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New Stable Neutral Radical with Intramolecular Hydrogen Bonding: Synthesis and Characterization of 2,5,8-Tri-*tert*-butyl-7-hydroxy-6-oxophenalenoxyl

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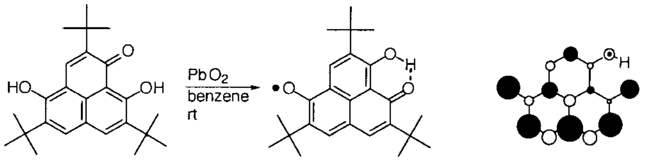
ABSTRACT

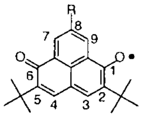


dark grayish green powder

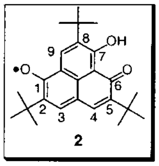
π-spin density distribution

A new stable neutral radical with intramolecular hydrogen bonding, 2,5,8-tri-*tert*-butyl-7-hydroxy-6-oxophenalenoxyl, was synthesized from the corresponding dihydroxyphenalenone and isolated as a stable solid under air atmosphere at room temperature. The structure was unequivocally determined by means of IR spectra, ESR/ENDOR techniques, and DFT calculations.

Neutral radicals such as triarylmethyl radical, nitroxide, phenoxyl, and conjugated multi-heteroatoms radicals have played a crucial role in the study and development of organic-based magnetic materials as spin sources.[1,2] Recently, introduction of hydrogen-bonding sites into organic radicals has drawn attention as a useful and interesting modification to control intermolecular magnetic interactions.[3] In this context, α-nitronyl nitroxide radicals substituted with aromatic rings having OH or NH groups have been extensively studied.[3] The preparation of new stable neutral radicals with inter- and/or intramolecular hydrogen bonding contributes to the elucidation of the effect of hydrogen bonding on the spin distribution and radical stability, serving as materials challenge for novel open-shell organic systems with a variety of organic spin sources. In the course of this project, we have recently achieved the synthesis and characterization of novel stable neutral radicals, 2,5-di-*tert*-butyl-6-oxophenalenoxyl derivatives **1a** and **1b**.[4] In this paper, we describe the synthesis, stability, and spin structure of a new hydroxy derivative of 6-oxophenalenoxyl **2** as the first example of the stable neutral radical coupled with an intramolecular hydrogen bonding.



1a R = H
1b R = *t*-Bu



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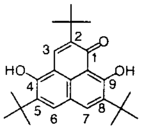
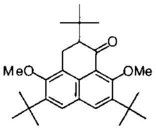


3



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The radical precursor **3**,[5] which exists as a tautomeric mixture (**3a**, **3b**, and **3c** in Scheme 1A), was prepared from

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(1) For recent overviews of organic-based magnetic materials, see: (a) *Molecular Magnetism*; Itoh, K., Kinoshita, M., Eds.; Kodansha, and Gordon and Breach Science Publishers: Tokyo, 2000; pp 1−347. (b) *Magnetic Properties of Organic Materials*; Lahti, P. M., Ed.; Marcel Dekker: New York, 1999; pp 1−728. (c) Kahn, O., Ed. *Mol. Cryst. Liq. Cryst.* **1999**, *334*, 1−712; *335*, 1−706. (d) Itoh, K., Miller, J. S., Takui, T., Eds. *Mol. Cryst. Liq. Cryst.* **1997**, *305*, 1−586; *306*, 1−520.

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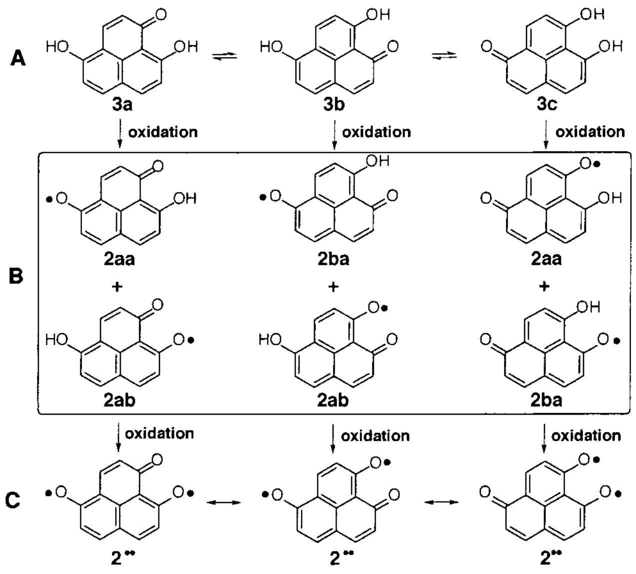

