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Bis[3-*tert*-butyl-5-(*N*-oxy-*tert*-butylamino)phenyl] Nitroxide in a Quartet Ground State: A Prototype for Persistent High-Spin Poly[(oxyimino)-1,3-phenylenes]

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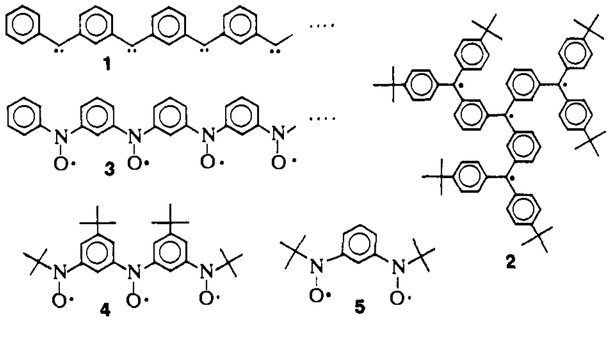
Abstract: The title trinitroxide **4** was synthesized via the bis[*m*-(hydroxyamino)phenyl] nitroxides **9** and **10**. The ESR spectra obtained in a toluene glass at 4.2 K was consistent with **4** in a quartet state with the zfs parameter $|D|/h\nu$ of $0.0087\ \mathrm{cm^{-1}}$. The quartet state was shown to be the ground state by the magnetic measurement of its microcrystalline sample on a Faraday balance. The maximum of the effective moment was $3.53\ \mu_B$ at ca. 140 K. The Weiss constant and the energy gap between the lowest excited doublet and the ground quartet states were estimated to be −19 and +240 K, respectively.

Intramolecular ferromagnetic interaction among the electron spins in polyradicals is of current interest in connection with design of molecular ferromagnets.[1] Poly(*m*-phenylenecarbenes) (**1**) have been most systematically studied inter alia and are accepted as the highest spin organic molecules.[2,3] Their high spin states are based on the ferromagnetic exchange coupling between the one-center π- and σ-unpaired electrons at the divalent carbons and among the topologically polarized π-spins. Recent synthesis of quintet tetraradical **2**[4] demonstrates that the latter interaction, namely, the periodicity of π-orbitals in alternant hydrocarbons, is sufficient in aligning π-spins in parallel. Both **1** and **2**, however, lack the stability for characterization under ambient conditions and have an inherent drawback for further extension to usable magnetic materials. We therefore turned our attention to persistent diaryl nitroxides[5] and also to ultimate polymer **3** and report here the synthesis and magnetic measurement of prototype trinitroxide **4** in which the radical centers are linked together through the *m*-phenylene coupling units in a linear fashion as in **1** and partly **2**.

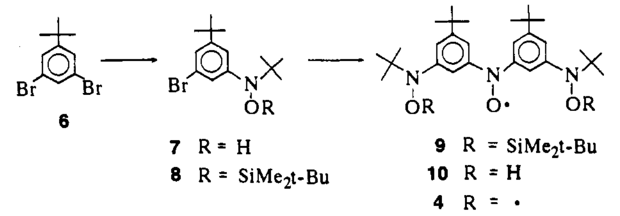


Results and Discussion

Dinitroxide **5**[6] is not necessarily fully persistent but changes into an isomeric aminoquinone imine *N*-oxide in a few hours in solution. In order to avoid such instability and obtain more persistent triradical, *tert*-butyl groups were introduced onto the phenyl rings for the purpose of steric protection.

Trinitroxide **4** was synthesized as shown in Scheme I. 3,5-Dibromo-*tert*-butylbenzene (**6**) was lithiated with *t*-BuLi in tetrahydrofuran (THF) and coupled with 2-methyl-2-nitrosopropane to give **7** (66%). After protection of the hydroxyamino group with a *tert*-butyldimethylsilyl group[7] in quantitative yield, **8** was lithiated with *t*-BuLi in THF and coupled with 0.5 equiv of *n*-pentyl nitrite[8] to give symmetrical diaryl nitroxide **9** (39%) that showed an ESR hyperfine structure consisting of a triplet of septet ($a_N = 10.4$ G, $a_H = 1.8$ G) at $g = 2.0053$ in CH_2Cl_2 solution. **4** was obtained in 80% yield by means of the desilylation of **9** with tetrabutylammonium fluoride trihydrate in THF (**10**, 55%) followed by the oxidation with Ag_2O in ether and purification by chromatography (alumina/CH_2Cl_2). The sample for ESR spectral and magnetic measurements was further purified by recrystallization from hexane. **4** is indefinitely stable in crystals and remains unchanged even in a solution under air for at least several weeks.

