containing no α-hydrogen atoms. Otherwise, one more destruction pathway to give hydroxylamine is possible (Scheme 2).

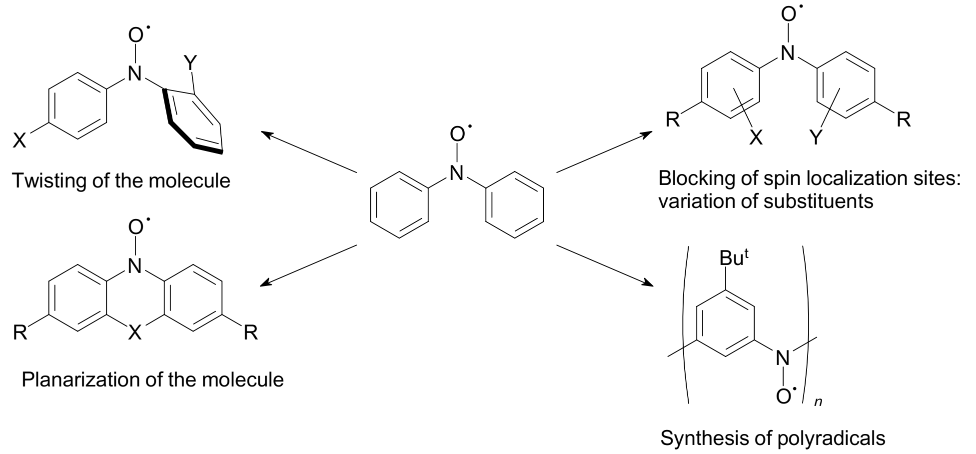
Thus, the first possible pathway of structural modification increasing the stability of diarylnitroxides is the protection of the *para*-position by an appropriate substituent (Scheme 3).

This strategy was implemented in numerous studies. For example, high stability was found for the nitroxide analogue of the well known Ballester radical, namely, perchlorodiphenylnitroxide, which was synthesized rather long ago:[55] it can be stored in the solid state for months without decomposition. Approximately at the same time, one more stable radical — bis(4,4′-*tert*-butylphenyl)nitroxide — was prepared.[56] Many years later, alternative pathways to this compound were developed and it was studied in detail by spectroscopy.[57, 58] An early publication mentions the synthesis of a series of substituted bis(4,4′-biphenyl)nitroxide radicals;[59] however, they were not adequately characterized (only the melting points were given, but no detailed spectral investigation was carried out).

The first unsymmetrically substituted diarylnitroxide **1d** stable not only in the crystal, but also in solution was synthesized relatively recently.[60] This stable radical contained methoxy and *N*-pyrrolyl substituents in the *para*-positions of the benzene rings and was characterized by X-ray crystallography. Although the pyrrolyl moieties are not involved in spin density delocalization, they promote closer packing in the crystal, which is favourable for additional CH(aryl) – π(NO) contacts (Fig. 1).

Indeed, comparison of the magnetic properties of this radical and related aryl(alkyl)nitroxide, in which the anisyl group has been replaced by a *tert*-butyl group, confirmed that closer intermolecular contacts and, hence, appearance of magnetic properties, are possible for planar spin-delocalized systems (diaryl derivatives). Depending on the nature of substituents linked to the nitroxide group, various interactions can occur in the

Scheme 3



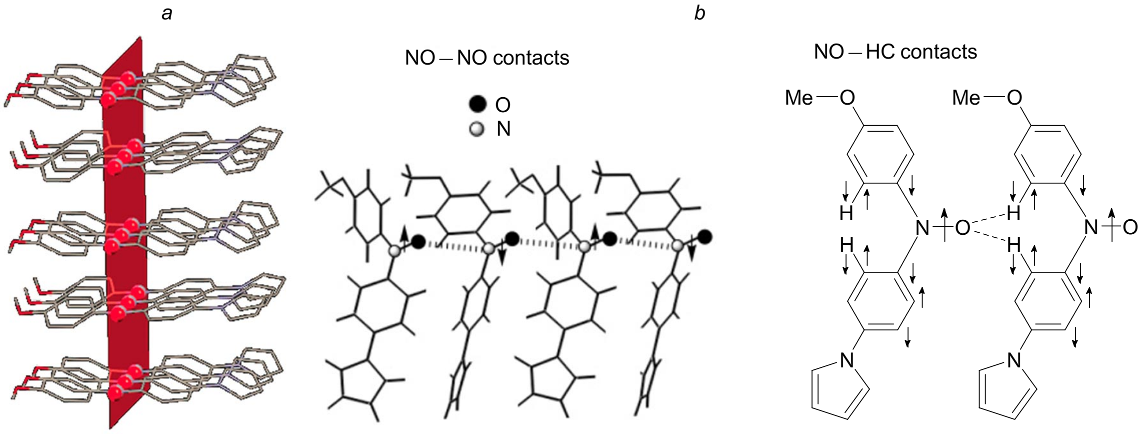


Figure 1. Crystal packing of 1-{4-(*N*-(*p*-methoxyphenyl)-*N*-aminoxyl]phenyl}pyrrole molecules (*a*) and close contacts responsible for the intermolecular exchange interactions (*b*).[60]

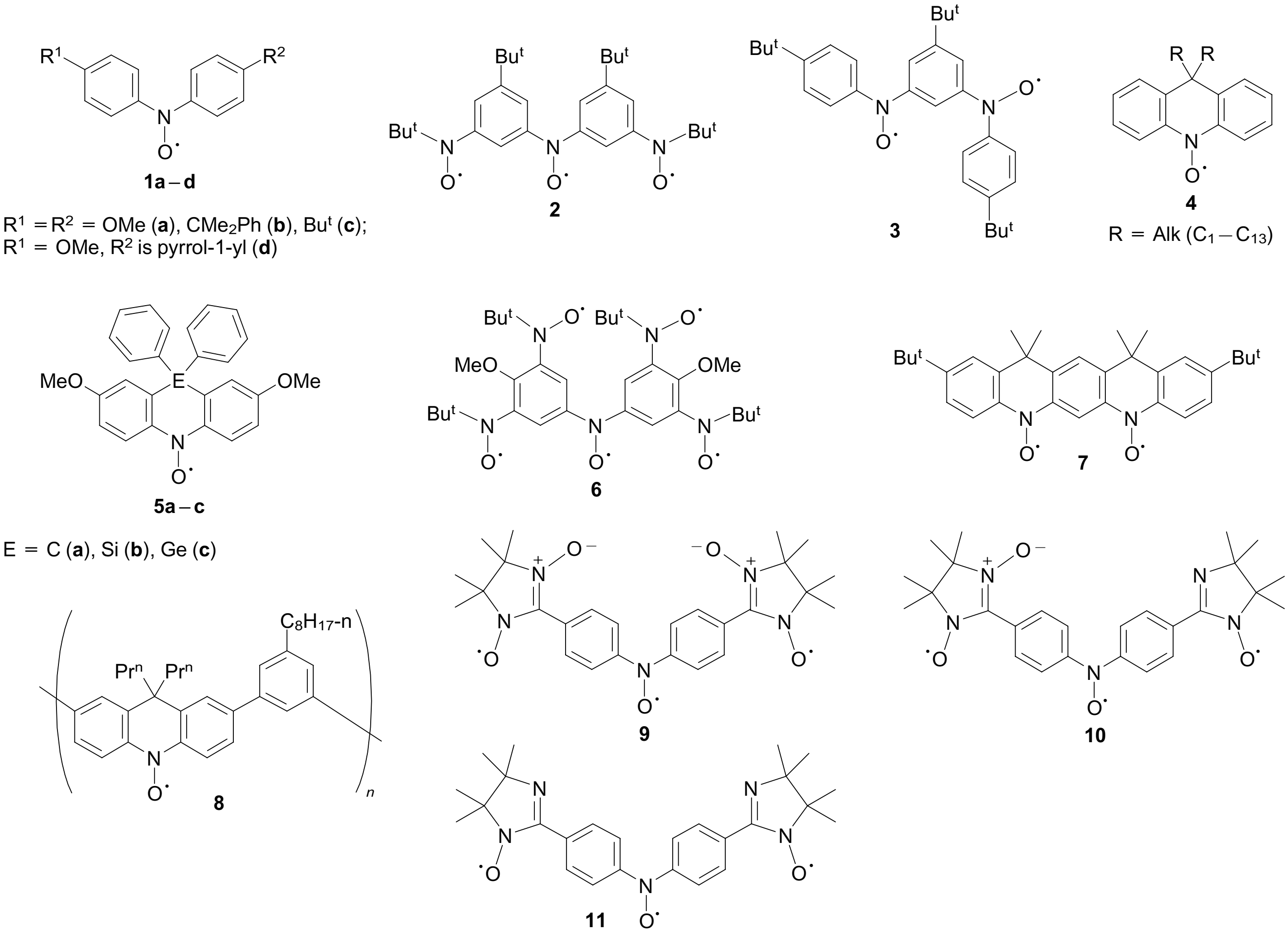
crystal and, as a consequence, it is possible to obtain materials possessing various magnetic properties. The possible types of interactions include coordination, electrostatic, $\pi-\pi$-stacking and other. Extensive opportunities are created by the introduction of stable nitroxide radicals into the coordination sphere of a paramagnetic metal ion. These systems are of interest as models for studying the exchange interactions between paramagnetic centres of various nature. It was shown that the magnetic properties of the system depend on the coordination mode of a radical to the metal complex, which opens up one more path towards fabrication of materials with specified properties. Since the first publications (for example, see a review[61]), quite a few such compound, including in particular nitroxide radicals, have been prepared and studied. Most often, the investigations concerned TEMPO derivatives or nitronyl nitroxides containing additional coordination sites (a lot of examples can be found in reviews[62,63]) and arylnitroxide polyradicals (such as **2** and **3**).[64–66] An enormous contribution to the development of this area was made by researchers from the Siberian Branch of the Russian Academy of Sciences. A recent review[18] addresses the molecular design of photo and thermally switchable molecular magnets, so-called breathing crystals, based on the paramagnetic Cu^{II} hexafluoroacetylacetonate complex and pyrazolyl-substituted nitroxide (nitronyl nitroxide), which acts a bridge between Cu^{II} ions giving rise to extended polymeric structures. The intercalation of stable nitroxides into an inorganic crystalline phase is also widely used to obtain hybrid materials. These materials also possess magnetic and optical properties considerably differing from those of molecular crystals owing to the presence of intermolecular host – guest interactions. Examples can be found in publications of Hemme *et al.*[67,68]

The magnetic properties of planar π-delocalized diarylnitroxides are, most often, generated by the extended π-conjugation chain, which provides spin density delocalization and close inter- and intramolecular contacts between different parts of the molecule (see Scheme 3).[69,70] By the way, this aspect has long served as the basis for a major trend in the molecular design of stable diarylnitroxides and as the driving force for virtually all subsequent investigations related to diarylnitroxides. This area was explored by many research teams, which resulted in the design of quite a few interesting mono- and polyradical structures.

Planarization of diarylnitroxides can be achieved by introducing a short linker connecting the *ortho*-positions of the phenyl moieties. This strategy was used in many studies. For example, a series of 9,9-disubstituted 9,10-dihydroacridin-10-yloxyl radicals with a broad range of either alkyl (from C_1 to C_{13}, compound **4**) or aryl (Ph, Tol) substituents were prepared and characterized by low-temperature X-ray diffraction.[59,71–73] In an X-ray diffraction study of radicals, inter- and intramolecular contacts determining the mechanism of magnetic interactions were identified.[72] These radicals are fairly stable in the crystalline state, but in solutions, further transformations are induced owing to the unsubstituted *para*-position of the phenyl moieties. This ‘drawback’ was later corrected by introducing methoxy substituents into 9,9-diphenyl-9,10-dihydroacridin-10-yloxyl **5** and its diphenylsilyl- and diphenylgermyl-bridged analogues.[74] To date, this is the only publication addressing the effect of the bridging heteroatom on the physicochemical properties and stability of nitroxide radicals. It was shown that the spin density on the nitroxide nitrogen atom is maximum in the Ge derivative. As shown by X-ray crysrallography, this is attributable to some elongation of the C – N bond upon introduction of an element with a greater atomic radius, which reduces the interaction of the aromatic π-system and the nitrogen p orbital.

