5176 *J. Org. Chem.* **1999,** *64,* 5176−5182

3,5-Di-*tert*-butyl-3′-(*N*-*tert*-butyl-*N*-aminoxy)-4-oxybiphenyl: A Heterospin Diradical with Temperature Dependent Behavior

Yi Liao,[†] Chunping Xie,[†] Paul M. Lahti,*[,†] Ralph T. Weber,[‡] JinJie Jiang,[‡] and David P. Barr[‡]

Department of Chemistry, University of Massachusetts, Amherst, Massachusetts 01003 and
Bruker Instruments Inc., Billerica, Massachusetts 01821

Received February 19, 1999

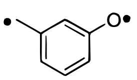
The title diradical was synthesized and investigated by ESR and UV−vis spectroscopy. It was found to have a lifetime of weeks even in the presence of oxygen, and even survives brief heating in toluene up to about 60 °C. In the UV−vis spectrum, the diradical showed reversible thermochromic behavior in the −10 to 50 °C range. In the ESR spectrum, hyperfine analysis showed nearly isolated behavior by the phenoxyl and nitroxide spin carrying units. Upon warming, additional, broad lines appeared at the expense of the lower temperature lines. This temperature behavior was reversible over the 0 to 50 °C range, so long as the raised temperatures were not maintained for long time periods. The spectral behavior is interpreted as being due to temperature-dependent conformational effects on the exchange coupling between the spin carrying units, i.e., *J*-modulated exchange behavior.

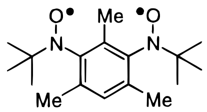
Introduction

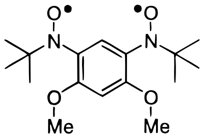
Conjugated diradicals have been a topic of considerable theoretical and experimental interest since the late 19 century.[1,2] During the past 30 years, advances in experimental technology and theoretical understanding have yielded a variety of qualitative structure−property relationships for diradicals and related open-shell molecules.[3−9] Despite such better understanding, some facets of diradical behavior remain to be extensively probed. In particular, heterospin open shell systems have not been greatly studied, by which in this case we specifically refer to organic systems having hypovalent sites of different types.

Heterospin diradicals are important probes of the interplay between frontier orbital energy level perturbation by substitution, versus the parity-based tendencies of such systems to give high-spin ground-state multiplicities. In an archetypal example, *m*-benzoquinomethane, **1**, has been experimentally shown to have a triplet ground state (or possibly a near-degeneracy of triplet and singlet states).[10] Recent multiconfiguration self-consistent field computations are in agreement with the experiment, and show a favoring of the triplet over the singlet state by about 10 kcal/mol.[11] The triplet preference is observed despite the fact that a naïve perturbation-based analysis suggests **1** to have an appreciable splitting of its singly occupied frontier molecular orbitals (MOs), a factor typically seen as favoring singlet state behavior.

In another comparison, nondisjoint dinitroxide diradicals such as **2** and **3** have been found experimentally to have singlet ground states with low-lying excited triplet states,[12,13] in spite of the fact that qualitative parity models suggest high spin ground states. In these cases, a connectivity-based preference for the high spin state is offset by conformational dependence of intramolecular exchange between the unpaired electrons, as well as by heteroatom substituent effects upon the exchange. A review has detailed a number of such so-called “violations of Hund’s rule”.[14] Overall, although widely accepted structure−property guidelines exist for predicting the ground-state multiplicities of open-shell molecules, complex combinations of molecular connectivity and substitution pattern can confound the guidelines.


1


2


3

Relatively few heterospin open-shell molecules have been made, by comparison to the numbers of systems having all the same spin carrying units. Mixed carbene/nitrene,[15] carbene/nitroxide,[16] nitrene/nitroxide,[17] and

---

[†] University of Massachusetts.

[‡] Bruker Instruments Inc.

(1) *Diradicals*; Borden, W. T., Ed.; John Wiley and Sons: New York, 1982.

(2) Michl, J.; Bonacic-Koutecky, V. *Tetrahedron* **1988**, *24*, 7559.

(3) Longuet-Higgins, H. C. *J. Chem. Phys.* **1950**, *18*, 265, 275, 283.

(4) Longuet-Higgins, H. C. In *Theoretical Organic Chemistry, Kekule Symposium*; Butterworth: London, 1958; pp 9−19.

(5) Klein, D. J.; Nelin, C. J.; Alexander, S.; Matsen, F. E. *J. Chem. Phys.* **1982**, *77*, 3101.

(6) Klein, D. J. *Pure Appl. Chem.* **1983**, *55*, 299.

(7) Misurkin, I. A.; Ovchinnikov, A. A. *Russ. Chem. Res. (Engl.)* **1977**, *46*, 967.

(8) Ovchinnikov, A. A. *Theor. Chim. Acta* **1978**, *47*, 297.

(9) Borden, W. T.; Davidson, E. R. *J. Am. Chem. Soc.* **1977**, *99*, 4587.

(10) Rule, M.; Matlin, A. R.; Seeger, D. E.; Hilinski, E. F.; Dougherty, D. A.; Berson, J. A. *Tetrahedron* **1982**, *38*, 787.

(11) Horvat, D. A.; Murcko, M. A.; Lahti, P. M.; Borden, W. T. *J. Chem. Soc., Perkin Trans. 2* **1998**, 1037.

(12) Dvolaitzky, M.; Chiarelli, R.; Rassat, A. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 180.

(13) Kanno, F.; Inoue, K.; Koga, N.; Iwamura, H. *J. Am. Chem. Soc.* **1993**, *115*, 847.

(14) Borden, W. T.; Iwamura, H.; Berson, J. A. *Acc. Chem. Res.* **1994**, *27*, 109.

(15) Tukada, H.; Mutai, K.; Iwamura, H. *Chem. Commun.* **1987**, 1159.

(16) Matsuda, K.; Iwamura, H. *Chem. Commun.* **1996**, 1131−1132.

(17) Esat, B.; Walton, R.; Lahti, P. M. *J. Am. Chem. Soc.* **1998**, *120*, 5122.