Scheme I. Synthetic Route to Trinitroxide **4**



ESR spectra of **4** showed a broad signal with a peak to peak line width of 14 G in a dilute solution due to intramolecular dipole–dipole and exchange interactions among the unpaired electrons and also probably due to overlap of different resonances of conformational isomers (Figure 1a). In a toluene glassy matrix at 4.2 K was obtained a fine structure characteristic of randomly oriented species in a quartet state (Figure 1b). The fine structure due to a quartet species should consist of 3 × 3 allowed transitions. The broad, simplified, and symmetrical spectrum obtained for **4** suggests that several conformers and/or anisotropic g values might be involved and that $E \ll D \ll h\nu$. Under the last conditions, the separation of the two outermost signals corresponds to $4D'$ $(=4D/g\mu_B)$.[9] In the present case, $H_{z1} = 3178$ G and $H_{z3} = 3551$ G. The $|D|$ value is therefore estimated to be $0.0087_3\ \mathrm{cm^{-1}}$ by assuming $|E|/h\nu \leq 0.0003\ \mathrm{cm^{-1}}$. The observed spectrum was reproduced reasonably well (Figure 1c) by using these zero-field splitting parameters, although the calculated spectrum was rather insensitive to the anisotropy in the g value and the $|E|$ value. This $|D|$ value lies between $0.012\ \mathrm{cm^{-1}}$ for dinitroxide **5**[6b] and $0.002\,83\ \mathrm{cm^{-1}}$ for tetratrityl **2**,[4] indicating that D values are qualitatively in inverse proportion to the size of π-conjugate systems. No signal assigned to a transition $\Delta m_S = 2$ or 3 was observed.

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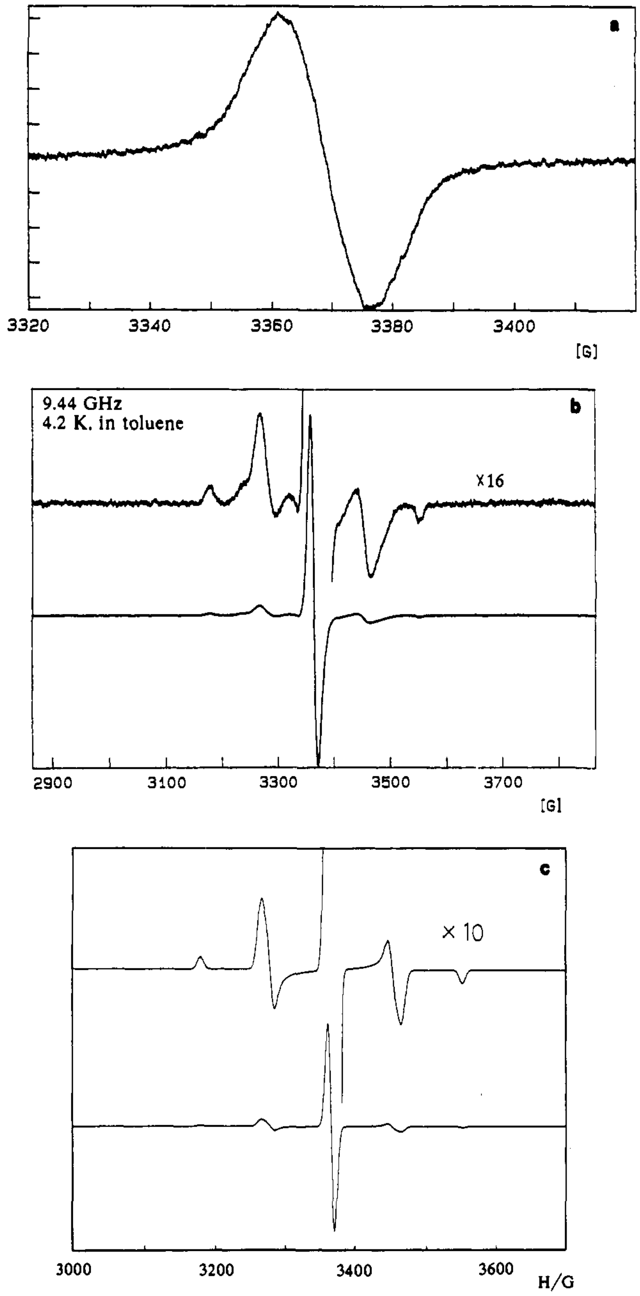