An increase in the spin density can be attained by introducing several nitroxide groups into the molecule. This strategy was implemented in many studies in combination with protection of the *para*-position of the aromatic ring with an appropriate group, as noted above. This combination proved to be fairly successful. Mixed diaryl(arylalkyl)pentanitroxide **6** is stable in the solid state, with strong intermolecular antiferromagnetic interactions occurring in the crystal; however, in solu-

Structures 1 – 11



tion, this compound is insufficiently stable.[75] In a benzene or THF solution, the EPR signal intensity considerably decreases as soon as within 24 h. This may be caused by the remaining unsubstituted aryl *para*-positions (relative to the nitroxide groups), which bear a considerable spin density. The mixed arylalkyl triradical **2** is stable not only in the crystal, but also in solution for at least several weeks.[76] A considerable stabilizing effect comes from the bulky *tert*-butyl group in the *meta*-position of the benzene rings. However, structurally related biradical **3**, containing only aryl substituents at the nitroxide moiety, is stable only at low temperature;[77] the *anti*-conformation is preferred for this molecule.

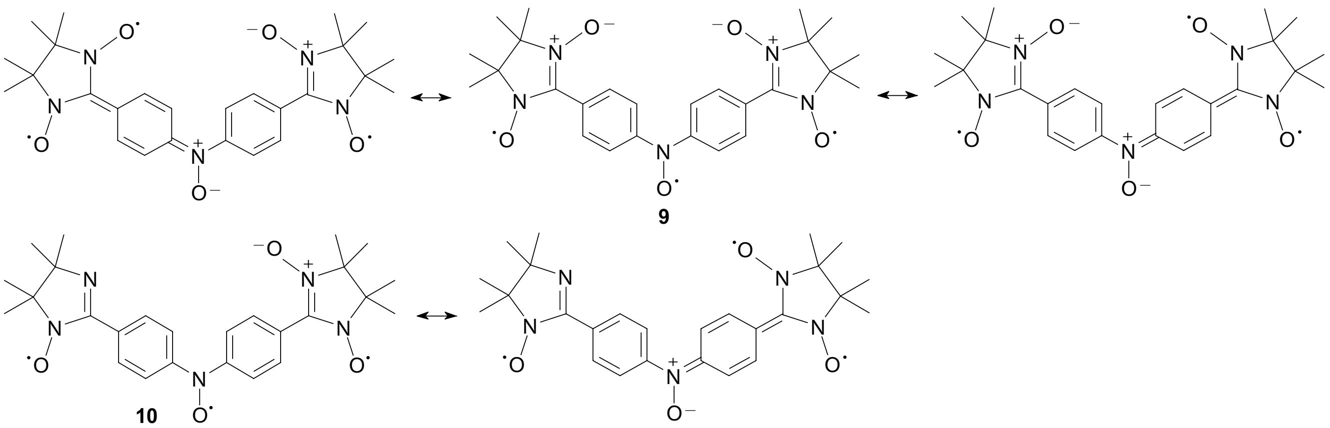
Compound **7** is the first example of a diarylnitroxide biradical[78] that is stable not only in the crystalline state, but also in a benzene solution. This is apparently a result of classical molecular design, in particular, substituted *para*-positions of the phenyl groups. Owing to the annulated structure, which promotes planarization of the molecule, this compound is not only stable, but also exhibits strong ferromagnetic coupling.

The targeted molecular design, which finally allowed the preparation of stable diarylnitroxide polyradical **8** with a rather high spin density (0.71) per repeating unit,[79] is based on the use of two structural moieties that previously proved to be efficient: 9,9-dialkyl-substituted 9,10-dihydroacridin-10-yloxyl as a source of spin density and 1,3-phenylene as a linker. The polymer comprising, on average, 11 units was prepared by the Suzuki – Miyaura reaction. Once the number of monomer units and spin density per repeating unit are known, it is possible to find out that one molecule contains, on average, eight radical centres and that at least three of them are magnetically coupled. The polymer is stable both in the solid state and in solution and shows strong intramolecular through-bond spin coupling.

An earlier study[80] reports the synthesis and investigation of fairly curious stable polyradicals containing three types of nitroxides in one molecule, namely, diphenylnitroxide, nitronyl nitroxide and imino nitroxide (compounds **9** – **11**). The structures of compounds were confirmed by X-ray crystallography. It is noteworthy that the nitronyl nitroxide moiety of unsymmetrical triradical **10**, unlike that of symmetrical triradical **9**, is conjugated with the diphenylnitroxide radical centre, whereas the imino nitroxide moiety does not form a quinoid structure with the central nitroxide moiety (Scheme 4).

The above structures of relatively stable diarylnitroxides **1** – **11** known to date indicate that until recently, the molecular design was focused on the maximum planarization of the structure and introduction of stabilizing substituents, which is caused by the desire to

Scheme 4

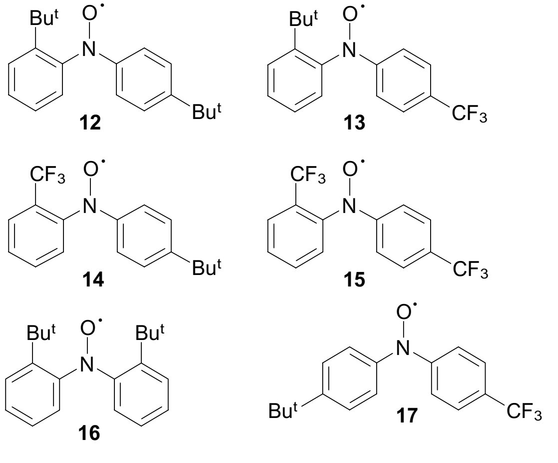


obtain new types of molecular magnets. However, there are also other important practical applications of this class of compounds based on the redox transformations and requiring diarylnitroxides that would be stable not only in the solid state, but also in solution. One of them is the development of efficient redox-active materials for energy storage devices in which only alkyl type nitroxides were tested so far. However, dialkylnitroxides are able to generate stable redox forms only upon oxidation, as the oxoammonium cations are stabilized *via* conjugation. The aminoxyl anions resulting from reduction are unstable;[48] therefore, these compounds are not used as anode materials. Virtually all results of electrochemical investigations of diarylnitroxides obtained until quite recently (see below) are also indicative of stability of only the oxidized form. Hence, the targeted design of diarylnitroxides able to form give oxidized and reduced forms should be based on principles differing from those described above while considering organic magnets.

A fundamentally different trend of the molecular design of stable diarylnitroxides[46,81] is to vary the rotation angle of the aromatic ring (for example, by introducing a bulky substituent into the *ortho*-position of one aromatic ring or bridging groups of various length between the rings). This makes it possible to vary the degree of conjugation of the spin centre with the aromatic groups. It was shown[46] that diarylnitroxide radicals in which one aromatic ring is removed from conjugation with the nitroxide centre, while the other ring remains in the NO group plane, thus providing the $\pi-\pi$ interaction with the radical centre, is the optimal structure for both kinetic and thermodynamic stabilization (see Scheme 3). The *para*-position of the ring involved in conjugation should be protected by an appropriate substituent, while the ring removed from conjugation may be free. Therefor, first, the donor-acceptor properties of the molecule (and, hence, the redox potentials) can be varied over a broad range, and, second, not only the radicals, but also the oxoammonium cations and aminoxyl anions, which result from oxidation and reduction, respectively, can be stabilized in this way (see below Section 5).

This approach was used to prepare a series of twisted 2,2′- and 2,4′-substituted diarylnitroxides **12** – **16** containing a *tert*-butyl and/or trifluoromethyl group in various combinations.[46] These substituents are sufficiently bulky to prevent the conjugation of the *ortho*-substituted ring and they possess opposite electronic effects, which made it possible to investigate the influence of the electronic nature of the substituent on the relative arrangement of the aromatic rings in the diarylnitroxide molecule (see below Sections 4 and 5). These compounds are the first diarylnitroxides unsubstituted in the *para*-position [46,81] that are stable not only in the crystalline state, but also in solution. For comparison, 4,4′-substituted radical **17** was prepared. The amount of radical species detected by EPR for nitroxides **12** and **13** after storage for two weeks in a benzene solution at room temperature without light protection was 100% of the initial value. The stability of isomeric nitroxide **14** is somewhat lower (85%); however, in comparison with most of the previously known compounds of this type, this is a good result. It is noteworthy that these compounds are relatively stable also in halogenated solvents in which the previously known stable diarylnitroxides decompose in 10 – 15 min (see, for example, Ref. 74). Indeed, a sample of radical **12** did not undergo noticeable changes after being stored in $CDCl_3$ for 30 h without light protection.

Structures 12 – 17

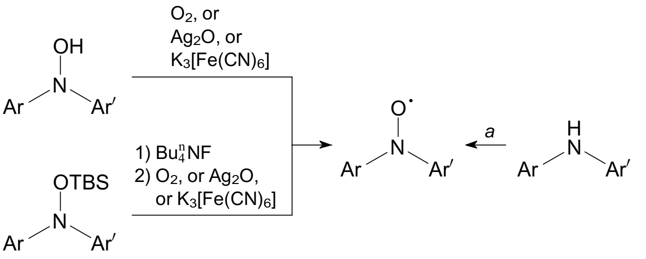


3. Key approaches to the synthesis of diarylnitroxides

The reactions giving the nitroxide group proceed with different efficiency in the case of alkyl and aryl derivatives and are accompanied by a number of side reactions. In the case of aryl derivatives, the problems are often associated with the stability of final products — this aspect has already been addressed in the previous Section. Although quite a few diarylnitroxides are known to date, no publications analyzing details of the synthesis of these radicals are available as yet.

There are two key approaches to the introduction of a nitroxide group to the molecule, in particular, oxidation of either amino or hydroxylamino group (Scheme 5). The former precursors (diarylamines) are more readily available from the synthetic standpoint. This is especially facilitated by the vigorous development of metal-catalyzed amination techniques observed in recent years.[82, 83] Therefore, we will first consider the methods based on the oxidation of the secondary amino group.

Scheme 5



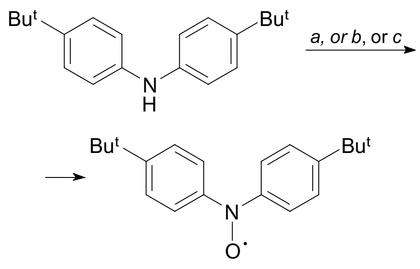
(*a*) mCPBA, or DMDO, or H_2O_2, Na_2WO_4; TBS = $SiBu^tMe_2$

The reagents employed most often for the oxidation of diarylamines are *m*-chloroperbenzoic acid (mCPBA), H_2O_2 in the presence of catalytic amounts of tungstates, and acetone oxide (dimethyldioxirane, DMDO). It is of interest to compare the efficiency of application of these reagents in various occasions.

Unlike oxidation of dialkylamines in which the nitrogen lone pair is not delocalized, oxidation of diarylamines can also involve the aryl *ortho*- and *para*-positions relative to the amino group. The regioselectivity of oxidation depends considerably on how potent is the chosen oxidant, *i.e.*, on the redox potential of the oxidant. Indeed, the oxidation of bis(4,4′-*tert*-butylphenyl)amine with mCPBA at 0 °C or with DMDO at −78 °C for 1 h gives the target nitroxide in 40% – 60% yield (Scheme 6),[77] which is much lower than that for alkylnitroxides under the same conditions (virtually quantitative yield[84]). However, the oxidation of the same amine with hydrogen peroxide in the presence of Na_2WO_4 affords the nitroxide in 80% yield, although this requires much more drastic conditions (refluxing in methanol for several hours).[57]

A comparison of these three oxidants and thorough analysis of side products were carried out[85] in relation to the oxidation of a pentacyclic aromatic diamine (Scheme 7). The yields of dinitroxide **7** in the reactions with DMDO and mCPBA were 10% and 20%, respectively. The reaction was accompanied by the formation of numerous diamagnetic side products as a result of oxidation of aromatic moieties at carbon atoms. The researchers cited[85] proposed a modification for the oxidation of this diamine with the $H_2O_2 - Na_2WO_4$ system based on phase transfer catalysis. The reaction was carried out at room temperature in a water – dichloromethane mixture in the presence of dodecyltrimethylammonium chloride for 14 h. This afforded mononitroxide in a yield of 30% together with another unidentified paramagnetic product. Thus, the use of the $H_2O_2 - Na_2WO_4$ system as the mildest oxidant results in a lower degree of oxidation (to mononitroxide) and higher regioselectivity (Scheme 7).