10.1021/jo990317l CCC: $18.00

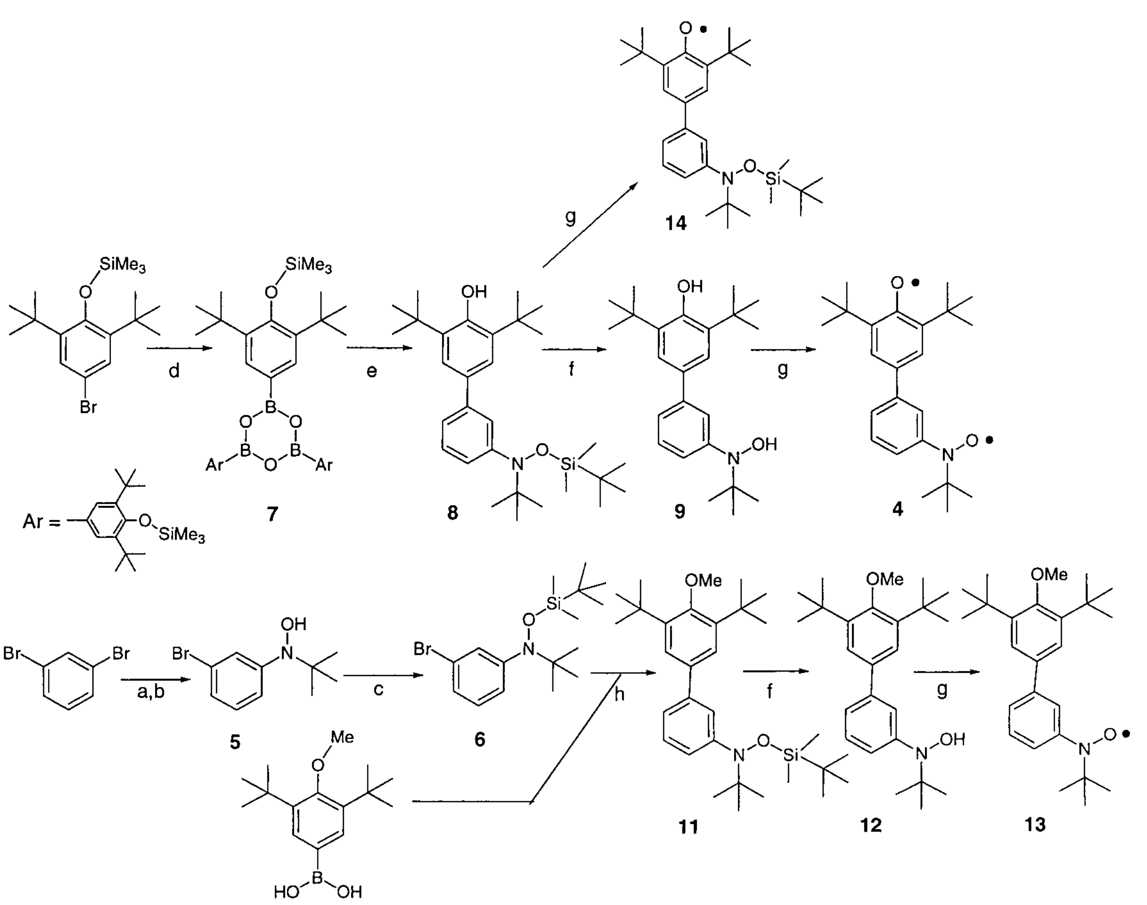


Figure 1. Synthesis of diradical **4**, monoradicals **13** and **14**. (a) *n*-BuLi, Et_2O, −78 °C; (b) $Me_2C(NO)Me$, room temp; (c) $ClSiMe_2$-*t*-Bu, imidazole, DMF, 50 °C; (d) *t*-BuLi, Et_2O, −78 °C, then B(O-*iso*-Pr)$_3$, then hydrolyze; (e) **6**, $Pd(OAc)_2$, PBu_4, THF; (f) Bu_4NF, THF, 50 °C; (g) PbO_2, toluene, room temp; (h) $Pd(OAc)_2$, PPh_3, NaOEt, THF.

nitroxide/radical-ion combinations have been synthesized and investigated. We aimed to synthesize systems incorporating phenoxyl and nitroxyl spin carrying units, both of which have been used in polyradicals and molecular magnetic materials. In this report, we describe the synthesis and spectral analysis of the diradical 3,5-di-*tert*-butyl-3′-(*N*-*tert*-butyl-*N*-aminoxy)-4-oxybiphenyl, **4**.

Background

Sterically hindered nitroxide radicals have been known for almost 40 years as stable hypovalent molecules.[18] Their stability is primarily due to blockading of possible dimerization pathways. Some degree of spin delocalization is observable in arylnitroxide analogues, based on the smaller nitrogen hyperfine coupling constants (hfc, a_N) that are observed experimentally by comparison to alkylnitroxides. If one makes the usual assumption that hfc is proportional to spin density in the nitroxides, only a small amount of the nitroxide spin density delocalizes onto the benzene ring in an aryl *tert*-butylnitroxide. This is in part due to the two-center, three-electron nature of the nitroxide spin carrying unit, and in part due to a varying degree of twisting of the *tert*-butylnitroxide (tBN) group relative to an attached aryl group. The torsion of the nitroxide reduces the possibility of spin delocalization, resulting in overall localized behavior for tBNs.

Sterically stabilized phenoxyl radicals have also been known for decades.[19] By contrast to tBNs, phenoxyl radicals show large spin delocalization. ESR hfc analysis of phenoxyl itself shows that the radical has a large contribution from carbonyl-containing resonance structures and is well represented as having its main spin density on the position *para* to the hypovalent oxy site. This tendency toward delocalization of phenoxyl radicals has made them a much-used spin carrying unit in molecular magnetism studies, in the anticipation that spin delocalization will increase intramolecular exchange values. However, the delocalization also destabilizes the phenoxyl system, to the extent that dimerization occurs fairly readily even in many sterically *ortho*/*para* blockaded systems.