Scheme 1. Possible Tautomers of Dihydroxyphenalenone **3** (**A**) and Three Pairs of Monoradical Structures (**B**) and Single Diradical (**C**) Involving Corresponding Resonance Isomers

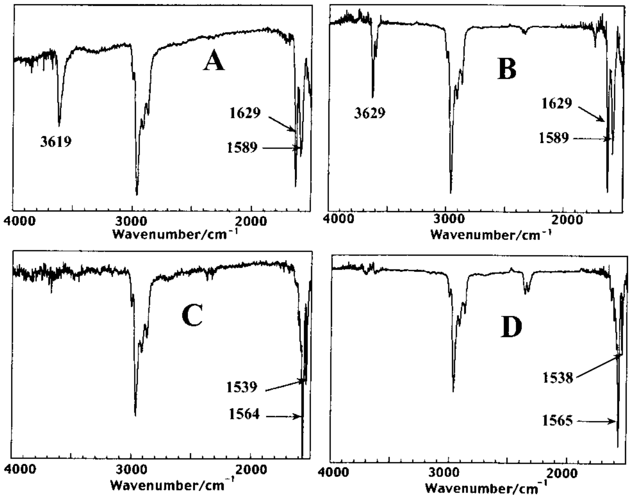

Figure 1. IR spectra of **3** (KBr pellet, **A**; CCl$_2$CCl$_2$ solution, **B**) and **2** (KBr pellet, **C**; CCl$_2$CCl$_2$ solution, **D**) at room temperature.

the dimethoxyphenalanone derivative **4**[4] by the following steps: (i) dehydrogenation by an excess amount of DDQ (2,3-dichloro-5,6-dicyano-1,4-benzoquinone) in toluene at 110 °C for 8 h, yield 100%, (ii) demethylation by an excess amount of LiI in HMPA at 170 °C for 2.5 h, followed by dehydration and aerobic oxidation by the treatment with 2 M aqueous HCl, and recrystallization from benzene, yield 95%. In the ^{1}H NMR spectrum in CDCl$_3$ measured at room temperature, dihydroxyphenalenone **3** shows only three C−H broad signals in the aromatic region, indicating the reversible exchange of the O−H protons by the tautomeric behavior, which was also observed in 6-hydroxyphenalenone derivatives.[4] In the IR spectra, compound **3** shows absorption bands at nearly the same frequencies within a resolution of 4.0 cm^{-1} in the solid (KBr) state (1629 and 1589 cm^{-1}) and in a dilute solution (CCl$_2$CCl$_2$, 1×10^{-3} M, 1629 and 1589 cm^{-1}) (Figure 1 A,B). These absorption bands are assigned to C═O and C═C stretching vibrations, respectively. This result clearly indicates the exclusive tendency to form intramolecular hydrogen bonding in both conditions, which is in full accord with the IR spectra observed in 9-hydroxyphenalenone.[6] Furthermore, a band of 3629 cm^{-1} seen in Figure 1B is assignable to a free O−H stretching vibration, since the IR spectrum of 9-hydroxyphenalenone does not show any band corresponding to the stretching vibrations of the O−H group in the 3700−3100 region. Disappearance of the band is due to the shift into the region of C−H absorption band and great broadening.[6]

The radical **2** was obtained as a dark grayish green powder in quantitative yield by treatment of **3** with a large excess of active PbO$_2$[7] in CH$_2$Cl$_2$ at room temperature.[8,9] In the