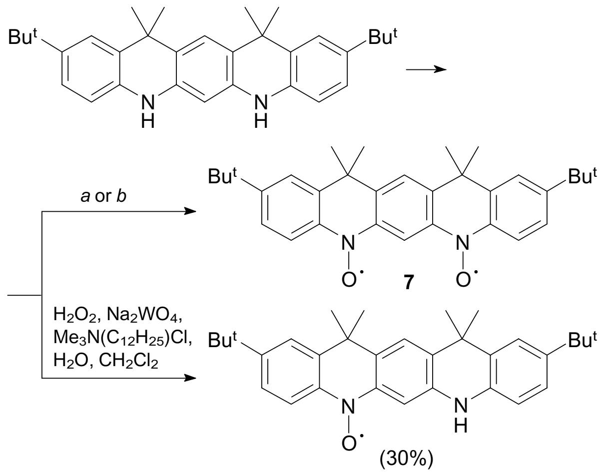
Scheme 6



1c

(*a*) DMDO, CH_2Cl_2, Me_2CO, −78 °C (40% – 60% yield); (*b*) mCPBA, $CHCl_3$, 0 °C (60% – 70%); (*c*) H_2O_2, Na_2WO_4, MeOH, 65 °C (70% – 80%)

Scheme 7



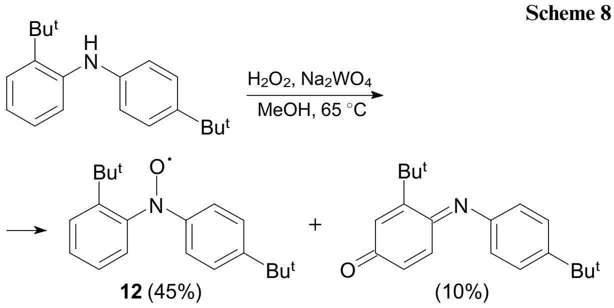
(*a*) DMDO, CH_2Cl_2, Me_2CO, −78 °C (10% yield); (*b*) mCPBA, $CHCl_3$, 0 °C (20%)

The lower oxidative ability of the $H_2O_2 - Na_2WO_4$ system is also manifested in the fact that the nitroxide yields depend appreciably on the electron-donating properties of substituents in the initial amine. The oxidation of *para*-CF_3-substituted diarylamine with this oxidant gives the nitroxide in ~30% yield, while the oxidation of the *ortho*-isomer with more pronounced electron-withdrawing properties does not give the target product at all.[46] In the latter case, diarylnitroxide can be obtained only with mCPBA as the oxidant.

The lower efficiency of the $H_2O_2-Na_2WO_4$ system in the oxidation of diarylamines compared with aliphatic analogues has already been noted in early publications (see monograph[86]). A rather efficient alternative method has been proposed,[87] but for some reason it has not found wide use. The idea is to heat diarylamines with a benzene solution of *tert*-butyl hydroperoxide in the presence of catalytic amounts of cobalt stearate. Acridane-derived nitroxides (compounds **4** and **5**) were synthesized by this procedure.[87]

It is worth noting that the yields of aromatic mononitroxides upon the oxidation with mCPBA are also highly dependent on the structure of the amine. Oka *et al.*[79] synthesized bridged *para*-phenyl-substituted diarylnitroxide **8**, with the yield in the oxidation step being 35%. This outcome is apparently attributable to the possibility for the oxidation to affect the *para*-phenyl substituents involved in delocalization of the nitrogen lone pair. This is confirmed by the fact that the planar bridged diarylamines of a similar structure containing a methoxy group in the *para*-position are oxidized to nitroxides (for example, compound **5**) in a much higher yield (60% – 70%), which is a consequence of the intelligent structural design consisting in protection of the *para*-position by an appropriate substituent. Similar results were obtained[46] upon the oxidation of diarylamines with bulky *ortho*-substituents (nitroxides **12** and **13**). The side product isolated in this reaction had a quinoid structure, indicating the occurrence of the oxidation of the unsubstituted *para*-position of the aryl moiety (Scheme 8).

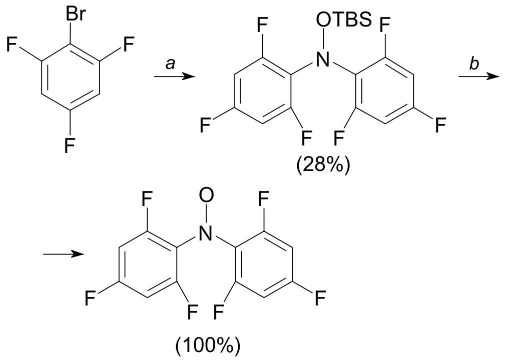
Scheme 8



Alternatively, hydroxylamines can be used as the precursors of diarylnitroxides. These compounds are very easily oxidized, in particular, with air oxygen;[57] therefore, the desired nitroxide can often be obtained directly without isolation of the intermediate hydroxylamine.[60, 88] Diarylhydroxylamines are usually generated by treatment of nitroso derivatives with organolithium or -magnesium compounds. Direct synthesis of symmetrical diarylnitroxides, for example, **1a – c**, by the treatment of pentyl nitrite (AmONO) with Grignard reagents has been proposed.[88] The nature of the oxidant converting hydroxylamine to nitroxide in this reaction has not been reliably established. Presumably,[88] this is air oxygen. The disadvantages of the method include a large number of side products (phenols, biphenyls and diarylamines) and low yields of nitroxides based on the initial aryl bromide (which is taken in a 1.5-fold excess over the stoichiometric amount).

Apart from air oxygen, silver oxide Ag_2O and an alkaline solution of $K_3[Fe(CN)_6]$ are efficient oxidants able to transform hydroxylamines to nitroxides. As a rule, hydroxylamine is not isolated in the free state, but is oxidized immediately after generation. A possible alternative are O-silylated hydroxylamine derivatives,[10, 80] which can be easily isolated. The subsequent deprotection is carried out together with oxidation as a one-pot reaction (see, for example, Scheme 9).

Scheme 9

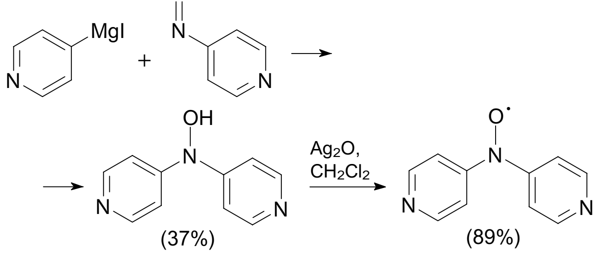


(*a*) 1) Bu^nLi, THF, −78 °C; 2) AmONO; 3) NH_4Cl (aq.); 4) TBSCl, imidazole; (*b*) 1) Bu^n_4NF; 2) $K_3[Fe(CN)_6]$, NaOH

In the case of pyridyl substituents, which are highly electron-withdrawing, hydroxylamine becomes more stable to air oxygen and can be isolated.[89] The subsequent oxidation with silver oxide gives the target nitroxide (Scheme 10).

As follows from the above examples, a drawback of all the synthetic routes to nitroxides *via* hydroxylamines is the low yield in the step of formation of hydroxylamine or its protected analogue and the necessity to use organometallic reagents, which have low tolerance to functional groups in the substrate molecule. Unfortunately, the nature of the side reactions that accompany the formation of hydroxylamine from nitroso compounds and organolithium or -magnesium derivatives has not been studied in detail. One-electron transfer can presumably be the major competing reaction,

Scheme 10



because organometallic compounds are strong reducing agents, while nitroso compounds are rather active oxidants. This is indirectly supported by the formation of diaryls and phenols as side products.[88]

Thus, analysis of the data available from the literature indicates that secondary aromatic amines are the most convenient precursors of diarylnitroxides. There is a wide choice of methods for the synthesis of these compounds, including those tolerating the presence of reactive functional groups in the molecule. Nevertheless, the step of amine oxidation to nitroxide requires thorough selection of the oxidant and reaction conditions, especially in the case of electron-deficient amines with the electron-withdrawing groups in the molecule. Conversely, diarylhydroxylamines can be oxidized rather easily to the corresponding nitroxides; however, problems can arise in the preparation of hydroxylamines. Hydroxylamines with electron-withdrawing substituents prove to be convenient for the isolation and subsequent oxidation, whereas electron-deficient diarylamines are rather difficult to oxidize. In this respect, the two considered synthetic approaches to diarylnitroxides (*via* diarylamines and hydroxylamines) complement each other

4. Structural features of diarylnitroxides and how they are reflected in the EPR spectra

The spin density distribution in diarylnitroxides is highly sensitive to their structural features, and this is reflected in the EPR spectra. In all cases, the spectra exhibit a triplet signal as a result of splitting at the nitrogen atom. However, the hyperfine coupling constant (hfcc) a(N) can vary over a rather broad range depending on the degree of spin density delocalization over the aromatic system (Table 1).

Table 1 presents the results of EPR investigation of relatively stable diarylnitroxides of various structural types. In all cases, the data were collected in aromatic hydrocarbons such as benzene,[55, 72, 93, 94] toluene[60] or xylene,[46, 54] which makes it possible to compare the hfcc values. It can be seen that the a(N) values are considerably lower for diarylnitroxides than for TEMPO or mixed aryl – alkyl derivatives (entries 1, 21 and 22 in Table 1). This attests to a significant contribution of the aromatic ring to the spin density delocalization; this contribution can be varied by introducing different substituents. The introduction of π-donor substituents into the *para*-position of the phenyl moiety decreases the degree of its involvement in spin density delocalization, which leads to increasing a(N) (entries 2 – 5 in Table 1). The most pronounced spin density delocalization is observed for perchlorinated diphenylnitroxide radical, which leads to a pronounced decrease in a(N) (entry 9 in Table 1).

The planarization of the radicals caused by introduction of an additional bridge between the phenyl moieties is favourable, as expected, for spin delocalization, resulting in a considerable increase in $a(\mathrm{H}_{ortho})$ and a decrease in a(N) (entries 10 – 12 in Table 1).

Suzuki *et al.*[74] investigated the effect of the nature of the bridging heteroatom (C, Si, Ge) on the spin density distribution in the dihydroacridine type radical (entries 13 – 15 in Table 1). Comparison of the a(N) values indicates that the spin density on the nitrogen atom is much higher in the Ge derivative than in the carbon and silicon counterparts. The large atomic radius of Ge leads to distorted molecular geometry and an elongated N – C bond. This decreases the efficiency of p – π overlap and hampers spin density delocalization over the aromatic moiety.

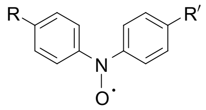
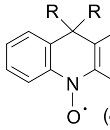
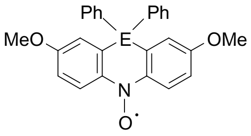
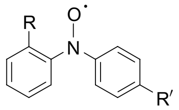
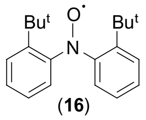
A study of twisted diarylnitroxides by EPR spectroscopy may serve as direct experimental evidence for the lack of conjugation between the *ortho*-substituted ring and the nitroxide radical centre. Table 1 presents the experimental g-factors and hfcc for the N, H and F nuclei in the series of these compounds. The signals were assigned relying on the results of density functional theory calculations (B1LYP/cc-pVDZ).[46] Good agreement between the experimental and theoretical data may imply the applicability of this method for quantitative prediction of EPR parameters for diarylnitroxides.

Analysis of the type of splitting in the EPR spectra and hyperfine coupling constants for a series of isomeric bis(*tert*-butylphenyl)nitroxides clearly demonstrates (entries 4, 18 and 20 in Table 1, Fig. 2) that in the case of *ortho*-substituted compounds, the aromatic ring is actually removed from the plane of conjugation with the nitroxide centre. The constant a(N) is the highest for the 2,2′-isomer, somewhat lower for the 2,4′-isomer and the lowest for the 4,4′-isomer in which the spin density is delocalized over both aromatic rings. Further splitting from the protons is also different for the three isomers.[46]

The spectra of fluorinated nitroxides are more intricate because of additional splitting caused by ^{19}F (see Fig. 2). However, the constant a(F) is also sensitive to rotation of the phenyl moieties. For example, the values for the *ortho*- and *para*-substitution differ more than fivefold (entries 16 and 17 in Table 1; isomeric nitroxides **13**, **14**).