Our goal in this study was to combine the spin-delocalizing capability of the 2,6-di-*tert*-butylphenoxyl moiety with the stability of a phenyl *tert*-butylnitroxide moiety to make a heterospin diradical system. We are not aware of other reported examples of nondisjoint heterospin exchange between a phenoxyl and a nitroxide radical.

Synthesis

The overall scheme of Figure 1 was followed to synthesize **4** and related model monoradicals. The two spin-carrying units were made separately as protected forms, coupled, and deprotected to give the appropriate bis-

---

[18] Forrester, A. R.; Hay, J. M.; Thomson, R. H. *Organic Chemistry of Stable Free Radicals*; Academic Press: New York, 1968.

[19] Altwicker, E. R. *Chem. Rev.* **1967**, *67*, 475.

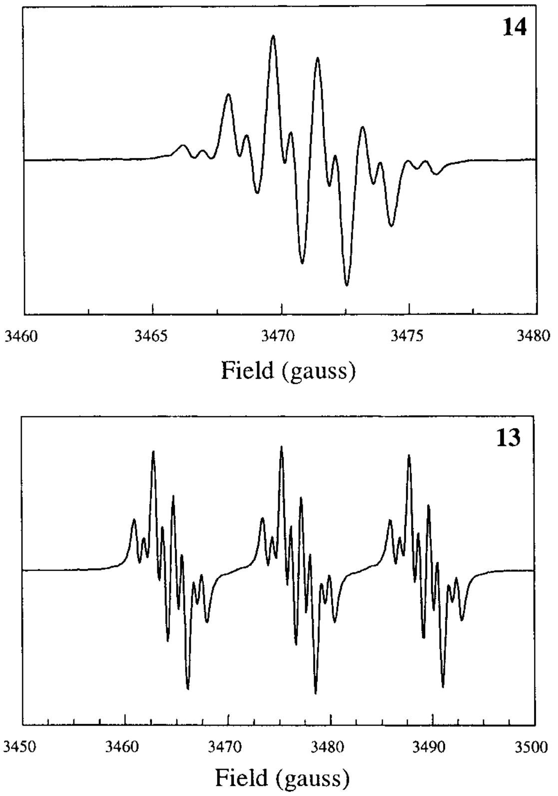


Figure 2. Electron spin resonance spectra for phenoxyl radical **14** ($\nu_0 = 9.762$ GHz) and nitroxide radical **13** ($\nu_0 = 9.802$ GHz) at room temperature in benzene solutions.

hydroxy precursor. Hydroxylamine **5** was made by trapping 3-bromo-phenyllithium with 2-methyl-2-nitrosopropane and quickly converted to the *tert*-butyldimethylsilanyl ether **6** to minimize air oxidation. Tris[3,5-bis(*tert*-butyl)-4-(trimethylsilyloxy)phenyl]boroxin, **7**, was conveniently made by Satoh's method[20] as the protected phenol unit. The assembly of the two halves to make precursor **8** was accomplished under Suzuki conditions, during which the trimethylsiloxy group was cleaved. The protected intermediate **8** was deblocked to the bis-hydroxy precursor **9** by treatment with tetrabutylammonium fluoride. Precursor **9** discolored readily upon storage in atmospheric oxygen, apparently due to air oxidation of the hydroxylamine group. The oxidation was demonstrated by observation of a typical nitroxide 1:1:1 triplet spectrum in the ESR of discolored solution samples of **9**.

Figure 1 also shows the synthesis of a monoradical model compound via Suzuki coupling of 2,6-di-*tert*-butylanisole-4-boronic acid **10** with **6** to give compound **11**. The silyl ether group in **11** was deprotected using tetrabutylammonium fluoride to give hydroxylamine **12**. Precursor **12** could then be used to generate model monoradical **13**, as described below. The analogous phenoxyl spin-site monoradical **14** was generated by oxidation of intermediate **8**.

Results

The monoradicals **13** and **14** were made by heterogeneous phase oxidation in benzene using lead dioxide. Both gave strong and persistent ESR spectra, as shown in Figure 2. The hfc for these radicals were obtained by

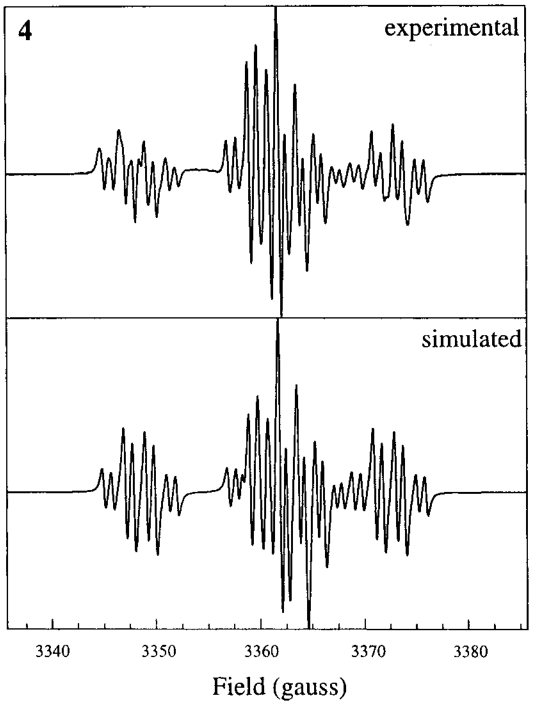


Figure 3. Electron spin resonance spectrum from oxidation of **9** ($\nu_0 = 9.430$ GHz) to **4** at room temperature in toluene solution. The top spectrum is experimental, the lower spectrum is line shape fitted using program BIRADG (ref 22).

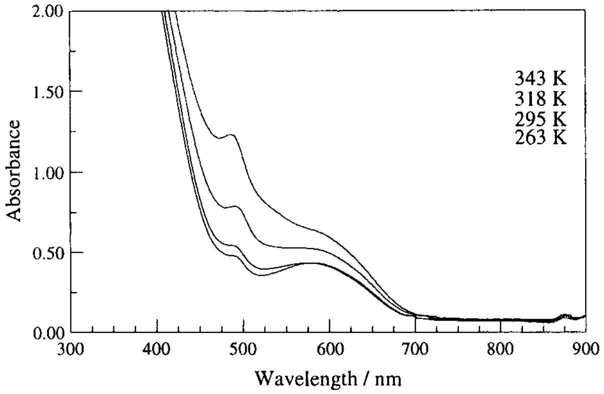


Figure 4. UV-vis spectra at varying temperatures from oxidation of **9** in toluene solution.

line shape fitting, using the WINSIM program of Duling.[21] The detailed hfc data are given in the Experimental Section.