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(2) For recent overviews of the stable neutral radicals, see: (a) Forrester, A. R.; Hay, J. M.; Thomson, R. H. *Organic Chemistry of Stable Free Radicals*; Academic Press: London and New York, 1968. (b) Rozantsev, E. G. *Free Nitroxyl Radicals*; Plenum Press: New York and London, 1970. (c) Aurich, H. G. In *Nitrones, Nitronates and Nitroxides*; Patai, S., Rappoport, Z., Eds.; Wiley: Chichester, 1989; Chapter 4. (d) Volodarsky, L. B.; Reznikov, V. A.; Ovcharenko, V. I. *Synthetic Chemistry of Stable Nitroxides*; CRC Press: Boca Raton, FL, 1994. (e) Iwamura, H.; Koga, N. *Acc. Chem. Res.* **1993**, *26*, 346−351.

(3) (a) Hernàndez, E.; Mas, M.; Molins, E.; Rovira, C.; Veciana, J. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 882−884. (b) Cirujeda, J.; Ochando, L. E.; Amigó, J. M.; Rovira, C.; Rius, J.; Veciana, J. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 55−57. (c) Cirujeda, J.; Hernàndez-Gasió, E.; Lanfranc de Panthou, F.; Laugier, J.; Mas, M.; Molins, E.; Rovira, C.; Novoa, J. J.; Rey, P.; Veciana, J. *Mol. Cryst. Liq. Cryst.* **1995**, *272*, 1−12. (d) Veciana, J.; Cirujeda, J.; Rovira, C.; Vidal-Gancedo, J. *Adv. Mater.* **1995**, *7*, 221−225. (e) Cirujeda, J.; Hernàndez-Gasió, E.; Rovira, C.; Stanger, J.-L.; Turek, P.; Veciana, J. *J. Mater. Chem.* **1995**, *5*, 243−252. (f) Cirujeda, J.; Mas, M.; Molins, E.; de Panthou, F. L.; Laugier, J.; Park, J. G.; Paulsen, C.; Rey, P.; Rovira, C.; Veciana, J. *J. Chem. Soc., Chem. Commun.* **1995**, 709−710. (g) Cirujeda, J.; Rovira, C.; Veciana, J. *Synth. Met.* **1995**, *71*, 1799−1800. (h) Jürgens, O.; Cirujeda, J.; Mas, M.; Mata, I.; Cabrero, A.; Vidal-Gancedo, J.; Rovira, C.; Molins, E.; Veciana, J. *J. Mater. Chem.* **1997**, *7*, 1723−1730. (i) Sugawara, T.; Matsushita, M. M.; Izuoka, A.; Wada, N.; Takesa, N.; Ishikawa, M. *J. Chem. Soc., Chem. Commun.* **1994**, 1723−1724. (j) Okuno, T.; Otsuka, T.; Awaga, K. *J. Chem. Soc., Chem. Commun.* **1995**, 827−828. (k) Akita, T.; Mazaki, Y.; Kobayashi, K. *J. Chem. Soc., Chem. Commun.* **1995**, 1861−1862. (l) Lang, A.; Pei, Y.; Ouahab, L.; Kahn, O. *Adv. Mater.* **1996**, *8*, 60−62. (m) Yoshioka, N.; Irisawa, M.; Mochizuki, Y.; Kato, T.; Inoue, H.; Ohba, S. *Chem. Lett.* **1997**, 251−252. (n) Akita, T.; Kobayashi, K. *Adv. Mater.* **1997**, *9*, 346−348. (o) Matsushita, M. M.; Izuoka, A.; Sugawara, T.; Kobayashi, T.; Wada, N.; Takeda, N.; Ishikawa, M. *J. Am. Chem. Soc.* **1997**, *119*, 4369−4379. (p) Otsuka, T.; Okuno, T.; Awaga, K.; Inabe, T. *J. Mater. Chem.* **1998**, *8*, 1157−1163.