It is of interest that the rotation of the phenyl moiety depends not only on the bulk of the *ortho*-substituent, but also on the electronic properties of substituents in both aromatic rings. The observed a(N) values markedly differ between 2,4′-bis(*tert*-butylphenyl)nitroxide (**12**) and 2-*tert*-butyl-4′-trifluoromethyldiphenylnitroxide (**13**) (10.34 and 9.7 G), although the steric crowding of both compounds is the same, because it is caused by the presence of the same Bu^t group. It was shown[46] that the dihedral angle θ between the NO group and the plane of the benzene ring removed from the conjugation is an important parameter reflecting the overall influence of the steric and electronic factors on the spin density distribution in the diarylnitroxide molecule. As can be seen in Fig. 3, the calculated dihedral angles are well correlated with the spin density on the carbon atoms of the *ortho*-substituted phenyl moiety. The Newman projection shown in Fig. 3 illustrates the π – π interaction between the NO group and the benzene ring deviating from its plane. Figure 3 presents the dihedral angles not only for 2,4′-, but also for 4,4′-disubstituted nitroxides. It can be seen that in the latter case, the benzene rings do not deviate much from the NO-group plane, while the spin density on the *para*-substituted rings is, conversely, the highest. For the unsymmetrical 4,4′-substituted nitroxide **17**, the dihedral angles of the two rings are different; therefore, two points correspond to one structure.

Table 1. g-Factors and hyperfine coupling constants for the N nuclei and protons of the phenyl moieties in diarylnitroxides.

Entry	Nitroxide		g-Factor	a(N) /G	a(H) /G			Ref.
					ortho	*meta*	*para*	
1		$R = R' = H$	2.0055	9.66	1.83	0.79	1.83	54, 90
2		$R = R' = Me$	2.0055	9.79	1.93	0.79		54
3		$R = R' = OMe$ (**1a**)	2.0055	10.07	1.89	0.74		54, 91
4		$R = R' = Bu^t$ (**1c**)	2.0059	9.74	1.81	0.91		46
5		$R = R' = F$	2.0056	10.37	1.96	0.83		54
6		$R = R' = Br$	2.0068	9.30	1.84	0.85		54
7		$R = OMe$, R' is pyrrol-1-yl (**1d**)	–	9.73	1.72[a] 1.98[b]	0.89		60
8		$R = Bu^t$, $R' = CF_3$ (**17**)	2.00595	9.29	0.82 (rel. CF_3) 0.74 (rel. Bu^t)	2.86 (rel. CF_3) 0.88 (rel. Bu^t)	2.86 a(F)	46
9	$(C_6Cl_5)_2NO^{\bullet}$		2.0060	8.4				55
10	 (**4**)	$R = Pr^n$	2.0050	8.82	2.37	0.77	2.37	72
11		$R = Ph$	2.0053	8.94	2.32	0.78	2.32	71
12		$R = p$-Tol	2.0053	8.94	2.32	0.78	2.32	71
13		$E = C$ (**5a**)	2.0052	9.30	2.44	0.60		74
14		$E = Si$ (**5b**)	2.0046	9.33	2.23	0.70		74
15		$E = Ge$ (**5c**)	2.0048	9.66	2.21	0.54		74
16		$R = Bu^t$, $R' = CF_3$ (**13**)	2.00611	9.70	2.61(2H) 0.43(1H)	0.92 0.63 0.48	0.24 3.74 a(F)	46
17		$R = CF_3$, $R' = Bu^t$ (**14**)	2.00607	10.02	2.52(2H) 0.4(1H) 0.63 a(F)	0.85(2H)		46
18		$R = R' = Bu^t$ (**12**)	2.00580	10.34	2.65(2H) 0.50(1H)	0.88(2H) 0.66(1H)	0.43(1H)	46
19		$R = R' = CF_3$ (**15**)	2.00610	9.39	2.57(2H) 0.51(1H) 3.43 a(F)	1.05(2H) 0.40(1H) 0.44(1H)	0.49(1H) 0.16 a(F)	46
20	 (**16**)		2.00621	10.59	1.40	1.21 0.67	0.82	46
21	p-$O_2NC_6H_4(NO^{\bullet})Bu^t$		2.0059	10.46	2.23	0.90		92
22	TEMPO		2.0061	14.48				93, 94

[a] For anisyl moiety; [b] for pyrrolophenyl moiety.

The conclusions about spin density delocalization over the aromatic system derived from analysis of experimental EPR data for nitroxides are in good agreement with the results of DFT quantum chemical calculations.[46, 95] Figure 4 shows the spatial distribution of the singly occupied orbitals (SOMO) for alkylnitroxide (TEMPO), planar diarylnitroxide [$(4\text{-}MeOC_6H_4)_2NO$, **1a**] and twisted diarylnitroxide **13**, in which one aromatic ring is displaced from the nitroxide group plane because of steric hindrance created by the bulky Bu^t substituent in the *ortho*-position. It can be seen that in the alkyl derivatives, the spin density is localized only on the nitroxide moiety (see Fig. 4 *a*), whereas in the 4,4′-disubstituted diarylnitroxide molecule, the spin density is delocalized throughout the extended π-system comprising both aromatic rings (see Fig. 4 *b*). The deviation of the phenyl moiety from the nitroxide group plane substantially decreases the spin density on its atoms (see Fig. 4 *c*), which leads to decreasing contribution of the undesirable radical reactions and increasing stability of the compounds.

Apart from stabilization of the radicals, an important issue is the possibility to generate stable redox forms. As shown by calculations,[47] rotation of one of

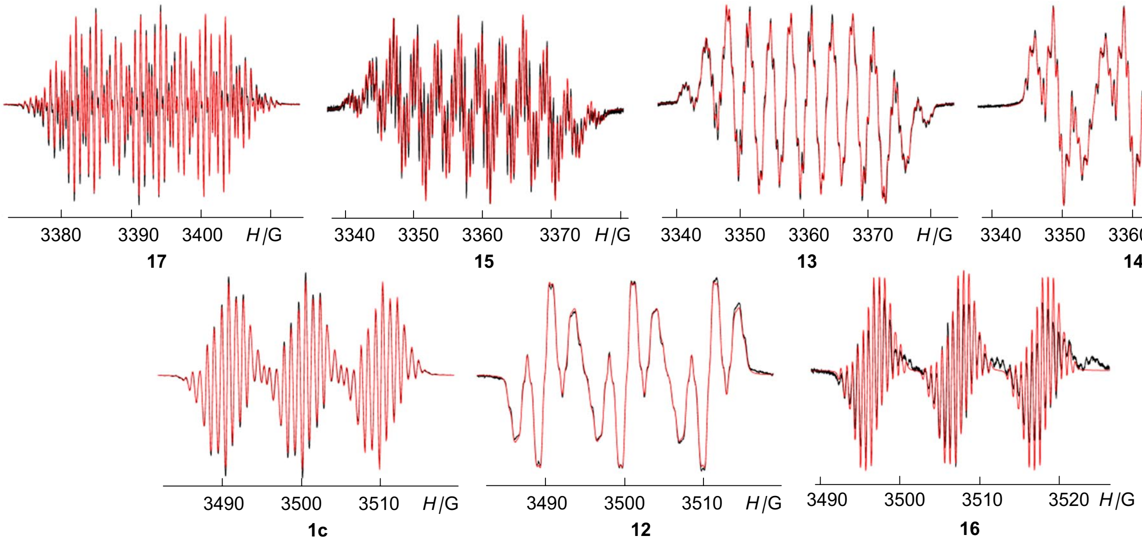


Figure 2. Experimental and simulated EPR spectra for twisted nitroxides **12** – **16** and bis-*para*-substituted **1c** and **17**.[46]

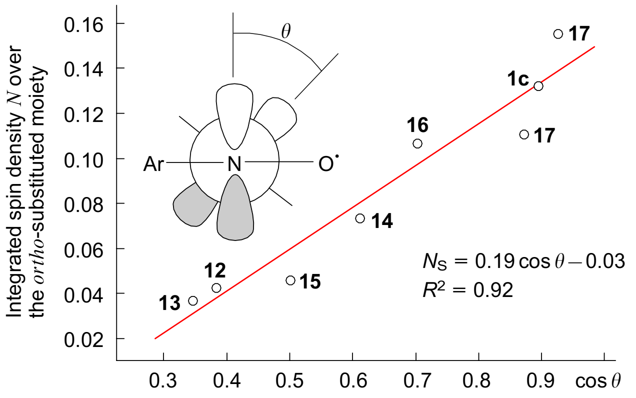


Figure 3. Spin density on the *ortho*-substituted moiety as a function of the dihedral angle for nitroxides **12** – **16** (according to Ref. 46).
The data for bis-*para*-substituted nitroxides **1c** and **17** are given for comparison.

the aromatic rings leads to a substantial stabilization of the reduced form (for details, see Section 5), which could not be achieved previously in the case of alkylnitroxides. Apart from the kinetic stabilization of the reaction centres, different positions of the rings open up new opportunities for the control of the donor-acceptor properties of the molecule and charge delocalization through both π- and σ-interactions. It should be emphasized that in the case of alkyl derivatives, the major contribution to stabilization of both the parent radicals and their reduced forms is made only by shielding of the reaction centre.

5. Redox properties of diarylnitroxides

Since the practical use of nitroxides is based to a large extent on their redox properties, the experimental and quantum chemical estimates of the redox potentials are of considerable interest.

The electrochemical behaviour of TEMPO derivatives and other alkylnitroxides has been studied in considerable detail (see, for example, Refs 48, 95 – 102). Rather recently, publications devoted to voltammetric investigations for mixed aryl(alkyl)nitroxides started to appear.[102 – 104] The electrochemical properties of diarylnitroxides are much less studied,[74, 80, 95, 105] first of all, because of the scanty number of stable compounds of this type known until recently.

Nitroxides can undergo one-electron oxidation to give oxoammonium cations and reduction to give ami-

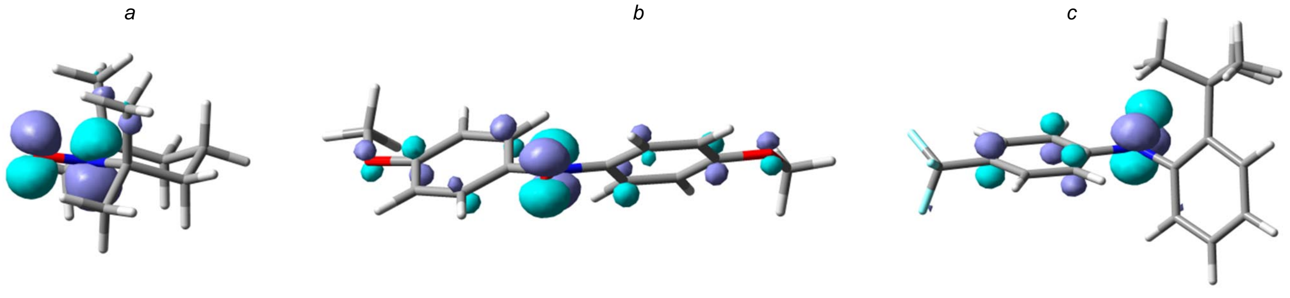
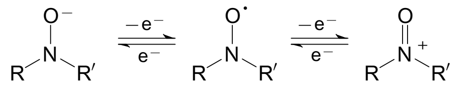


Figure 4. Singly occupied molecular orbitals for dialkylnitroxide (TEMPO) (*a*), dianisylnitroxide (**1a**) (*b*) and twisted diarylnitroxide **13** (*c*).[47]

Scheme 11

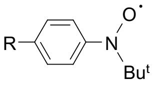
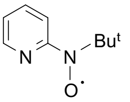
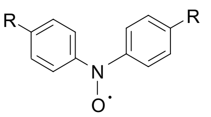
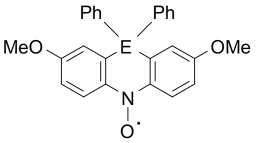
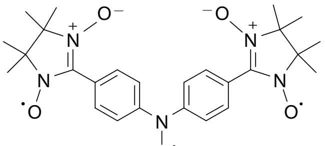
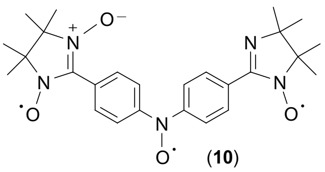
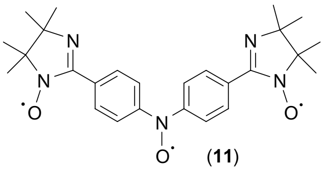


noxyl anions over the accessible range of potentials (Scheme 11).

