

A new family of stable 2-imidazoline nitroxides

Sergei F. Vasilevsky,^{*a} Eugene V. Tretyakov,^a Oleg M. Usov,^a Yuri N. Molin,^a Sergei V. Fokin,^b Yuri G. Shwedenkov,^b Vladimir N. Ikorskii,^b Galina V. Romanenko,^b Renad Z. Sagdeev^b and Victor I. Ovcharenko^{*b}

^a Institute of Chemical Kinetics and Combustion, Siberian Branch of the Russian Academy of Sciences, 630090 Novosibirsk, Russian Federation. Fax: +7 3832 342350; e-mail: vasilev@ns.kinetics.nsc.ru

^b International Tomography Centre, Siberian Branch of the Russian Academy of Sciences, 630090 Novosibirsk, Russian Federation. Fax: +7 3832 331399; e-mail: ovchar@tomo.nsc.ru

Methods of synthesising stable 2-imidazoline nitroxides linked to a pyrazole moiety either directly or through a phenylethynyl bridge have been developed; an unusually strong temperature dependence of μ_{eff} for 2-(1-methylpyrazolyl-5)-4,4,5,5-tetramethyl-1-oxyl-2-imidazoline-3-oxide is observed.

Polyfunctional stable nitroxides are very effective in the design of *n*-dimensional heterospin systems susceptible to magnetic ordering.^{1–4} This circumstance prompted us to synthesise a new family of stable nitroxides — pyrazole and acetylenylpyrazole derivatives of 2-imidazoline nitroxides — and to investigate the heterospin systems based on metal complexes with these spin-labelled ligands. Donor nitrogen atoms of the pyrazole ring are favourable for coordination by metal ions. The use of an acetylene fragment in the molecular structure allows one to reach specific distances between functional groups that is very desirable in the design of high dimensional molecular systems.

Noteworthy is the fact that only a few papers^{5–8} were devoted to the development of the synthesis of acetylenic derivatives of 2-imidazoline nitroxides due to their low stability.

We synthesised a series of new nitronyl- and imino-nitroxides **1–9** using a classical Ullman approach⁹ based on condensation of the corresponding aldehydes with 2,3-dimethyl-2,3-bis(hydroxylamino)butane or its sulfate derivative[†] and subsequent oxidation of the cyclic adducts with sodium periodate.[‡] Acetylene-containing starting materials have been prepared by the cross-coupling reaction of the corresponding iodopyrazoles¹⁰ with *p*-ethynylbenzaldehyde in the presence of Pd(PPh₃)₂(OAc)₂, CuI and NEt₃.

Nitroxides **1–9** were obtained in a good yield and are quite stable in solid and in solution at ambient temperature. They have EPR spectra intrinsic to 2-imidazoline nitroxides. Figures 1 and 2 exemplify the EPR spectra for nitroxides **6** and **7**.

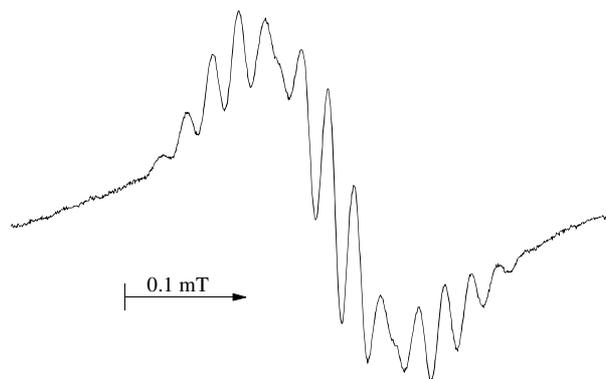
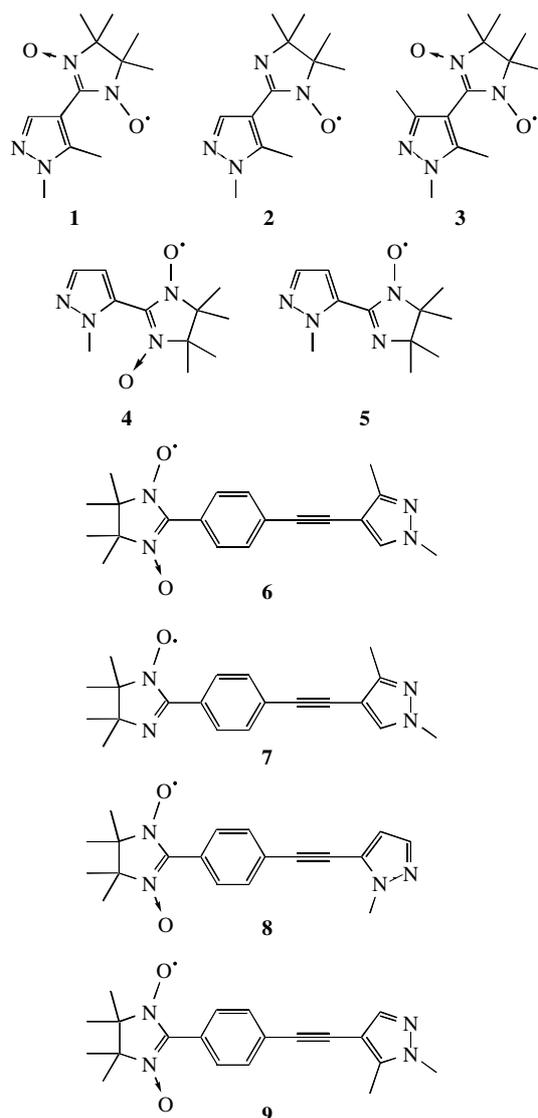