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(5) Selected physical data for **3**: mp 245−247 °C; TLC R_f 0.71 (5:1 hexane/ethyl acetate); ^{1}H NMR (270 MHz, CDCl$_3$) δ 1.54 (s, 9), 1.56 (s, 9), 1.57 (s, 9), 6.18 (s, 1), 7.88 (br s, 1), 7.91 (br s, 1), 8.28 (br s, 1); EI-MS *m/z* 380 (M$^+$, 42), 365 (M$^+$ − CH$_3$, 100). Anal. Calcd for C$_{25}$H$_{32}$O$_3$: C, 78.91; H, 8.48; N, 0.00. Found: C, 78.86; H, 8.43; N, 0.00.

(6) The C═O stretching frequencies of 9-hydroxyphenalenone in KBr or CCl$_4$ solution is 1630 and 1634 cm^{-1}, respectively; see: (a) Demura, Y.; Kawato, T.; Kanatomi, H.; Murase, I. *Bull Chem. Soc. Jpn.* **1975**, *48*, 2820−2824. (b) Orlov, V. D.; Solodar, S. L.; Surov, Y. N.; Vinogradov, L. M. *Zh. Org. Khim.* **1982**, *18*, 615−620.

(7) Kuhn, R.; Hammer, I. *Chem. Ber.* **1950**, *83*, 413−414. See also: Wilmarth, W. K.; Schwartz, N. *J. Am. Chem. Soc.* **1955**, *77*, 4543−4551.

(8) Selected physical data for **2**: mp 66−68 °C (dec); TLC R_f 0.68 (5:1 hexane/ethyl acetate). Anal. Calcd for C$_{25}$H$_{31}$O$_3$(CH$_2$Cl$_2$)$_{0.15}$: C, 77.01; H, 8.04; N 0.00. Found: C, 77.19; H, 8.10; N, 0.00.

solid state **2** exhibits extremely high stability in the absence of atmospheric oxygen, and even in air **2** shows high stability over a few weeks without noticeable decomposition, indicating comparable stability with those of **1b**. In degassed toluene also **2** shows extremely high stability for a long period of time at room temperature, but it decomposes in air. Scheme 1B and C summarize the possible structures of the neutral radicals generated from **3**. Depending on the positions of the oxidized O−H functional group of each tautomer, three kinds of monoradicals, **2aa**, **2ab**, **2ba**, and single diradical **2$^{\bullet\bullet}$** might be produced, which are expressed as the corresponding resonance structures. To determine the structure, we measured IR spectra in the solid (KBr) and in diluted condition (CCl_2CCl_2, 1 × 10^{-3} M). The generated radical **2** shows the absorption bands at almost the same frequencies both in the solid state (1564 and 1539 cm^{-1}) and in solution (1565 and 1538 cm^{-1}), indicating the formation of intramolecular hydrogen bonding (Figure 1 C,D). The following observation also supports the existence of intramolecular hydrogen bonding in the radical **2**, which excludes the isomer **2ab** as a possible structure: (i) the disappearance of O−H stretching vibration around 3600 cm^{-1} in solution, and (ii) the low-frequency shift of the C=O stretching vibration band, 1565 cm^{-1}, observed in solution compared with that of **1b** (1595 cm^{-1}) in the same condition.

Figure 2A shows an isotropic ESR spectrum of **2** observed from a degassed toluene solution of the isolated radical (10^{-4} M) at 290 K. This ESR spectrum is explained by assuming three kinds of ^1H nuclei and ^{13}C (1.1%) nuclei, giving six broad signals and eight small broad satellite signals, respectively.[10] Moreover, in a frozen toluene matrix at 140 K there was one broad featureless signal around the $g \approx 2$ region and no signal for the forbidden transition ($\Delta M_s = \pm 2$), indicating no production of diradical derivative **2$^{\bullet\bullet}$**. Furthermore, the observed g-value, 2.0043, is close to those of **1a** and **1b** (2.0046 and 2.0049, respectively).[4] Figure 2B, the liquid-phase ^1H ENDOR spectrum of this radical at 200 K, shows the three sharp pairs of lines and a pair of broad lines, which were attributed to the three protons on the phenalenyl skeleton and *tert*-butyl protons, respectively.[11,12] ^1H TRIPLE spectroscopy (Figure 2C) enabled us to unequivocally determine the relative signs of the three hfcc's of the phenalenyl ring protons that have the same sign. The spectral simulation based on the observed proton hfcc's and on the contribution of the ^{13}C atom effect (^{13}C hfcc = 23 MHz) is in good agreement with the observed ESR spectrum (Figure 2D).