Dihydroxy precursor **9** was oxidized in various solvents using both aqueous sodium periodate and lead dioxide. The latter conditions always gave the same ESR and UV–vis spectra within 15–30 min. These spectra are shown in Figures 3 and 4, respectively. Sodium periodate oxidized only the nitroxide group of **9**, based on the evidence of ESR spectra that showed only nitroxide hfc. In addition, sodium periodate oxidation gave only the reddish color of nitroxide radicals, by comparison to the greenish color obtained from diradical **4**. When a sodium periodate partially oxidized sample was stirred with lead dioxide, the typical spectra of diradical **4** were obtained, identical to those obtained by complete oxidation of **9** with lead dioxide only.

---

(20) Satoh, Y.; Shi, C. *Synthesis* **1994**, 1146.

(21) Duling, D. R. *J. Magn. Reson.* **1994**, *B104*, 105.

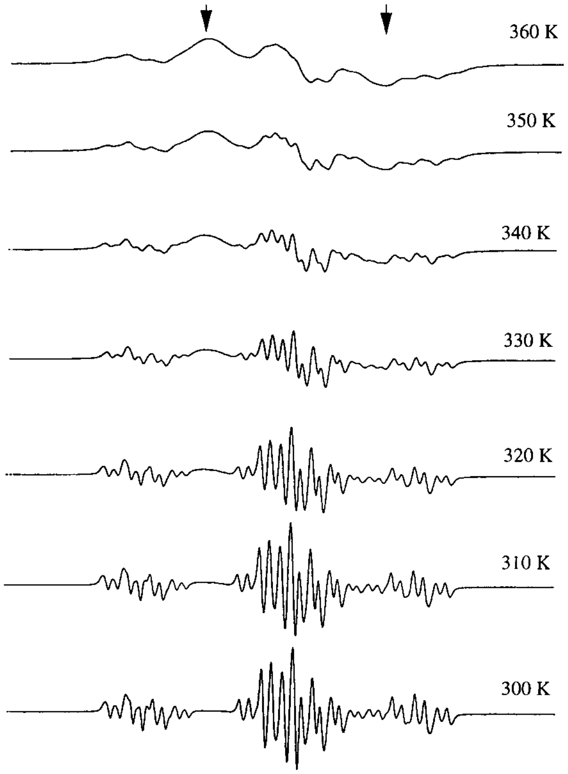


Figure 5. Electron spin resonance spectra at varying temperatures from oxidation of **9** in toluene solution ($\nu_0 = 9.430$ GHz).

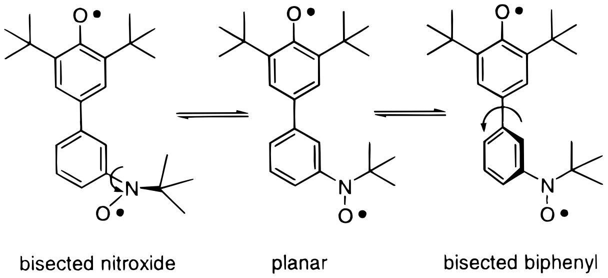
Line shape analysis of the ESR spectrum obtained by lead dioxide treatment of **9** was carried out using the program BIRADG, kindly made available to us by Dr. B. Kirste.[22] BIRADG is a line shape analysis program for weakly interacting diradicals, the input for which includes hfc for the radical fragments that interact to give the diradical, and the exchange coupling constant between the fragments. Figure 3 shows the simulated spectrum obtained by us. Further details of the fitted hfc data are given in the Experimental Section below.

Figure 4 also shows the results of experiments in which precursor **9** was oxidized with lead dioxide in toluene and subjected to variable temperature analysis of its UV−vis spectrum. The observed variation of the spectrum was reversible over multiple cycles between −10 and 60 °C. Upon storage at −30 °C, the same sample showed essentially no change in the intensity or line shape of its UV−vis spectrum for at least two months, despite not being under inert atmosphere.

Precursor **9** was also oxidized with lead dioxide in toluene, subjected to a 3-fold freeze−pump−thaw degassing, and sealed under vacuum for variable temperature ESR spectral analysis. The results are shown in Figure 5. As the sample was heated above room temperature, the highly hyperfine-split spectrum broadened and became complicated by the appearance of broad peaks within the original spectral extent. Over a temperature range of 0−60 °C, the line shape behavior was reversible so long as the sample was not subjected to the upper temperature range for extended times. But, if the temperature was raised above 70 °C the original spectrum could not be recovered, instead yielding a simpler spectrum that appeared to be dominated by the nitroxide hfc. During the temperature cycling, the sample varied from a greenish color at room temperature to a darkly reddish shade at higher temperatures. This thermochromic behavior was reversible and correlates with the spectral changes shown in Figures 4 and 5.

Discussion

Diradical **4** is a nondisjoint system by the Borden−Davidson[9] classification scheme and is expected to have a high-spin triplet ground state. 3,4′-Biphenyl analogues with carbene[23] and nitrene[24] spin-carrying units have been investigated and found to have high-spin ground states. However, as mentioned in the Introduction, a number of other systems have recently been described that contradict simple connectivity-based ground state predictions. Many of these latter systems incorporate nitroxide spin-carrying units. In particular, the nondisjoint dinitroxides **2** and **3** described in the Introduction are both known to have singlet ground states with low-lying excited triplet states. In the case of **2**, the discrepancy with theory is attributed to deconjugation of the nitroxide spin sites by steric-induced torsion. Since nitroxides are not greatly delocalized in the typical aryl nitroxides, the situation grows worse when torsion is larger than usual. For diradical **3**, a crystal structure has been obtained[13] showing the nitroxide units to be twisted by 65° and 75°, demonstrating the correlation between nitroxide torsion and a weakening of the parity rules for ground state prediction.