Figure 1. X-band ESR spectra of **4**: (a) in benzene solution at 25 °C; (b) in toluene glass at 4.2 K; and (c) simulation spectrum for randomly oriented quartet species with $|D|/h\nu = 0.008\,73$ cm^{-1}, $|E|/h\nu = 0.000\,25$ cm^{-1}, $g_{\text{iso}} = 2.0056$, and the line width 4.5 G.

The intensity of the ESR signals due to the quartet **4** decreased as the temperature was increased in the range 4.2–30 K in good agreement with a Curie law within the experimental error. Thus, whereas the quartet was concluded to be either a ground state or fully degenerate with lower spin states, it was not possible to determine how close the thermally accessible lower spin states lie above the ground quartet state.

Magnetic measurements were carried out on a Faraday magnetic balance from 2 to 300 K in a similar method as described elsewhere.[10] The temperature dependences of the magnetic susceptibility and the effective magnetic moment of **4** are shown in Figure 2. As the temperature increased, the moment of **4** increased from 1.05 μ_B at 2 K, reached a maximum 3.53 μ_B at around 140 K, and gradually decreased to 3.43 μ_B at 300 K. The latter decrease is due to the thermal population of the spins from a quartet ground state to excited doublet ones. The suppression at lower temperature is due to intermolecular antiferromagnetic couplings, which is confirmed by the fact that the lowest moment was smaller than 1.73 μ_B that isolated doublet species are expected to have.

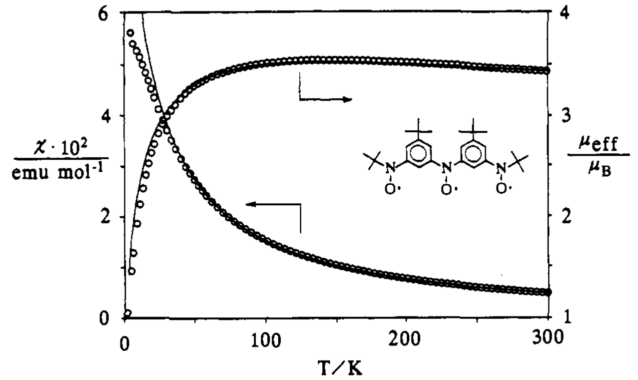

Figure 2. Temperature dependences of the molar magnetic susceptibility (χ) and the effective magnetic moment (μ_{eff}) for trinitroxide **4**. Solid lines are theoretical curves calculated with eq 1 for $\Theta = -19$ K and $J/k = 240$ K.

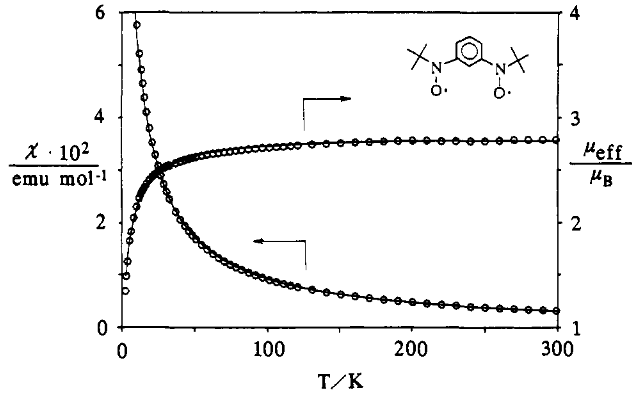

Figure 3. Temperature dependences of the molar magnetic susceptibility (χ) and the effective magnetic moment (μ_{eff}) for dinitroxide **5**. Solid lines are theoretical curves calculated with eq 2 for $\Theta = -7.8$ K and $J/k = 500$ K.