The oxidation is reversible in most cases and the electron transfer is rather fast. In the case of TEMPO, the standard rate constant for heterogeneous electron transfer is $k^\circ = 10^{-1}$ cm s^{-1} (Ref. 102), and for aryl(alkyl)nitroxides Bu^{t}NOC$_6$H$_4$R, values of the same order of magnitude were obtained, namely $k^\circ = 1.1 \times 10^{-1}$ cm s^{-1} for R = Bu^t and $k^\circ = 1.7 \times 10^{-1}$ cm s^{-1} for R = OMe.[102] It should be emphasized that the high rate of electron transfer typical of organic radicals makes them especially promising as redox mediators and electroactive materials. For comparison, k° for inorganic ions is of an order of $10^{-1} - 10^{-2}$ cm s^{-1} (for example, for Co$^{2+/3+}$, $k^\circ = 10^{-2}$ cm s^{-1}), while for the reduction of organic disulfides, which are also applicable as redox-active materials, $k^\circ = 10^{-8}$ cm s^{-1}.[106]

Table 2 summarizes the oxidation potentials of planar diarylnitroxides; for comparison, the values for TEMPO and two aryl(alkyl)nitroxides studied in most

Table 2. Oxidation half-wave potentials for some nitroxides.

Radical	$E_{1/2}$/V	Conditions [a]	$E_{1/2}$/V *vs.* Ag/AgCl, KCl$_{sat}$	Ref.
TEMPO	0.65	GC, 0.1 M Bu$^n_4$NBF$_4$, AN, SCE	0.70	103
	0.58	Pt, 0.1 M Bu$^n_4$NBF$_4$, AN, Ag$^+$/Ag	0.71	48
	0.68	Pt, 0.1 M Bu$^n_4$NBF$_4$, AN, Ag/AgCl	0.72	102
 R = Bu^t	0.71	GC, 0.1 M Bu$^n_4$NBF$_4$, AN, SCE	0.76	103
	0.75	Pt, 0.1 M Bu$^n_4$NBF$_4$, AN, Ag/AgCl	0.79	102
R = MeO	0.56	Pt, 0.1 M Bu$^n_4$NBF$_4$, AN, Ag/AgCl	0.60	102
	1.00	GC, 0.1 M Bu$^n_4$NPF$_6$, AN, SCE	1.08	104
 R = OMe (**1a**)	−0.14	Graphite, 1.0 M Et$_4$NBF$_4$, PC, Ag/AgNO$_3$	0.58	95
	0.12	Pt, 0.1 M Et$_4$NClO$_4$, AN, Fc$^+$/Fc	0.59	105
R = Bu^t (**1c**)	0.81	Pt, 0.1 M Bu$^n_4$NBF$_4$, AN, Ag/AgCl/KCl	0.81	47
R = CMe$_2$Ph (**1b**)	0.11	Graphite, 1.0 M Et$_4$NBF$_4$, PC, Ag/AgNO$_3$	0.83	95
 E = C (**5a**)	0.10	Pt, 0.1 M Bu$^n_4$NPF$_6$, AN, Fc$^+$/Fc	0.58	74
E = Si (**5b**)	0.19	Pt, 0.1 M Bu$^n_4$NPF$_6$, AN, Fc$^+$/Fc	0.67	74
E = Ge (**5c**)	0.17	Pt, 0.1 M Bu$^n_4$NPF$_6$, AN, Fc$^+$/Fc	0.65	74
 (**9**)	0.42,	Pt, 0.1 M Bu$^n_4$NClO$_4$, AN, Ag/Ag$^+$(AN)	0.86,	80
	0.97	Pt, 0.1 M Bu$^n_4$NClO$_4$, AN, Ag/Ag$^+$(AN)	1.41	80
 (**10**)	0.42,	Pt, 0.1 M Bu$^n_4$NClO$_4$, AN, Ag/Ag$^+$(AN)	0.86,	80
	0.82,	Pt, 0.1 M Bu$^n_4$NClO$_4$, AN, Ag/Ag$^+$(AN)	1.26,	80
	1.01	Pt, 0.1 M Bu$^n_4$NClO$_4$, AN, Ag/Ag$^+$(AN)	1.45	80
 (**11**)	0.68,	Pt, 0.1 M Bu$^n_4$NClO$_4$, AN, Ag/Ag$^+$(AN)	1.12,	80
	0.99	Pt, 0.1 M Bu$^n_4$NClO$_4$, AN, Ag/Ag$^+$(AN)	1.43	80

[a] Conditions of measurements: working electrode material, supporting electrolyte, solvent, reference electrode. Abbreviations: GC is glassy carbon, AN is acetonitrile, PC is propylene carbonate, Fc is ferrocene.

detail — *N-tert*-butyl-*N*-(4-*tert*-butylphenyl)nitroxide and *N-tert*-butyl-*N*-(pyridyl)nitroxide — are also included. Since the conditions of the voltammetric measurements in the cited publications are different, the oxidation potentials were referred to the same silver chloride reference electrode Ag/AgCl, $KCl_{(sat.)}$. In those cases where the oxidation involves several redox transitions (*e.g.*, if there are several radical centres in the molecule), the potentials are separated by commas.

A comparison of the oxidation potentials for TEMPO and aryl-containing nitroxides indicates that the spin density delocalization over the aromatic moiety induces an increase in the oxidation potential. Pyridyl derivatives, as well as arylnitroxides with electron-withdrawing substituents in the aromatic ring are oxidized at even higher anodic potentials. The plots shown in Fig. 5 clearly demonstrate[104] to what extent the oxidation potentials of arylnitroxides are more sensitive to functionalization *via* introduction of substituents than the oxidation potentials of alkyl derivatives. The ρ value (the slope) of the Hammett linear correlation is four times greater for aryl derivatives than for alkyl derivatives, which provides more extensive opportunities for structural tuning of the potential.

The structure – property relationships for alkylnitroxides have also been studied.[48, 98, 107, 108] Apart from the Hammett correlations, a good linear correlation was observed between the electrochemical potentials and group (Pauling) electronegativity of the β-substituents in cyclic dialkylnitroxides.[98] Linear correlations were obtained for both the oxidation and reduction potentials, although reduction is irreversible and is complicated by the subsequent chemical step.

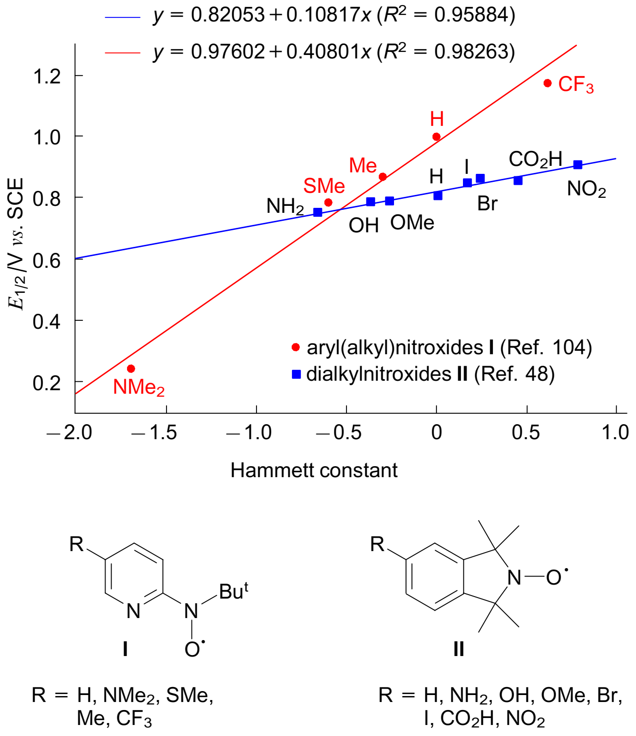
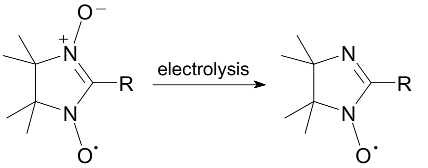


Figure 5. Oxidation potentials *vs.* the substituent nature for two series of nitroxides.
SCE is the saturated calomel electrode.

The influence of the nature of the bridging heteroatom (C, Si, Ge) on the oxidation potentials and oxidation pattern of diphenyldihydroacridine-derived nitroxides (compound **5**) is moderate: in all cases, reversible one-electron oxidation occurs at similar potentials.

The electrochemical properties of nitroxide triradicals **9** – **11** have been reported.[80] In symmetrical triradicals **9** and **11**, two identical radical centres are oxidized in one two-electron wave, whereas the oxidation of three radical centres in unsymmetrical triradical **10** proceeds successively: nitronyl nitroxide is the first, imino nitroxide is the second, and finally diarylnitroxide is oxidized at the most positive potential. It is worth noting that in the symmetrical nitronyl nitroxide triradical, the spin density delocalization involves both terminal radical centres, whereas in the unsymmetrical triradical only the nitronyl nitroxide moiety is involved in conjugation (see Scheme 4). Unlike phenyl-containing stable triradicals **9** – **11**, the nitronyl nitroxides studied by Kadirov *et al.*[109] using cyclic voltammetry in combination with EPR detection proved to be unstable and were spontaneously converted to the corresponding imino nitroxides upon elimination of an oxygen atom (Scheme 12). It was shown[109] that the transformation to the imino nitroxide can also be accomplished electrochemically by selecting an appropriate cathode potential.

Scheme 12



R is pyrazol-4-yl, pyrazol-5-yl, imidazol-5-yl, *etc.*

The electrochemical reduction of almost all nitroxides known until recently, including both alkyl and aryl derivatives, except for some nitronyl nitroxides and their derivatives (see, for example, Refs 110 – 112) is irreversible. The electron transfer is accompanied by fast chemical transformation (for example, protonation), because a highly basic anionic centre is formed on the oxygen atom (especially in the case of alkyl derivatives). This precluded the use of alkyl- or arylnitroxides as ambipolar redox-active materials.

A rather broad range of stable diarylnitroxides capable of reversible oxidation and reduction were prepared quite recently;[47] these compounds are representatives of twisted diarylnitroxides. A possible cause for the increased stability of aminoxyl anions was identified in this case by quantum chemical calculations. It was shown[47] that the CCNO dihedral angles of the *ortho*-substituted phenyl moiety are considerably different between the radicals and their oxidized or reduced forms (Table 3). For example, the dihedral angle is two times smaller in the reduced form of nitroxide **14** (R = *o*-CF_3, R′ = *p*-Bu^t) than in the initial radical,

Table 3. Oxidation and reduction half-wave potentials of twisted diarylnitroxides **12** – **16** and bis-*para*-substituted nitroxides **1c** and **17** and calculated dihedral angles in cationic, radical and anionic forms.[47]

Diarylnitroxide	Dihedral angle C – C – N – O /deg			Electrochemical properties (Pt, CH_3CN, *vs.* Ag/AgCl, KCl_{sat})		
	radical	cation	anion	oxidation $E_{1/2}$ /mV	reduction $-E_{1/2}$ /mV	ΔE /mV
12	67.4	45.4	44.6	952	919	1871
13	69.8	38.5	51.8	1230	648	1878
14	52.2	49.8	24.6	1079	809	1888
15	59.9	41.7	30.2	1391	91, 268, 538	1482
1c				808	866	1674
17				1015	451, 546, 1170	1466
16	45.3	37.5	37.5	920 [a]	940 [a]	1860

[a] Calculated data.

although the steric crowding does no change and is caused by the presence of one and the same trifluoromethyl group. The reason is that the electronic effect of this group is highly important for stabilization of the anion to counterbalance the adverse effect of the electron-donating alkyl substituent. Conversely, the dihedral angle in the oxidized cationic form of radical **14** is the greatest among the given series of compounds, which minimizes the destabilizing action of the electron-withdrawing CF_3 group. In the isomeric nitroxide **13** ($R = o$-Bu^t, $R' = p$-CF_3), the situation is the opposite: the molecule tends to counterbalance the influence of the CF_3 group in the cation by decreasing the torsion angle of the *ortho*-substituted ring as much as allowed by steric hindrance. This leads to stabilization of both the oxidized and reduced forms of the radical. Thus, the targeted molecular design of a twisted nitroxide may give rise to a smart self-tuning system, which would be of interest for various practical applications.