The room-temperature solution phase ESR spectrum of **4** is essentially that expected for a summation of isolated, noninteracting spin sites. Simulation of the spectrum (Figure 2) by BIRADG as a pair of weakly interacting nonequivalent radicals gives a very good fit to the experimental spectrum with an intramolecular exchange constant $J < 0.1$ G. If the spectrum is fitted as a summation of isolated radicals (WINSIM), another very good fit is obtained, for which the phenoxyl and nitroxide radical components are found each to comprise 50 ± 3% of the spectrum. All the room-temperature simulations are consistent with **4** having extremely weak exchange interaction between its spin units. Solution spectra obtained at temperatures below room temperature down to 0 °C show no further change of the narrow line features.

However, even at room temperature there was a weak, broad spectral feature that rises above the baseline between the low field nitroxide features and the central phenoxyl features. This peak and a corresponding one

---

(22) Kirste, B. *Anal. Chim. Acta* **1992**, *265*, 191.

(23) Teki, Y.; Fujita, I.; Takui, T.; Kinoshita, T.; Itoh, K. *J. Am. Chem. Soc.* **1994**, *116*, 11499.

(24) Minato, M.; Lahti, P. M. *J. Phys. Org. Chem.* **1991**, *4*, 459.

superimposed on the region between the central phenoxyl features and the high-field nitroxide features strengthened steadily as the temperature was raised to the 50−70 °C range, while the rest of the narrow line features broadened and weakened. When the sample was cooled again, the line shape returned to the original appearance. The cycling of the ESR spectrum could be repeated multiple times reproducibly, so long as the sample was not subjected to the higher temperature ranges for more time than was required to run a spectrum. A sample that was kept in a heated ESR spectral cavity for over 2 h and heated to >60 °C underwent irreversible changes, giving a spectrum that was essentially that of an isolated nitroxide unit. This sample also stopped showing thermochromic behavior. We did not further investigate this result, but postulate that the more reactive phenoxyl site in **4** undergoes irreversible chemical reaction at elevated temperatures.

The thermochromic behavior of **4** that is shown in Figure 4 correlates with the ESR behavior. One peak at about 490 nm increased as the sample was warmed, and decreased as the sample was cooled again. The visual effect was to change the greenish room temperature color to a darker green plus red color at elevated temperatures. Although one should not push qualitative reasoning too far, it is worth noting that many phenoxyl radicals are blue to green in color, while aryl nitroxides are commonly reddish. For this reason, we suspected that an increase in temperature led to an increase in nitroxide-like character in **4**.

The combination of ESR and UV−vis spectral results strongly supports the presence of conformationally controlled electronic variation in **4**. Both rotation of the nitroxide unit and phenyl−phenyl torsion within the biphenyl moiety would be expected to lead to changes in overall conjugation and intramolecular exchange behavior. It is not obvious from the experimental behavior which rotation—or mix of rotational behaviors—is most likely in this case.

We carried out computational investigation of **4** to probe the variation of exchange coupling as functions of the two major torsional modes, using the semiempirical molecular orbital plus configuration interaction (CI) methodology in MOPAC93[25] that has previously been established[26,27] to give good reproduction of experimental results for such diradical systems. Geometries were constrained at the multielectron CI (MECI) level with a CI = (6,2) active space. The *tert*-butyl groups on the phenoxyl unit were replaced with hydrogen atoms, and the *tert*-butyl group on the nitroxide group was replaced with a methyl group. Three cases were considered: (1) free optimization, (2) bisected biphenyl constraint, (3) bisected nitroxide constraint. At the PM3-CI[28] level of theory, the fully planar and bisected biphenyl conformers are nearly isoenergetic, with the bisected biphenyl conformer being 0.3 kcal/mol lower in energy. The bisected nitroxide geometry was found to be 2.7 kcal/mol higher in energy than the bisected biphenyl conformer.

The computed triplet−singlet state energy gap $\Delta E(T - S)$ varied as a function of geometry. At the fully planar geometry, $\Delta E(T - S) = 3.1$ kcal/mol, but $\Delta E(T - S) \sim 0.1$ kcal/mol at both the bisected biphenyl geometry and the bisected nitroxide geometry, with the triplet favored in both cases. The triplet−singlet gap at the planar geometry is consistent with the usual parity rule predictions for systems with effective intramolecular exchange. The very small gap at the bisected geometries is consistent with the experimental results and fits earlier computations showing that nitroxide delocalization is vitiated by torsion. Overall, the computations predict that twisting about the central bond in the biphenyl ring is easy at room temperature, and that the twisting would virtually eliminate effective exchange interaction between the spin-carrying sites.

The ESR spectra of the two monoradical models for **4**, systems **13** and **14**, are useful in demonstrating the different spin delocalization behaviors of the phenoxyl and nitroxide spin units in the diradical. The phenoxyl unit (**14**) showed strong spin delocalization onto the second phenyl ring, with hyperfine coupling being observed for all of the hydrogen atoms on the biphenyl system. Significantly, there was no resolvable hfc from the nitrogen atom in the spectrum of **14**. By contrast, the spectrum for **13** showed no resolvable hfc beyond that on the ring to which the nitroxide is attached. The nitrogen hfc $a_N = 12.5$ G at room temperature, which is in the upper range of hfc for aryl *tert*-butylnitroxides, consistent with modest spin delocalization at best.