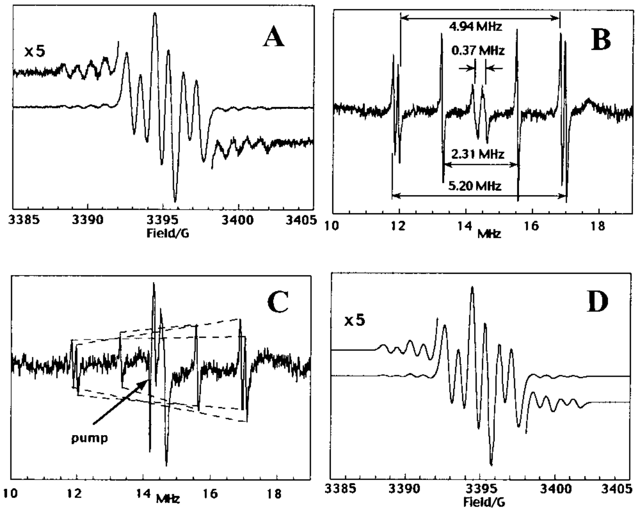

Figure 2. Hyperfine ESR (**A**, 290 K), ENDOR (**B**, 200 K), and ^1H TRIPLE spectra (**C**, 200 K) observed for **2** in toluene (1 × 10^{-4} M), microwave frequency 9.523596 GHz, and simulated ESR spectrum (**D**). Observed g-value is 2.0043. In spectrum **C**, the oblique arrows designate the pump frequency (14.26 MHz) and the dashed lines represent the TRIPLE effects appearing in the pairs of ENDOR signals.

To confirm the structure of radical **2**, the π-spin densities and hfcc's were calculated in terms of a local spin density functional theory by using *Gaussian 94* with the UBLYP/6-31G*//UBLYP/6-31G* method. First, Figure 3 shows the π-spin density distribution of the two possible tautomeric isomers correlated with **2ba**, **2ab**, as well as **2$^{\bullet\bullet}$** and 6-oxophenalenoxyl **1**.[4] In the case of **2aa**, the calculated result gave the same π-spin density distribution as that of **2ba**. The relative signs of the π-spin densities on C3, C4, and C9 in **2ba**, **2ab**, and **2$^{\bullet\bullet}$** are equal in accord with the experimental result, which does not serve to distinguish between the structures. Next we compared the calculated hfcc's obtained by the DFT method with the observed ones (Table 1). In the case of **2ba**, not only the absolute values but also the relative ratios to the hfcc of C9−H are consistent with the observed ones, while the calculated hfcc's of **2ab** and **2$^{\bullet\bullet}$** cannot reproduce the observed ones at all. The obtained neutral radical might exist as a mixture of tautomers. Nonetheless, these experimental and theoretical results indicate the dominant contribution of the structure **2ba**, which

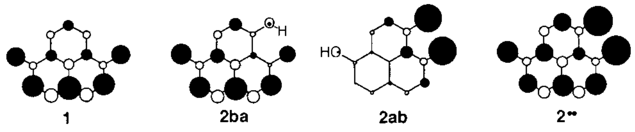

Figure 3. The π-spin density distribution of **1** (unsubstituted) and **2** calculated by a local spin density functional theory by using *Gaussian 94* with UBLYP/6-31G*//UBLYP/6-31G*. Vacant and filled circles denote negative and positive π-spin densities, respectively.

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(9) The radical purity can be estimated by TLC analysis.

(10) The relative intensity between these two kinds of signals was constant as a function of the concentration of the samples (10^{-4}, 10^{-5}, 10^{-6} M) at 298 K.