It should be noted that a change in the dihedral angle allows varying the redox potentials over rather broad limits. Thus, the oxidation potentials of isomeric nitroxides **13** and **14** differ by 151 mV, which exceeds the potential difference between nitroxides of **12** and **14**, which differ only by the nature of the *ortho*-substituent (127 mV, CF_3 and Bu^t). Of particular interest is the fact that a change in the dihedral angle allows one to shift the oxidation and reduction potentials to opposite directions (whereas a change in the substituent nature normally shifts the potentials to the same direction). This is important for the elaboration of ambipolar redox-active materials for which the electrochemical window determines the electromotive force (emf) of the future device. It should be emphasized that replacement of one highly electron-donating amino group by a highly electron-withdrawing nitro group in the dialkylnitroxides shown in Fig. 5 [48] leads to a minor change in the oxidation potential (< 100 mV). This comparison vividly demonstrates the efficiency of varying the dihedral angles in twisted diarylnitroxides as a molecular design tool.

Relatively low cost of nitroxide radicals and their ability to form stable oxidized and reduced forms over an accessible potential range make these compounds promising for the use in various energy devices. The design and synthesis of redox-active materials for the construction of hybrid and organic radical batteries have become more and more significant in recent years. Although currently these devices are inferior in efficiency to the widely used analogues based on inorganic materials, they have a number of important advantages, which stimulate research in the field of organic redox-active materials. First of all, this is dictated by modern requirements of the chemistry of sustainable development and related to the lower toxicity of organic compounds to the environment, inexhaustibility of raw materials and closed production cycle (renewable feedstock and the possibility of waste recycling).[49, 106] Recent reviews [2, 111] present a detailed description of various classes of organic compounds that may be of interest as redox-active materials for energy storage and conversion devices. Not the least of these are nitroxides, first of all, owing to the high electron transfer rate during oxidation, which is not accompanied by structural rearrangement of the molecule. The use of alkylnitroxides as cathode materials for organic lithium batteries,[20, 23, 113] organic [114 – 117] and flow [8, 113, 118, 119] batteries and so on has been described in numerous publications and they showed reasonably good efficiency. Detailed consideration of this issue is beyond the scope of this review; therefore, we will consider only several parameters. Figure 6 shows a comparison of redox potentials for a number of organic compounds that were proposed as redox-active materials (numerical values were taken from a review [111] and original papers [47, 103, 120]). The range of compounds includes phenoxyl radicals, nitroxides (TEMPO, alkylaryl, nitronyl and diaryl type nitroxides) as well as carbonyl compounds and fused thienothiophenes, which demonstrated reasonably good characteristics. It can be seen that aryl-containing nitroxides (both mixed alkylaryl and especially diaryl ones) provide much higher cathode potentials than their alkyl analogues and, hence, higher emf of the device. Some diarylnitroxides can operate as anode materials.

The plots shown in Fig. 7 compare the theoretical specific capacity and energy density that can be attained when the same set of compounds is used as cathode materials. It can be seen that quite competitive charac-

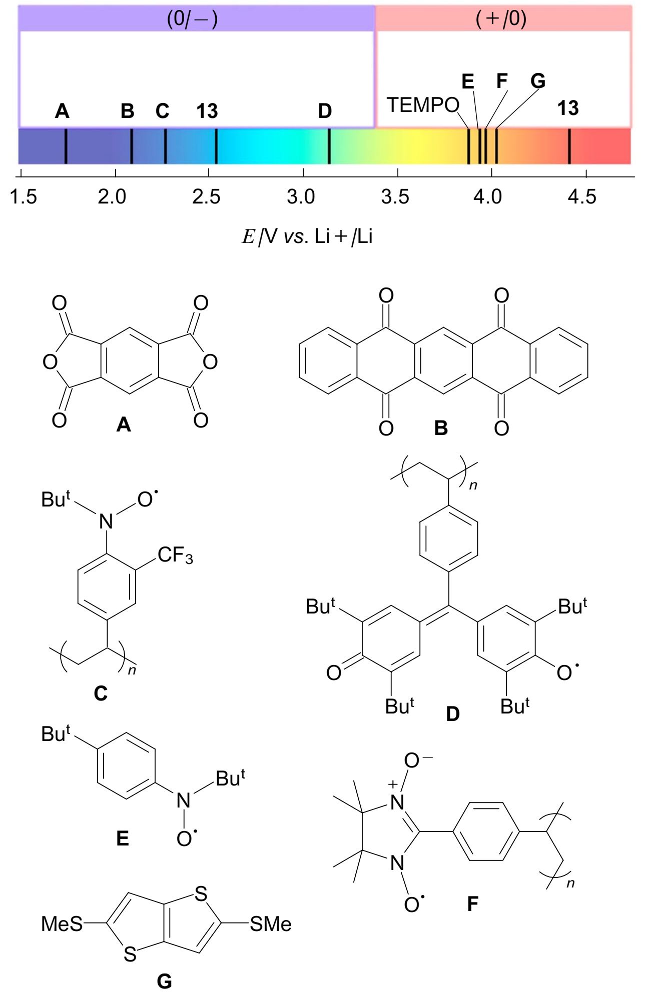


Figure 6. Comparison of the redox potentials for a number of organic compounds proposed as redox-active materials (according to Refs 47, 103, 111 and 120).

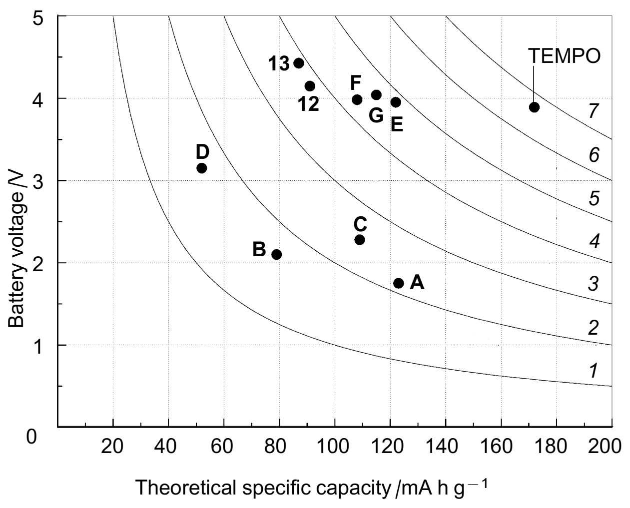


Figure 7. Comparison of the theoretical specific capacity and energy density for a number of organic compounds (according to Refs 47, 103, 111 and 120).
(*1*) 100, (*2*) 200, (*3*) 300, (*4*) 400, (*5*) 500, (*6*) 600, (*7*) 700 W h kg^{-1}. For the letter designations of the compounds, see Fig. 6.

teristics can be attained by means of the molecular design of twisted diarylnitroxides, and this trend will persist.

A highly promising and rapidly advancing area is the development of new ambipolar redox-active electrode materials for organic radical batteries. For this purpose, the compound must generate a stable redox pair both in the anodic and cathodic regions, preferably, with the difference between the standard potentials being as great as possible. The stability of the oxidized and reduced forms of twisted diarylnitroxides was demonstrated not only by means of cyclic voltammetry, but also by long-term experiments with repeated potential sweep in the anodic and cathodic redox transition regions, which did not result in a change of either current or transition potentials.[47]

It is noteworthy that only few organic molecules potentially suitable as ambipolar redox-active materials are known to date. The problem is that n-type nitroxides (able to form a stable redox pair in the cathodic region) are rarely encountered. Mention may be made of the recently synthesized [22] series of monomeric and polymer chain-grafted perfluoroarylalkylnitroxides, for which a reversible transition takes place at large negative potentials (−0.9 to −1.4 V *versus* Ag/AgCl/KCl). Nitronyl nitroxides also deserve mention; some of them produce stable redox pairs not only in the anodic, but also in the cathodic region.[111,121] However, the potential difference between the anodic and cathodic redox pairs for known nitronyl nitroxides is considerably smaller than that demonstrated by some twisted diarylnitroxides. For example, for nitronyl nitroxide **F** (see Fig. 6) and its analogue with the unsubstituted benzene ring considered by Liang *et al.*,[111] this value is 1.33 V, whereas for 2,4′-di-*tert*-butylphenylnitroxide (**12**) it is markedly larger (~1.9 V).[47]

6. Quantum chemical estimation of redox potentials of nitroxides as a molecular design tool

Since most of the practical applications of nitroxides are based on their redox properties and the synthesis of these compounds is fairly labourious, a theoretical estimation of the oxidation and reduction potentials may be very helpful. Quantum chemical calculations of redox potentials for a broad range of compounds help to identify the most appropriate candidates for the subsequent synthesis and experimental investigations. The obtained results underlie the molecular design of the most promising compounds. However, in this case, a key issue is sufficient accuracy of the theoretically calculated redox potentials.

The first publication [122] dealing with calculation of the oxidation potentials for TEMPO and some its derivatives appeared in 1999; the authors used the semi-empirical AM1 method in combination with the SM2 solvation model;[22] nevertheless, reasonably good agreement with experimental values was attained. Later, quantum chemical estimation of the redox potentials of nitroxides was carried out in some other studies.[15,48,99,122,123] A highly important part of quantum chemical calculations of redox potentials in solution is to consider the contribution of solvation. Most of the publications cited above used the continuum solvation models PCM and CPCM, which often provide a reasonably good agreement between experimental and theoretical values. As regards the choice of the type of the functional and the basis set, there seems to be no universal protocol: different approaches provided the best agreement for different types of nitroxides.

Blinco *et al.*[48] carried out DFT calculations and experimental studies for 25 piperidyl, isoindolyl, pyrrolidine and azaphenalene type dialkylnitroxides. It was shown that introduction of aromatic groups, even not directly linked to the nitroxide centre, affects the oxidation potential by making it 100 – 120 mV more anodic. Also, the presence of an aromatic ring makes it possible to insert a broad range of donor or acceptor substituents into the molecule, which, as expected, affects the potentials, although to a much lower extent than in the presence of conjugation. The appearance of this publication is symptomatic in some way: the possibility of functionalization of 'classical' alkylnitroxides is limited and this issue cannot go without aromatics.

The researchers cited[48] attained good agreement between the experimental and theoretical values of oxidation potentials. For all compounds they considered, except for azaphenalene derivatives, the error was ~ 50 mV; the energy was calculated at the G3(MP2)-RAD level and structure optimization was carried out using the B3LYP/6-31G(d) method and a continuum solvation model (PCM). In the case of azaphenalenes, the applied calculation algorithm proved to be inapplicable, resulting in a large error of 600 mV. Later the agreement between experimental and theoretical results was improved;[123] however, the presented data indicate that the quantum chemical approaches useful for alkyl compounds may possess much lower predictive power when the molecule contains aromatic moieties.

A relatively recent publication is devoted to quantum chemical calculations of the oxidation potentials of adamantyl and azabicyclic type dialkylnitroxides.[99] The calculations were carried out by the PBE1PBE/6-31 + G(d,p) method with a continuum solvation model. This resulted in a rather good correlation ($R^2 = 0.92 - 0.98$) between the experimental oxidation potential values and the calculated free energy difference between the initial radical and the oxidized form (ΔG).

A theoretical evaluation of the redox properties of arylalkyl type nitroxides is reported only in one publication.[104] This was done for a series of *N*-(2-pyridyl)-*N*-*tert*-butylnitroxides with various substituents in the pyridine ring. As in the publication cited above,[99] a good correlation was obtained between ΔG and experimentally determined oxidation potentials of the nitroxide radical – oxoammonium cation transition. The average deviation between the experimentally determined potentials and theoretical values obtained with this correlation is 30 mV. This confirms the predictive power of the proposed theoretical model (B3LYP/6-31G*, CPCM SCRF).