Monoradical **13** was also warmed in toluene solution to 67 °C in an effort to gauge the effect of temperature on the nitrogen hfc. Although some line broadening was observed, a_N remained essentially unchanged. It seemed likely that, if nitroxide rotation became sufficiently eased at elevated temperatures to improve the exchange coupling in **4**, then a similar change in nitroxide rotation would lead to a decrease (or at least a visible change) in a_N for **13**. Because temperature-dependent behavior of a_N was not observed for **13**, we tend to favor biphenyl central bond rotation as the conformational mode affecting the ESR spectrum for **4**. This is also in agreement with the greater stability of the bisected biphenyl geometry over the bisected nitroxide geometry in the semiempirical computations for **4**. We assign the spectral behavior shown in Figure 5 to modulation of the intramolecular exchange energy (*J*-modulation) by conformational mobility. As the temperature increases, phenyl−phenyl rotation becomes easier, and the biphenyl group becomes more planar as a time average. *J*-modulated line shape behavior can be complex,[29,30] and further experiments are needed to understand more fully the spectral behavior of Figure 5. However, the observed changes are not consistent with equilibration between two structurally different species, or with irreversible reactions of any sort. The spectrum cannot be interpreted in terms of a biradical for which the exchange and hyperfine constants are nearly equal, or for which the exchange is appreciably larger than the hyperfine. The remaining choice of a biradical having exchange much smaller than the hyperfine interaction presumably is correct, with the added complexity of conformationally induced *J*-modulation of the line shape behavior.

We were concerned with the possibility of incomplete oxidation of precursor **9**. Indeed, we found that use of

---

(25) Stewart, J. J. P. *J. Comput.-Aided Mol. Des.* **1990**, *4*, 1.

(26) Lahti, P. M.; Ichimura, A. S.; Berson, J. A. *J. Org. Chem.* **1989**, *54*, 958.

(27) Lahti, P. M.; Ichimura, A. S. *J. Org. Chem.* **1991**, *56*, 3030.

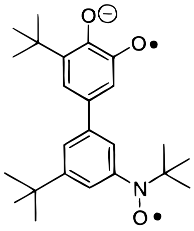
(28) Stewart, J. J. P. *J. Comput. Chem.* **1989**, *10*, 209, 221.

(29) Avdievich, N. I.; Forbes, M. D. E. *J. Phys. Chem.* **1996**, *100*, 1993.

(30) Avdievich, N. I.; Forbes, M. D. E. *J. Phys. Chem.* **1995**, *99*, 9660.

freshly prepared lead dioxide as opposed to commercial lead dioxide greatly speeded the oxidation process. If fresh oxidant was used, the ESR and UV−vis spectra failed to show further changes if stirring was continued for >30 min. Oxidation of **9** in carbon tetrachloride gave the usual ESR spectrum and in addition showed complete consumption of the distinctive phenolic OH peak in the room-temperature solution FTIR spectrum. In these and other typical cases, both 4-substituted-2,6-di-*tert*-butylphenols and aryl *tert*-butylhydroxylamines appear to undergo complete conversion to the corresponding radicals within 30 min or so of heterogeneous phase (fresh) lead dioxide treatment. Given the loss of the OH peak in the FTIR and the constancy of the ESR spectral appearance, we feel that oxidation of **9** is essentially complete under our conditions to give **4**.

We were not able to observe any dipolar splitting of the spectrum of **4** in frozen benzene or toluene at 77 K. The spectrum under these conditions was just a single, featureless peak. This is by contrast to the observable triplet dipolar splitting in analogue **15**, which was recently reported by Shultz and Farmer.[31] For **15**, the dipolar zero field splitting (zfs) $|D/hc| = 0.0084$ cm^{-1} in cryogenic matrix (with a sodium counterion). The cryogenic spectrum also showed a half-field transition that followed the Curie Law at varying temperatures, indicating that the triplet state of **15** is either the ground state, or is virtually degenerate with the singlet state. The room-temperature ESR spectrum of **15** was estimated to have hfc of $a_{\mathrm{N}} = 12.5$ G and $a_{\mathrm{H}} = 1.8$ G (3H), all on the nitroxide-bearing ring. It is interesting to note that **15** shows low-temperature zfs, while **4** does not. This suggests that the semiquinone-bearing system has more effective exchange than the phenoxyl bearing system. It not clear whether this is may be due to inherently stronger exchange between the spin sites, or perhaps a more planar conformation in **15**.



15

Conclusions

Diradical **4** was found not to be a robustly exchange-coupled system. Instead, it showed an unusual thermal variation in exchange behavior, apparently governed by conformational effects on exchange strength. The summary of evidence seems most consistent with torsion of the *tert*-butylnitroxide group as causing the exchange variation. The unusual stability of the diradical and its reversible spectral line shape behavior is consistent with **4** exhibiting conformationally controlled exchange effects. These findings demonstrate that fine-tuning is possible for exchange behavior in open-shell systems with small ground-to-excited state energy splittings, especially when conformational effects are important relative to molecular connectivity effects.

Experimental Section

General Procedures. 2-Methyl-2-nitrosopropane was prepared by the procedure of Stowell.[32] Diethyl ether and tetrahydrofuran (THF) were distilled under argon after drying over sodium. *N*,*N*-Dimethylformamide (DMF) was dried over anhydrous magnesium sulfate. Toluene was dried over sodium. All the other starting materials were obtained from Aldrich Chemical Corp. and used without further purification. Elemental analyses were carried out by the University of Massachusetts Microanalytical Laboratory.

***tert*-Butyl(3-bromophenyl)-hydroxylamine (5).** To a solution of 2.0 g (8.5 mmol) of 1,3-dibromobenzene in 35 mL of diethyl ether was added 3.6 mL (8.9 mmol) of a 2.5 M solution of *n*-butyllithium in hexane at −78 °C under nitrogen. After being stirred for 30 min, the solution was warmed to room temperature and then cooled to −78 °C. A solution of 1.11 g (12.7 mmol) of 2-methyl-2-nitrosopropane[32] in diethyl ether was added, and the solution was stirred overnight at ambient temperature. Next, 10 mL of saturated ammonium chloride aqueous solution was added. The organic layer was separated and washed with water. The aqueous layer was extracted with diethyl ether (30 mL × 3), and the organic layers were combined. Evaporation of the organic solvent layer under reduced pressure gave 1.6 g (80% yield) of pale yellow crystals. This product was used as soon as possible in the next step, to avoid oxidation by ambient air. ^{1}H NMR ($CDCl_3$) δ 1.13 (s, 9 H), 5.70 (br s, 1 H), 7.10−7.45 (m, 4 H). IR (KBr, cm^{-1}) 3195 (N−OH str).