Figure 1 Central component of the EPR spectrum of radical **6**. Oxygen-free hexane solution (5×10^{-5} M) of radical **6** at room temperature.

[†] Synthesis of formylpyrazoles and (1,3-dihydroxy-4,4,5,5-tetramethylimidazolyl-2)pyrazoles will be published elsewhere.

[‡] *General procedure for the synthesis of 2-imidazoline nitroxides 1–9.* To a suspension of the anhydro adduct (0.01 mol) of 2,3-bis(hydroxylamino)-2,3-dimethylbutane and the corresponding aldehyde in chloroform (50 ml) at 10–15 °C was added an aqueous solution (50 ml) of sodium periodate (0.015 mol), and the reaction mixture was stirred for 50 min to 4 h. The organic layer was immediately separated, dried over CaCl₂ and concentrated *in vacuo*. The residue was chromatographed on a silica gel column ('KSK', Russia, 100–200 mech, air dried) with chloroform as the eluent. After evaporation of the solvents from the eluate the remaining solid was twice recrystallized from an appropriate solvent to afford nitroxides **1–9**.

All compounds were identified by elemental analyses and spectroscopic data which was consistent with the assigned structures.

1: mp 100–101 °C (from benzene–hexane), yield 85%. **2:** mp 71–72 °C (from hexane), yield 9%. **3:** mp 139–140 °C (from benzene–hexane), yield 65%. **4:** mp 143–144 °C (from benzene–hexane), yield 39%. **5:** mp 114–115 °C (from hexane), yield 14%. **6:** mp 130.5–131 °C (from benzene–hexane), yield 71%. **7:** mp 106.5–107 °C (from hexane), yield 15%. **8:** mp 144–145 °C (from benzene–hexane), yield 56%. **9:** mp 117–118 °C (from benzene–hexane), yield 63%.

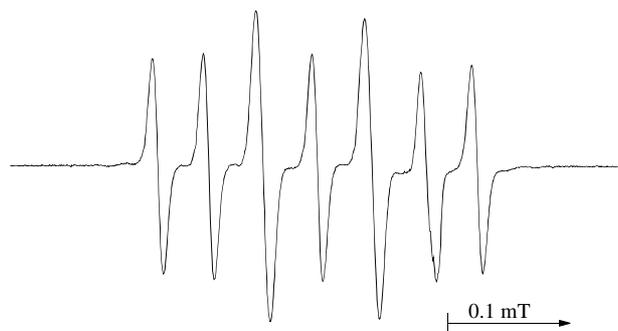


Figure 2 EPR spectrum of radical **7** (5×10^{-5} M) in an oxygen-free hexane solution at room temperature.

spectrum of radical **6** is a quintet (1:2:3:2:1), caused by hyperfine interaction between two equivalent nitroxide nitrogen nuclei ($a_N = 0.74$ mT), each line of the quintet being additionally

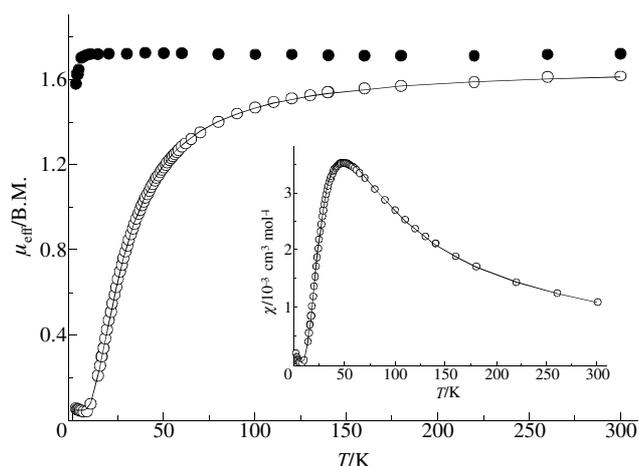


Figure 3 Experimental dependences $\mu_{\text{eff}}(T)$ for **5** (●) and **4** (○). Insert: plot χ versus T for **4**. The solid lines represent the optimal theoretical curves.