The situation with the calculation of reduction potentials is much more complicated. For none of the types of functionalized alkylnitroxides studied by Blinco *et al.*[48] was it possible to generate a reversible redox transition in the cathodic region; the electron transfer was accompanied by fast chemical transformations of aminoxyl anions, first of all, protonation. Therefore, the experimentally measured reduction potentials are not thermodynamic values. This requires introduction of additional corrections and hampers comparison of experimental and theoretically calculated potentials for the reduction of nitroxide radicals to aminoxyl anions.

Since quantum chemical calculations serve as a tool for screening of the optimal structures for the subsequent synthesis, they should not be too complicated and take too much computing time. In this respect, mention should be made of the recently proposed[124] method for calculating the redox potentials of diarylnitroxides based on the density functional theory with the gradient-corrected PBE functional and the L2 basis set implemented in the PRIRODA program package[125] in combination with the two-step procedure for considering solvation in terms of the continuum model. The two-step method[126] for calculation of the solvation energy was proposed not long ago. The first step is calculation of the molecular wave function and calculation of the atomic charges according to Merz – Kollman[127, 128] without considering the interaction with the solvent. This protocol for determination of atomic charges is based on approximation of the electrostatic potential, calculated by quantum chemical methods, by an electrostatic potential generated by a system of charges located at the centres of atoms forming the molecule. The next stage is solving the Boltzmann – Poisson equation for the molecular system of charges defined in this way for known solvent parameters. This approach made it possible to attain good agreement of the potentials with experimental values for both alkyl- and arylnitroxides (the average deviation is 33 mV); it was used to perform rough calculations of the oxidation potentials for several previously unknown diarylnitroxides,[124] which may be of interest for practical applications.

7. Conclusion

The presented analysis of published data dealing with diarylnitroxides indicates that the potential of this important class of radicals is far from being exhausted. Currently, two major trends have been formed in the molecular design of diarylnitroxides, which supplement each other and are directed towards solution of different problems.

The first trend has been developed since rather long ago; it is aimed at the design of structures stable in the crystalline state and planarized as fully as possible, which gives rise to spin delocalization over the extended p – π conjugation system and to numerous inter – and intramolecular contacts. These compounds are of interest for the design of molecular magnets. Polyradicals containing several diarylnitroxide moieties, which ensure high spin density, are especially attractive for this purpose.

The second trend in the design of stable diarylnitroxides has appeared rather recently. It is based on exactly the opposite idea: for the preparation of a structure stable not only in the crystalline state, but also in solution, it is necessary to remove one of the aromatic rings from the plane of conjugation with the nitroxide centre. This can be achieved by introducing a rather bulky substituent into the *ortho*-position of the aromatic ring. Both kinetic and thermodynamic stabilization of the radicals is possible in this system. More-over, the dihedral angle between the aromatic ring and the plane of the NO moiety can serve as an additional tool for fine tuning of the physicochemical properties of nitroxides (redox potentials, spectral characteristics and so on), apart from traditional tools such as varying the nature, number and positions of substituents in the aromatic ring. This approach can be used to obtain radicals stable in solution, which opens up the way for a variety of practical applications.

As indicated in recent publications, the latter approach to the molecular design of diarylnitroxides stabilizes not only the radicals, but also their oxidized and, what is especially important, reduced forms, which could not be attained previously for either aliphatic or aromatic nitroxide derivatives. The additional stabilization of the oxidized and reduced forms comes from the spontaneous change in the dihedral angle (and, hence, the degree of conjugation) between the aromatic ring and the NO moiety upon oxidation or reduction. The molecule itself adjusts the fine balance between the electronic stabilization of charged particles (cations and anions) and steric crowding, which depends on both the bulkiness of the *ortho*-substituent and the electronic nature of the substituent in both phenyl moieties.

The diarylnitroxides that are stable in solution and able to form stable oxidized and reduced forms are of great interest as possible redox-active cathode materials for lithium ion batteries and ambipolar materials for organic radical batteries. The latter circumstance is especially promising, because ambipolar redox-active materials can be used to design stable polarless devices with high tolerance to the type of membrane separating the cathode and anode compartments.

The review was written with the financial support of the Russian Science Foundation (Project No. 16-13-10282).

References

1. G.I.Likhtenshtein, J.Yamauchi, S.Nakatsuji, A.I.Smirnov, R.Tamura. *Nitroxides. Applications in Chemistry, Biomedicine, and Materials Science*. (Weinheim: Wiley-VCH, 2008)
2. S.Muench, A.Wild, C.Friebe, B.Häupler, T.Janoschka, U.S.Schubert. *Chem. Rev.*, **116**, 9438 (2016)
3. C.J.Hawker, A.W.Bosman, E.Harth. *Chem. Rev.*, **101**, 3661 (2001)
4. H.Karoui, F.Le Moigne, O.Ouari, P.Tordo, in *Stable Radicals: Fundamentals and Applied Aspects of Odd-Electron Compounds*. (Ed. R.G.Hicks). (Chichester: Wiley, 2010). P. 173
5. A.Studer, T.Schulte. *Chem. Rec.*, **5**, 27 (2005)
6. R.B.Grubbs. *Polym. Rev.*, **51**, 104 (2011)
7. B.P.Soule, F.Hyodo, K.-i.Matsumoto, N.L.Simone, J.A.Cook, M.C.Krishna, J.B.Mitchell. *Free Radical Biol. Med.*, **42**, 1632 (2007)
8. J.Winsberg, T.Hagemann, T.Janoschka, M.D.Hager, U.S.Schubert. *Angew. Chem., Int. Ed.*, **56**, 686 (2017)
9. Y.Iwabuchi. *Chem. Pharm. Bull. (Tokyo)*, **61**, 1197 (2013)
10. T.Yoshino, S.Nishida, K.Sato, S.Nakazawa, R.D.Rahimi, K.Toyota, D.Shiomi, Y.Morita, M.Kitagawa, T.Takui. *J. Phys. Chem. Lett.*, **2**, 449 (2011)
11. E.Coronado, A.Epstein. *J. Mater. Chem.*, **19**, 1670 (2009)
12. J.B.Mitchell, A.Samuni, M.C.Krishna, W.G.DeGraff, M.S.Ahn, U.Samuni, A.Russo. *Biochemistry*, **29**, 2802 (1990)
13. M.C.Krishna, W.DeGraff, O.H.Hankovszky, C.P.Sár, T.Kálai, J.Jekö, A.Russo, J.B.Mitchell, K.Hideg. *J. Med. Chem.*, **41**, 3477 (1998)
14. S.Goldstein, A.Samuni, K.Hideg, G.Merenyi. *J. Phys. Chem. A*, **110**, 3679 (2006)
15. J.L.Hodgson, M.Namazian, S.E.Bottle, M.L.Coote. *J. Phys. Chem. A*, **111**, 13595 (2007)
16. S.Goldstein, G.Merenyi, A.Russo, A.Samuni. *J. Am. Chem. Soc.*, **125**, 789 (2003)
17. A.Nilsen, R.Braslau. *J. Polym. Sci., Part A: Polym. Chem.*, **44**, 697 (2006)
18. M.V.Fedin, S.L.Veber, E.G.Bagryanskaya, V.I.Ovcharenko. *Coord. Chem. Rev.*, **289** – **290**, 341 (2015)
19. K.Nakahara, S.Iwasa, M.Satoh, Y.Morioka, J.Iriyama, M.Suguro, E.Hasegawa. *Chem. Phys. Lett.*, **359**, 351 (2002)
20. H.Nishide, S.Iwasa, Y.-J.Pu, T.Suga, K.Nakahara, M.Satoh. *Electrochim. Acta*, **50**, 827 (2004)
21. T.Suga, H.Nishide, in *Stable Radicals: Fundamentals and Applied Aspects of Odd-Electron Compounds*. (Ed. R.G.Hicks). (Chichester: Wiley, 2010). P. 507
22. T.Jähnert, T.Janoschka, M.D.Hager, U.S.Schubert. *Eur. Polym. J.*, **61**, 105 (2014)
23. K.Nakahara, K.Oyaizu, H.Nishide. *Chem. Lett.*, **40**, 222 (2011)
24. T.Suga, Y.-J.Pu, S.Kasatori, H.Nishide. *Macromolecules*, **40**, 3167 (2007)
25. T.Shiga, Y.Kato, Y.Hase. *J. Mater. Chem. A*, **5**, 13212 (2017)
26. B.J.Bergner, C.Hofmann, A.Schürmann, D.Schröder, K.Peppler, P.R.Schreiner, J.Janek. *Phys. Chem. Chem. Phys.*, **17**, 31769 (2015)
27. Z.Zhang, P.Chen, T.N.Murakami, S.M.Zakeeruddin, M.Grätzel. *Adv. Funct. Mater.*, **18**, 341 (2008)
28. F.Kato, N.Hayashi, T.Murakami, C.Okumura, K.Oyaizu, H.Nishide. *Chem. Lett.*, **39**, 464 (2010)
29. T.Murakami, F.Kato, K.Oyaizu, H.Nishide. *J. Photopolym. Sci. Technol.*, **23**, 353 2010)
30. J.Min, J.Won, Y.S.Kang, S.Nagase. *J. Photochem. Photobiol., A: Chem.*, **219**, 148 (2011)
31. J.Y.Lee, C.Lee, Y.M.Lee, K.Y.Cho, J.W.Choi, J.-K.Park. *J. Solid State Electrochem.*, **16**, 657 (2012)
32. R.A.Sheldon, I.W.C.E.Arends. *Adv. Synth. Catal.*, **346**, 1051 (2004)
33. T.Vogler, A.Studer. *Synthesis*, 1979 (2008)
34. J.M.Bobbitt, C.Brückner, N.Merbouh. *Org. React.*, **74**, 103 (2009); doi:10.1002/0471264180.or074.02
35. R.Ciriminna, M.Pagliaro. *Org. Process Res. Dev.*, **14**, 245 (2010)
36. L.Tebben, A.Studer. *Angew. Chem., Int. Ed.*, **50**, 5034 (2011)
37. R.Ciriminna, M.Ghahremani, B.Karimi, M.Pagliaro. *ChemistryOpen*, **6**, 5 (2017)
38. P.L.Anelli, S.Banfi, F.Montanari, S.Quici. *J. Org. Chem.*, **54**, 2970 (1989)
39. M.Shibuya, M.Tomizawa, I.Suzuki, Y.Iwabuchi. *J. Am. Chem. Soc.*, **128**, 8412 (2006)
40. C.Bolm, A.S.Magnus, J.P.Hildebrand. *Org. Lett.*, **2**, 1173 (2000)
41. R.A.Miller, R.S.Hoerrner. *Org. Lett.*, **5**, 285 (2003)
42. A.De Mico, R.Margarita, L.Parlanti, A.Vescovi, G.Piancatelli. *J. Org. Chem.*, **62**, 6974 (1997)
43. X.He, Z.Shen, W.Mo, N.Sun, B.Hu, X.Hu. *Adv. Synth. Catal.*, **351**, 89 (2009)