***tert*-Butyl(3-bromophenyl)(*tert*-butyldimethylsiloxy)-amine (6).** To a solution of 1.0 g of **5** (4.10 mmol) in 5.0 mL of DMF were added 1.23 g (8.20 mmol) of *tert*-butyldimethylchlorosilane and 0.74 g (12.30 mmol) of imidazole. The solution was stirred for 24 h under nitrogen at about 50 °C. The solution was extracted with hexane (40 mL × 3), and the organic layers were combined and evaporated under reduced pressure. The resulting residue was chromotographed on silica gel with hexane to give 0.94 g of **2** (64% yield) as a colorless oil. ^{1}H NMR ($CDCl_3$) δ −0.11 (s, 6 H), 0.91 (s, 9 H), 1.10 (s, 9 H), 7.11−7.43 (m, 4 H).

Tris[3,5-bis(*tert*-butyl)-4-(trimethylsilyloxy)phenyl]-boroxin (7). This compound was synthesized by the method of Satoh and Shi.[20]

3,5-Di-*tert*-butyl-3′-[*N*-*tert*-butyl-*N*-(*tert*-butyldimethylsiloxy)amino]-4-hydroxybiphenyl (8). To a stirred suspension of 0.0157 g (0.07 mmol) of $Pd(OAc)_2$ in 0.5 mL of THF was added 0.0142 g (0.07 mmol) of tributylphosphine in 0.5 mL of THF under nitrogen. After being stirred for 10 min, this solution was added to a solution of 0.5 g (1.4 mmol) of **6** plus 0.5 g (1.55 mmol) of boroxin **7** in 10 mL of THF. To this solution was added a sodium methoxide solution prepared by reaction of 0.113 g (5 mmol) of sodium with 2 mL of methanol. The resulting reaction mixture was stirred for 24 h under nitrogen at room temperature. The solution was washed with water. The organic solvent was evaporated under reduced pressure to give a crude brownish oil that was chromotographed on silica gel with hexane to give 0.08 g of **8** as colorless crystals (12%, mp 99−101 °C). ^{1}H NMR ($CDCl_3$) δ −0.08 (s, 6 H), 0.94 (s, 9 H), 1.12 (s, 18 H), 1.49 (s, 18 H), 5.21 (s, 1 H), 7.22−7.48 (m, 6 H). IR (KBr, cm^{-1}) 3643 (phenolic OH). Anal. Calcd for $C_{30}H_{49}NO_2Si$: C, 74.48; H, 10.21; N, 2.90. Found: C, 74.78; H, 10.16; N, 2.81.

3,5-Di-*tert*-butyl-3′-(*N*-*tert*-butyl-*N*-hydroxyamino)-4-hydroxybiphenyl (9). To a stirred solution of 15 mg (0.031 mmol) of **8** in 1 mL of THF was added 0.15 mL of a 1.0 M solution of tetrabutylammonium fluoride in THF. The solution was stirred for 24 h under argon at about 50 °C, following which an additional 0.15 mL of the tetrabutylammonium fluoride solution was added and the reaction stirred for another 24 h of stirring. Next, an aqueous saturated ammonium chloride solution was added. The organic layer was separated and washed with water. The aqueous layer was extracted with diethyl ether (5 mL × 3), and the organic layers were

---

[31] Shultz, D. A.; Farmer, G. T. *J. Org. Chem.* **1998**, *63*, 6254.

[32] Stowell, J. C. *J. Org. Chem.* **1971**, *36*, 3055.

combined. The organic solvent was evaporated under reduced pressure, and the residue was purified by preparative thin layer chromotography to give 9 mg of **9** as colorless crystals (78%, mp 104−105 °C) that turned slightly orange if allowed to stand in air. ^{1}H NMR (CDCl$_3$) δ 1.19 (s, 9 H), 1.49 (s, 18 H), 5.22 (s, 1 H), 5.61 (s, 1 H), 7.20−7.40 (m, 6 H). IR (KBr disk, cm^{-1}) 3440 (N−OH), 3630 (phenolic OH). Anal. Calcd for C$_{24}$H$_{35}$NO$_2$: C, 78.00; H, 9.55; N, 3.78. Found: C, 78.01; H, 9.54; N, 3.67.

2,6-Di-*tert*-butylanisole-4-boronic Acid (10). 4-Bromo-2,6-di-*tert*-butylanisole[33] (6.0 g, 20 mmol) was dissolved in 40 mL of dry THF under argon and cooled to −78 °C. Next, 23.5 mL (40 mmol, 1.7 M in hexanes) of *tert*-butyllithium was added dropwise by syringe, and the reaction stirred for 2 h at −78 °C. Triisopropyl borate (4.4 mL, 20 mmol) was added by syringe, and the solution was allowed to warm slowly to room temperature. Dilute aq HCl was added until the aqueous layer was acidic. The layers were separated, and the aqueous layer was extracted with 2 × 20 mL of dichloromethane. The combined organic layers were extracted with 8 × 10 mL of 1 N aq NaOH. The combined aqueous layers were then acidified by slow addition of 2 N aq HCl. A white precipitate formed and was compound **10** was collected by filtration. Sometimes this product was obtained as a mixture of the acid and the cyclic "anhydride" boroxin form[20]—such mixtures are acceptable for use in the next step, synthesis of **4** by Suzuki coupling. Yield: 3.6 g (68%), mp 295−297 °C. ^{1}H NMR (200 MHz, CDCl$_3$): δ 1.52 (s, 18 H), 3.76 (s, 3 H), 8.16 (s, 2 H).