split due to hyperfine interaction with 12 protons of the $-\text{methyl}$ groups [$a_{\text{H}}(\text{Me}) = 0.021$ mT] and with *ortho*-protons of the benzene ring ($a_{\text{ortho}} = 0.054$ mT). This is illustrated by Figure 1, where a central component of the quintet is depicted. The EPR spectrum of radical **7** presented in Figure 2 is caused by HFI with two non-equivalent nitrogen of the imidazoline moiety, the hyperfine coupling constants differing by a factor about two ($a_{\text{N}1} = 0.907$ mT and $a_{\text{N}3} = 0.432$ mT). g -Factors of radicals **6** and **7** are 2.0065 and 2.0059, respectively. Nitroxides **1–9** have effective magnetic moments at room temperature corresponding

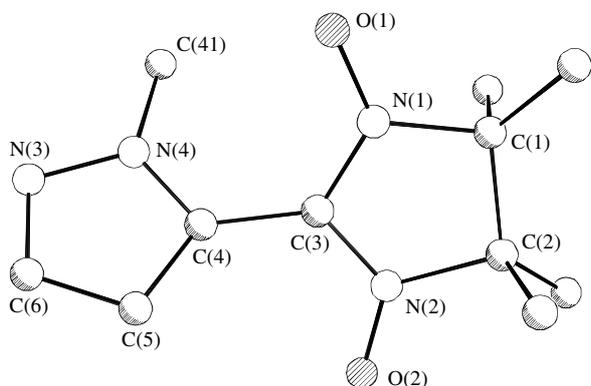


Figure 4 General view of molecule **4**. Selected bond lengths (\AA): N(1)–O(1) 1.279(2), N(1)–C(3) 1.340(2), N(1)–C(1) 1.496(2), C(1)–C(2) 1.536(3), C(2)–N(2) 1.507(2), O(2)–N(2) 1.277(2), N(2)–C(3) 1.344(2), C(3)–C(4) 1.446(2), C(4)–N(4) 1.353(2), C(4)–C(5) 1.370(3), C(5)–C(6) 1.384(3), C(6)–N(3) 1.327(3), N(3)–N(4) 1.348(2); selected bond angles ($^\circ$): O(1)–N(1)–C(3) 126.0(2), O(1)–N(1)–C(1) 123.0(1), C(3)–N(1)–C(1) 111.0(1), N(1)–C(1)–C(2) 100.5(2), N(2)–C(2)–C(1) 100.4(1), O(2)–N(2)–C(3) 126.4(1), O(2)–N(2)–C(2) 122.5(1), C(3)–N(2)–C(2) 110.6(1), N(1)–C(3)–N(2) 109.3(2), N(1)–C(3)–C(4) 125.0(2), N(2)–C(3)–C(4) 125.4(2).

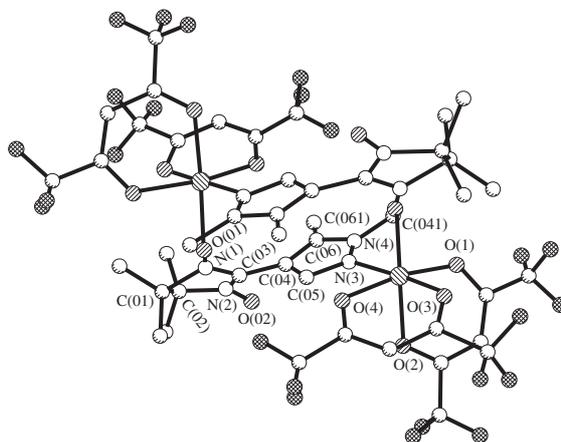


Figure 5 General view of binuclear molecule $\text{Ni}_2(\text{hfacac})_2(\text{C}_6\text{H}_6)$. Selected bond lengths (\AA): Ni–O(1) 2.008(1), Ni–O(4) 2.016(1), Ni–O(1)' 2.052(1), Ni–O(3) 2.058(2), Ni–O(2) 2.090(1), Ni–N(3) 2.093(2), O(01)–N(1) 1.302(2), N(1)–C(03) 1.282(3), N(1)–C(01) 1.562(2), C(01)–C(02) 1.537(4), C(02)–N(2) 1.527(2), N(2)–O(02) 1.245(2), N(2)–C(03) 1.344(3), C(03)–C(04) 1.471(2); selected bond angles ($^\circ$): O(4)–Ni–O(3) 85.92(6), O(1)–Ni–O(2) 87.76(6), N(1)–O(01)–Ni' 124.0(1), C(03)–N(1)–O(01) 127.5(2), C(03)–N(1)–C(01) 112.3(2), O(01)–N(1)–C(01) 118.4(2), N(2)–C(02)–C(01) 103.4(2), N(2)–C(02)–C(021) 107.9(2), O(02)–N(2)–C(03) 128.1(1), O(02)–N(2)–C(02) 123.7(2), C(03)–N(2)–C(02) 108.1(2), N(1)–C(03)–N(2) 111.8(2), N(1)–C(03)–C(04) 123.6(2), N(2)–C(03)–C(04) 124.7(2).