(11) The ENDOR measurements were carried out on a Bruker ESR 300/350 X-band spectrometer at 12.5 kHz field modulation in order to avoid line shape distortion due to sideband formation.

(12) The signals attributed to the *tert*-butyl protons were not discriminated since the differences of their hfcc were smaller than the ENDOR line width. The poor resolution gave a possible rationale for not discriminating between the ^1H ENDOR signal of the O−H proton and those of the *tert*-butyl protons.[13]

Table 1. Observed and Calculated Proton Hfcc's for **2**[a]

	A_H/mT		
	3	4	9
observed[b]	+0.187 (2.25)	+0.177 (2.13)	+0.083 (1)
2ba[c]	+0.146 (2.18)	+0.131 (1.96)	+0.067 (1)
2ab[c]	+0.033 (0.11)	+0.348 (1.14)	+0.305 (1)
2$^{\bullet\bullet}$ [c]	+0.143 (0.30)	+0.445 (0.94)	+0.471 (1)

[a] The values in parentheses are relative ratios of hfcc's based on the values of hfcc's on C9−H. [b] Observed hfcc's were determined by ^{1}H-ENDOR spectra in toluene at 200 K. The relative signs of the hfcc's were determined in terms of ^{1}H-TRIPLE spectroscopy. [c] Calculated hfcc's were determined by using *Gaussian 94* with UBLYP/6-31G*//UBLYP/6-31G* method.

might be thermodynamically more stable than **2aa** by the resonance stabilization effect.

The OH functional group may influence the electronic structure and also cause the lowering of symmetry of the radical structure via intramolecular hydrogen bonding. On the other hand, the π-spin density distribution of **2** is similar to that of 6-oxophenalenoxyl (Figure 3);[4] this finding strongly indicates the stability of the electronic structure of 6-oxophenalenoxyl system **2ba** compared with those of **2aa** and **2ab**. Such an extensively delocalized nature of the unpaired electron over the phenalenyl skeleton and two oxygen atoms contributes to the stability of this radical in addition to the steric effect of *tert*-butyl substituents.[4,14,15]

In conclusion, we have efficiently synthesized and characterized a new type of neutral radical **2**. The crystalline solid of **2** can survive for a few weeks under atmospheric oxygen at room temperature. While the well-known α-nitronyl nitroxide radicals have a localized spin nature, radical **2** has an extensively delocalized one. This electronic feature and the existence of the phenolic OH and carbonyl functional groups may contribute to the crystalline molecular arrangements and to the control of magnetic interactions, as well as the dynamic behavior of the electronic structure correlated with intramolecular proton transfer.[16] Further progress toward the crystal structural analysis and magnetic properties of radical **2** will be reported in due course.

Acknowledgment. This work was supported by Grants-in-Aid for Scientific Research on Priority Area "Delocalized π-Electronic Systems" (no. 297) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

Supporting Information Available: Experimental procedures and full characterization of new compounds **2** and **3**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(13) The hfcc value of the O−H protons of tris(3,5-di-*tert*-butyl-4-hydroxyphenyl)methyl radical in toluene is 0.14 MHz at 200 K, ca. 0.7 MHz at 300 K; see: Kirste, B.; Harrer, W.; Kurreck, H. *J. Am. Chem. Soc.* **1985**, *107*, 20−28.

(14) Goto, K.; Kubo, T.; Yamamoto, K.; Nakasuji, K.; Sato, K.; Shiomi, D.; Takui, T.; Kubota, M.; Kobayashi, T.; Yakushi, K.; Ouyang, J. *J. Am. Chem. Soc.* **1999**, *121*, 1619−1620.

(15) The neutral radical generated from 2,5,8-tri-*tert*-butyl-9-hydroxy-4-methoxyphenalenone by PbO_2 oxidation reaction exhibited very unstable nature at room temperature in air.

(16) The reversible electron transfer between phenol and phenoxyl radical derivatives with an assistance of hydrogen bonding has recently been reported; see: Maki, T.; Araki, Y.; Ishida, Y.; Onomura, O.; Matsumura, Y. *J. Am. Chem. Soc.* **2001**, *123*, 3371−3372.