3,5-Di-*tert*-butyl-3′-(*N*-*tert*-butyl-*N*-aminoxy)-4-oxybiphenyl (4). To a stirred solution of 5.0 mg (0.0135 mmol) of **9** in 1 mL of degassed toluene was added 9.3 mg (0.0675 mmol) of freshly prepared lead dioxide[34] at room temperature. After 40 min of stirring under argon, the brownish-green suspension was allowed to settle, and aliquots could be removed by pipet for spectroscopic study. UV−vis (toluene, room temp, nm): 390 (strong), 490, 576 (broad). ESR (toluene, 9.430 GHz, modulation frequency = 100 kHz, hfc derived by simulation with WINSIM): nitroxide-derived portion of spectrum, $a_N = 11.98$ G, $a_1 = 1.97$, 2.09, 2.09 (protons *ortho*, *para* to nitroxide), $a_2 = 0.87$ (proton *meta* to nitroxide), simple linewideth = 0.33 G, spectrum is 47.8% of total simulated area; phenoxyl-derived portion of spectrum, $a_1 = 1.73$, (2 H, 3,5-protons on phenoxyl ring), $a_2 = 1.74$, 1.80, 1.81 (phenoxyl hfc to 2′, 4′, 6′ protons on nitroxide ring), $a_3 = 0.73$ (phenoxyl hfc to 5′ proton on nitroxide ring), simple line width = 0.36 G, spectrum is 52.2% of total simulated area. See Figure 5 for comparison of experiment and simulation by the alternate BIRADG method.[22] Both the UV−vis and ESR spectra were persistent for at least two months of storage at −30 °C, with almost no loss of spectral intensity in the UV−vis.

3,5-Di-*tert*-butyl-3′-[*N*-*tert*-butyl-*N*-aminoxy]-4-methoxybiphenyl (11). A solution of 0.37 g (1.4 mmol) of **10** and 0.5 g (1.4 mmol) of **6** was prepared in 2.5 mL of degassed THF. A catalytic solution of 15.7 mg (0.07 mmol) of Pd(OAc)$_2$ plus 12 mg (0.06 mmol) of tributylphosphine was separately prepared in a similar amount of THF and then transferred into the reaction vessel. Next, 80 mg of sodium was carefully added to 2 mL of anhydrous ethanol (CAUTION: FIRE HAZARD), and the resultant sodium ethoxide solution was cooled to room temperature and added to the reaction vessel. The reaction was stirred at room temperature under nitrogen overnight (turns black). The precipitates were filtered away, and the filtrate was concentrated by rotary evaporation to give a black oil, which was purified by column chromatography (silica gel, 9:1 hexane:ethyl acetate). The resultant yellow oil was allowed to stand overnight and crystallized. Recrystallization from hexane gave colorless needles (mp 126−128 °C, 0.13 g, 19%). ^{1}H NMR (CDCl$_3$) δ −0.08 (s, 6 H), 0.95 (s, 9 H), 1.12 (s, 9 H), 1.48 (s, 18 H), 3.74 (s, 3 H), 7.26 (m, 4 H), 7.45 (s, 2 H).

3′-[*N*-*tert*-Butyl-*N*-aminoxy]-3,5-di-*tert*-butyl-4-methoxybiphenyl (13). To a solution of 3,5-di-*tert*-butyl-3′-[*N*-*tert*-butyl-N-(*tert*-butyldimethylsiloxy)amino]-4-methoxybiphenyl (**11**, 4.1 mg, 0.008 mmol) in 1.5 mL of benzene was added 0.4 mL of 1 N tetrabutylammonium fluoride in tetrahydrofuran (Aldrich). The reaction was stirred at room temperature for 48 h, until no starting material was detected by thin-layer chromatography. The solution of **12** was passed through a plug of silica gel and immediately used for the subsequent oxidation. The solution of **12** in 1 mL of degassed benzene was added excess freshly prepared lead dioxide at room temperature. Within 30 min, the orange-red suspension was allowed to settle and was used as is for spectroscopic study by withdrawing aliquots by pipet. UV−vis (benzene) shows a long, tailing absorption from 200 nm out into the visible region. ESR (toluene, 9.802 GHz, modulation amplitude = 0.031, modulation frequency = 12.5 kHz, hfc derived by simulation with WINSIM): $a_N = 12.48$ G, $a_1 = 1.79$, 1.81, 1.96 (protons *ortho*, *para* to nitroxide), $a_2 = 0.80$ (proton *meta* to nitroxide), simple line width = 0.49 G, correlation coefficient of fit is 0.993.

3,5-Di-*tert*-butyl-3′-[*N*-*tert*-butyl-*N*-(*tert*-butyldimethylsiloxy)amino]-4-oxybiphenyl (14). To a stirred solution of 6 mg (0.01 mmol) of **8** in 1 mL of degassed benzene was added an excess of recently prepared lead dioxide at room temperature. Almost at once a purple suspension formed and persisted. The suspension was allowed to settle and was used as is for spectroscopic studied by withdrawing aliquots by pipet. UV−vis (benzene, nm, λ_{max}): 481, 514, 554. ESR (toluene, 9.762 GHz, modulation amplitude = 0.031 G, modulation frequency = 12.5 kHz, hfc derived by simulation with WINSIM): $a_1 = 1.74$, (2 H, 3,5-protons on phenoxyl ring), $a_2 = 1.62$, 1.63, 1.87 (phenoxyl hfc to 2′, 4′, 6′ protons on nitroxide ring), $a_3 = 0.65$ (phenoxyl hfc to 5′ proton on nitroxide ring), simple line width = 0.37 G, correlation coefficient of fit is 0.996.

Acknowledgment. Support of this work by the National Science Foundation (CHE-9521594 and CHE-9809548) is gratefully acknowledged. The opinions expressed in this paper are solely those of the authors and not necessarily those of the Foundation.

Supporting Information Available: General spectral procedures, ^{1}H NMR spectra for compounds **5**, **6**, and **10**, and descriptions of the hyperfine coupling data for radicals **13**−**14** and biradical **4**. This material is available free of charge via the Internet at http://pubs.acs.org.

JO990317L

---

[33] For a preparation of 4-bromo-2,6-di-*tert*-butylanisole, see Dhami, K. S.; Stothers, J.B. *Can. J. Chem.* **1966**, *44*, 2855.

[34] Fresh PbO$_2$ was prepared by addition of lead tetraacetate to distilled water, filtration, washing of the product with distilled water to neutral pH, and drying in air to give a very dark brown powder of suitable quality for oxidation.