44. S.Wertz, A.Studer. *Adv. Synth. Catal.*, **353**, 69 (2011)
45. J.M.Hoover, S.S.Stahl. *J. Am. Chem. Soc.*, **133**, 16901 (2011)
46. O.A.Levitskiy, D.B.Eremin, A.V.Bogdanov, T.V.Magdesieva. *Eur. J. Org. Chem.*, **2017**, 4726 (2017)
47. O.A.Levitskiy, V.V.Sentyurin, T.V.Magdesieva. *Electrochim. Acta*, **260**, 459 (2018)
48. J.P.Blinco, J.L.Hodgson, B.J.Morrow, J.R.Walker, G.D.Will, M.L.Coote, S.E.Bottle. *J. Org. Chem.*, **73**, 6763 (2008)
49. P.Poizot, F.Dolhem. *Energy Environ. Sci.*, **4**, 2003 (2011)
50. H.Wieland, K.Roth. *Ber. Dtsch. Chem. Ges.*, **53**, 210 (1920)
51. H.Wieland, F.Kögl. *Ber. Dtsch. Chem. Ges.*, **55**, 1798 (1922)
52. A.R.Forrester, J.McKay Hay, R.H.Thomson. *Organic Chemistry of Stable Free Radicals*. (New York: Academic Press, 1968)
53. A.Calder, A.R.Forrester. *J. Chem. Soc. C*, 1459 (1969)
54. P.H.H.Fischer, F.A.Neugebauer. *Z. Naturforsch., A*, **19**, 1514 (1964)
55. M.Ballester, J.Riera, C.Onrubia. *Tetrahedron Lett.*, 945 (1976)
56. Yu.A.Ivanov, A.I.Kokorin, A.B.Shapiro, É.G.Rozantsev. *Bull. Acad. Sci. USSR, Div. Chem. Sci.*, **25**, 2069 (1976)
57. V.A.Golubev, V.D.Sen'. *Russ. J. Org. Chem.*, **49**, 555 (2013)
58. V.A.Golubev, V.V.Tkachev, V.D.Sen'. *Russ. J. Org. Chem.*, **50**, 678 (2014)
59. T.Ishida, M.Nakagawa, R.Imachi, Y.Akui, S.-Y.Masaoka, M.Suzuki, D.Hashizume, M.Yasui, F.Iwasaki, T.Nogami. *Mol. Cryst. Liq. Cryst. Sci. Technol., Sect. A: Mol. Cryst. Liq. Cryst.*, **334**, 89 (1999)
60. Z.Delen, P.M.Lahti. *J. Org. Chem.*, **71**, 9341 (2006)
61. S.V.Larionov. *Zh. Strukt. Khim.,* **23**, 125 (1982)
62. S.Kaizaki. *Coord. Chem. Rev.*, **250**, 1804 (2006)
63. H.Oshio, T.Ito. *Coord. Chem. Rev.*, **198**, 329 (2000)
64. H.Iwamura, K.Inoue, N.Koga. *New J. Chem.*, **22**, 201 (1998)
65. A.S.Markosyan, T.Hayamizu, H.Iwamura, K.Inoue. *J. Phys.: Condens. Matter*, **10**, 2323 (1998)
66. K.Inoue, T.Hayamizu, H.Iwamura, D.Hashizume, Y.Ohashi. *J. Am. Chem. Soc.*, **118**, 1803 (1996)
67. W.L.Hemme, W.Fujita, K.Awaga, H.Eckert. *Dalton Trans.*, 7995 (2009)
68. W.L.Hemme, W.Fujita, K.Awaga, H.Eckert. *J. Solid State Chem.*, **182**, 3330 (2009)
69. *Magnetic Properties of Organic Materials*. (Ed. P.M.Lahti). (New York: Marcel Dekker, 1999)
70. J.A.Crayston, J.N.Devine, J.C.Walton. *Tetrahedron*, **56**, 7829 (2000)
71. R.Imachi, T.Ishida, M.Suzuki, M.Yasui, F.Iwasaki, T.Nogami. *Chem. Lett.*, **26**, 743 (1997)
72. M.Nakagawa, T.Ishida, M.Suzuki, D.Hashizume, M.Yasui, F.Iwasaki, T.Nogami. *Chem. Phys. Lett.*, **302**, 125 (1999)
73. M.Seino, Y.Akui, T.Ishida, T.Nogami. *Synth. Met.*, **133** – **134**, 581 (2003)
74. R.Suzuki, R.Tada, Y.Miura, N.Yoshioka. *J. Mol. Struct.*, **1106**, 399 (2016)
75. J.Fujita, Y.Matsuoka, K.Matsuo, M.Tanaka, T.Akita, N.Koga, H.Iwamura. *Chem. Commun.*, 2393 (1997)
76. T.Ishida, H.Iwamura. *J. Am. Chem. Soc.*, **113**, 4238 (1991)
77. A.Rajca, M.Vale, S.Rajca. *J. Am. Chem. Soc.*, **130**, 9099 (2008)
78. A.Rajca, K.Shiraishi, S.Rajca. *Chem. Commun.*, 4372 (2009)
79. H.Oka, H.Kouno, H.Tanaka. *J. Mater. Chem.*, **17**, 1209 (2007)
80. M.Tanaka, K.Matsuda, T.Itoh, H.Iwamura. *J. Am. Chem. Soc.*, **120**, 7168 (1998)
81. O.A.Levitskiy, V.V Sentyurin, A.V.Bogdanov, T.V.Magdesieva. *Mendeleev Commun.*, **26**, 535 (2016)
82. D.S.Surry, S.L.Buchwald. *Chem. Sci.*, **2**, 27 (2011)
83. S.V.Ley, A.W.Thomas. *Angew. Chem., Int. Ed.*, **42**, 5400 (2003)
84. R.W.Murray, M.Singh. *Tetrahedron Lett.*, **29**, 4677 (1988)
85. A.Rajca, K.Shiraishi, P.J.Boratyński, M.Pink, M.Miyasaka, S.Rajca. *J. Org. Chem.*, **76**, 8447 (2011)
86. E.G.Rozantsev. *Svobodnye Iminokcil'nye Radikaly*. (Free Iminoxide Radicals). (Moscow: Khimiya, 1970)
87. L.A.Kalashnikova, M.B.Neiman, E.G.Rozantsev, L.A.Skripko. *Zh. Org. Khim.*, **2**, 1529 (1966)
88. C.Berti. *Synthesis*, 793 (1983)
89. K.Murashima, T.Watanabe, S.Kanegawa, D.Yoshihara, Y.Inagaki, S.Karasawa, N.Koga. *Inorg. Chem.*, **51**, 4982 (2012)
90. P.Astolfi, P.Carloni, E.Damiani, L.Greci, M.Marini, C.Rizzoli, P.Stipa. *Eur. J. Org. Chem.*, **2008**, 3279 (2008)
91. O.Takizawa. *Bull. Chem. Soc. Jpn.*, **49**, 583 (1976)
92. A.Staško, K.Erentová, P.Rapta, O.Nuyken, B.Voit. *Magn. Reson. Chem.*, **36**, 13 (1998)
93. R.S.Dhale, P.K.Sahu, M.Sarkar. *J. Phys. Chem. B*, **121**, 7934 (2017)
94. B.Dobosz, R.Krzyminiewski, J.Kurczewska, G.Schroeder. *Mater. Chem. Phys.*, **198**, 297 (2017)
95. K.Nakahara, S.Iwasa, J.Iriyama, Y.Morioka, M.Suguro, M.Satoh, E.J.Cairns. *Electrochim. Acta*, **52**, 921 (2006)
96. J.E.Baur, S.Wang, M.C.Brandt. *Anal. Chem.*, **68**, 3815 (1996)
97. X.Qiu, H.Zhao, M.Lan. *J. Organomet. Chem.*, **694**, 3958 (2009)
98. S.Manda, I.Nakanishi, K.Ohkubo, H.Yakumaru, K.-i.Matsumoto, T.Ozawa, N.Ikota, S.Fukuzumi, K.Anzai. *Org. Biomol. Chem.*, **5**, 3951 (2007)
99. M.Shibuya, F.Pichierri, M.Tomizawa, S.Nagasawa, I.Suzuki, Y.Iwabuchi. *Tetrahedron Lett.*, **53**, 2070 (2012)
100. M.Carbó López, G.Royal, C.Philouze, P.Y.Chavant, V.Blandin. *Eur. J. Org. Chem.*, **2014**, 4884 (2014)
101. S.Manda, I.Nakanishi, K.Ohkubo, T.Kawashima, K.-i.Matsumoto, T.Ozawa, S.Fukuzumi, N.Ikota, K.Anzai. *Chem. Lett.*, **36**, 914 (2007)
102. T.Suga, Y.-J.Pu, K.Oyaizu, H.Nishide. *Bull. Chem. Soc. Jpn.*, **77**, 2203 (2004)
103. L.Marx, B.Schöllhorn. *New J. Chem.*, **30**, 430 (2006)
104. J.A.Bogart, H.B.Lee, M.A.Boreen, M.Jun, E.J.Schelter. *J. Org. Chem.*, **78**, 6344 (2013)
105. D.Serve. *Electrochim. Acta*, **20**, 469 (1975)
106. F.R.Brushett, J.T.Vaughey, A.N.Jansen. *Adv. Energy Mater.*, **2**, 1390 (2012)
107. S.Morris, G.Sosnovsky, B.Hui, C.O.Huber, N.U.M.Rao, H.M.Swartz. *J. Pharm. Sci.*, **80**, 149 (1991)
108. V.D.Sen', I.V.Tikhonov, L.I.Borodin, E.M.Pliss, V.A.Golubev, M.A.Syroeshkin, A.I.Rusakov. *J. Phys. Org. Chem.*, **28**, 17 (2015)
109. M.K.Kadirov, E.V.Tret'yakov, Yu.G.Budnikova, K.V.Kholin, M.I.Valitov, V.N.Vavilova, V.I.Ovcharenko, R.Z.Sagdeev, O.G.Sinyashin. *Russ. J. Phys. Chem. A*, **83**, 2163 (2009)
110. T.Sukegawa, A.Kai, K.Oyaizu, H.Nishide. *Macromolecules*, **46**, 1361 (2013)
111. Y.Liang, Z.Tao, J.Chen. *Adv. Energy Mater.*, **2**, 742 (2012)
112. M.Kadirov, E.Tretyakov, Yu.Budnikova, M.Valitov, K.Holin, T.Gryaznova, V.Ovcharenko, O.Sinyashin. *J. Electroanal. Chem.*, **624**, 69 (2008)

113. J.Winsberg, T.Janoschka, S.Morgenstern, T.Hagemann, S.Muench, G.Hauffman, J.-F.Gohy, M.D.Hager, U.S.Schubert. *Adv. Mater*., **28**, 2238 (2016)
114. T.Suga, H.Ohshiro, S.Sugita, K.Oyaizu, H.Nishide. *Adv. Mater*., **21**, 1627 (2009)
115. K.Koshika, N.Chikushi, N.Sano, K.Oyaizu, H.Nishide. *Green Chem*., **12**, 1573 (2010)
116. H.Nishide, K.Oyaizu. *Science*, **319**, 737 (2008)
117. T.Janoschka, M.D.Hager, U.S.Schubert. *Adv. Mater*., **24**, 6397 (2012)
118. X.Wei, W.Xu, M.Vijayakumar, L.Cosimbescu, T.Liu, V.Sprenkle, W.Wang. *Adv. Mater*., **26**, 7649 (2014)
119. T.Liu, X.Wei, Z.Nie, V.Sprenkle, W.Wang. *Adv. Energy Mater*., **6**, 1501449 (2016)
120. S.E.Burkhardt, S.Conte, G.G.Rodriguez-Calero, M.A.Lowe, H.Qian, W.Zhou, J.Gao, R.G.Hennig, H.D.Abruña. *J. Mater. Chem*., **21**, 9553 (2011)
121. W.Duan, R.S.Vemuri, J.D.Milshtein, S.Laramie, R.D.Dmello, J.Huang, L.Zhang, D.Hu, M.Vijayakumar, W.Wang, J.Liu, R.M.Darling, L.Thompson, K.Smith, J.S.Moore, F.R.Brushett, X.Wei. *J. Mater. Chem. A*, **4**, 5448 (2016)
122. S.D.Rychnovsky, R.Vaidyanathan, T.Beauchamp, R.Lin, P.J.Farmer. *J. Org. Chem*., **64**, 6745 (1999)
123. G.Gryn'ova, J.M.Barakat, J.P.Blinco, S.E.Bottle, M.L.Coote. *Chem. – Eur. J*., **18**, 7582 (2012)
124. O.A.Levitskiy, T.V.Magdesieva. *Mendeleev Commun*., **28**, 187 (2018)
125. D.N.Laikov, Yu.A.Ustynyuk. *Russ. Chem. Bull., Int. Ed*., **54**, 820 (2005)
126. M.Schmidt am Busch, E.-W.Knapp. *J. Am. Chem. Soc*., **127**, 15730 (2005)
127. B.H.Besler, K.M.Merz Jr., P.A.Kollman. *J. Comput. Chem*., **11**, 431 (1990)
128. C.I.Bayly, P.Cieplak, W.Cornell, P.A.Kollman. *J. Phys. Chem*., **97**, 10269 (1993)