to the values usual for one unpaired electron per molecule (1.71 ± 0.05 B.M.). The values of the effective magnetic moments of **1–3** and **5–9** hardly change in the temperature range 5–300 K.[§] As a typical example of the experimental $\mu_{\text{eff}}(T)$ dependence for this group of nitroxides the $\mu_{\text{eff}}(T)$ plot for **5** (filled) is shown in Figure 3.

Special attention should be given to the magnetic behaviour of **4**. We revealed an unexpectedly strong temperature dependence of μ_{eff} for solid **4** (Figure 3, empty). The experimental temperature dependence of the magnetic susceptibility of **4** (Figure 3, insert) is very well fitted (solid line) by the Bleaney–Bo wers model¹¹ for isolated two-centre exchange clusters with spin 1/2 ($g = 2.0$, $J = -39$ K). This correlates well with an X-ray structure investigation of a single crystal of **4**, which revealed packing by pairs of molecules in solid **4**.[¶] However, the mechanism of such a strong exchange interaction in nitroxide pairs needs an in

[§] Magnetic measurements were made using a Quantum Design SQUID magnetometer over the temperature range 2–300 K. EPR spectra were recorded on a Bruker EMX EPR spectrometer.

[¶] *Crystal data for 4*: $\text{C}_{11}\text{H}_{17}\text{N}_4\text{O}_5$, $M = 237.29$, monoclinic, space group $P2_1/c$, 293(2) K, $a = 7.0846(9)$, $b = 17.447(2)$, $c = 12.763(1)$ \AA , $\beta = 126.72(1)^\circ$, $V = 1264.5(2)$ \AA^3 , $Z = 4$, $D_c = 1.246$ g cm^{-3} . 1587 I_{hkl} were measured on a four-circle automated Enraf Nonius CAD4 diffractometer (λ MoK α , graphite monochromator, $\theta/2\theta$ -scan, $2.34 < \theta < 24.96^\circ$). The structure was solved by the program SIR97 and refined by a full-matrix least-squares technique in anisotropic approximation for all non-hydrogen atoms. Positions of all hydrogen atoms were located in a difference Fourier map and then refined in isotropic approximation. The final R -indexes are: $R_1 = 0.0316$, $wR_2 = 0.0803$ for 1431 unique $I_{hkl} > 2\sigma_f$, GOOF = 0.868.

Crystal data for Ni2(hfacac)2(C6H6): $\text{C}_{25}\text{H}_{24}\text{F}_{12}\text{N}_4\text{NiO}_6$, $M = 763.19$, monoclinic, space group $P2_1/c$, 293(2) K, $a = 16.442(2)$, $b = 13.500(2)$, $c = 15.858(2)$ \AA , $\beta = 115.50(1)^\circ$, $V = 3177.1(7)$ \AA^3 , $Z = 4$, $D_c = 1.596$ g cm^{-3} . 3124 I_{hkl} were measured on a four-circle automated Enraf Nonius CAD4 diffractometer (λ MoK α , graphite monochromator, $\theta/2\theta$ -scan, $1.37 < \theta < 22.47^\circ$). The structure was solved by the automated Patterson interpretation program and refined by a full-matrix least-squares technique in anisotropic approximation for all non-hydrogen atoms. The positions of all hydrogen atoms were located in a difference Fourier map and then refined in an isotropic approximation. The final R -indexes are: $R_1 = 0.0485$, $wR_2 = 0.0666$ for 3001 unique $I_{hkl} > 2\sigma_f$, GOOF = 0.674. All calculations for both compounds were carried out using the SHELXL97 program. Bond lengths, bond angles and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre (CCDC). For details, see 'Notice to Authors', *Mendeleev Commun.*, 1998, Issue 1. Any request to the CCDC for data should quote the full literature citation and the reference number 1139/31.

depth quantum-chemical analysis. This is of particular interest because there are no intermolecular contacts shorter than 3 Å in the crystal structure of **4**. A general view of the separate nitronyl nitroxide molecule is given in Figure 4, with some selected bond lengths and bond angles. In Figure 5 are given additionally some selected data for binuclear complex $\text{Ni}_2(\text{hfacac})_4 \cdot 2(\text{C}_6\text{H}_6)$. The structure of the molecule of this (first structurally characterised) metal complex with spin-labelled pyrazole, shown in Figure 5, demonstrates (as mentioned in the introduction) the possibility of pyrazole 2-imidazoline derivatives behaving as a bridge function.

Full details of this investigation will be published elsewhere.

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