The magnetic interactions in a linear triradical system can be described by the spin Hamiltonian $-2J(\mathbf{S}_1\cdot\mathbf{S}_2 + \mathbf{S}_2\cdot\mathbf{S}_3)$, which assumes an isotropic exchange interaction and neglects intramolecular coupling (J') between the terminal radicals. For polyradicals like **1** and **2**, J' is estimated to be two orders of magnitude smaller than J.[11] The eigenvalues of this Hamiltonian are $E_1 = 2J$ ($S = {}^1/_2$), $E_2 = 0$ ($S = {}^1/_2$), and $E_3 = -J$ ($S = {}^3/_2$).[12] The molar susceptibility is given by eq 1, where all symbols have

$$\chi = \frac{Ng^2\mu_B{}^2}{4k(T-\Theta)}\,\frac{10 + \exp(-J/kT) + \exp(-3J/kT)}{2 + \exp(-J/kT) + \exp(-3J/kT)} \qquad (1)$$

their usual meaning. The temperature correction factor $T/(T-\Theta)$ is introduced as the Weiss molecular field appoximation. Best fit parameters were $\Theta = -19 \pm 2$ K and $J/k = 240 \pm 20$ K. The energy gap between the quartet state and the lower doublet one was estimated to be 240 K = 170 cm^{-1} = 480 cal/mol.

m-Phenylenebis(*tert*-butyl nitroxide) biradical (**5**) was reexamined for a reference. The effective moment increased as temperature increased and reached nearly 2.8 μ_B at 300 K (Figure 3). When the spin Hamiltonian is drawn as $-2J(\mathbf{S}_1\cdot\mathbf{S}_2)$, the molar susceptibility is given by eq 2,[13] where $2J$ is a singlet–triplet energy

$$\chi = \frac{2Ng^2\mu_B{}^2}{k(T-\Theta)}\,\frac{1}{3 + \exp(-2J/kT)} \qquad (2)$$

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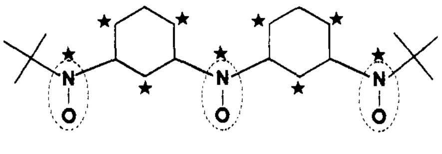
gap. The observed magnetic behavior was interpreted in terms of a triplet ground state of **4** with best fit parameters of $\Theta = -7.8$ K and $2J/k \gg 300$ K. Mukai et al.[6] reported similar results on **4** except the somewhat larger negative Weiss constant (−19 K). The difference may be due to different crystal sizes or forms of the sample.

The intramolecular exchange coupling was strongly ferromagnetic in both cases. Since the π-atomic orbital of more electronegative heteroatoms is lower in energy, the degeneracy of nonbonding molecular orbitals of hydrocarbon polyradicals will be lifted by introduction of a heteroatom radical center. The results obtained here suggest that the perturbation due to the introduction of heteroatoms is small and the topological consideration developed for alternant hydrocarbons can be applied to heteroatom–perturbed conjugated alternant systems. This assumption is supported by the report that *m*-phenylenedinitrene has a quintet ground state.[14] Even unsymmetrical (*m*-nitrenophenyl)methylene is a ground-state quintet species.[15] Furthermore, the validity of this assumption has been discussed by Berson and his co-workers theoretically and experimentally in the oxygen-perturbed systems.[16] The topology appears to be more important than the Coulombic integral of the constituent atoms in determining the ground-state spin multiplicity.

It is noteworthy that the starred–unstarred rule for predicting the ground-state spin S (eq 3) of alternant hydrocarbons on the basis of VB theory[17] holds also for systems containing nitroxide functions only when a pair of nitrogen and oxygen atoms is starred once. Here n^* and n are the number of starred and unstarred

$$S = (n^* - n)/2 \qquad (3)$$

carbon atoms (or nitroxide groups), respectively. The S value should be 1 for **5** and $^3/_2$ for **4** since $n^* = 5$ and $n = 3$ for **5** and $n^* = 9$ and $n = 6$ for **4**, as shown by **4′**. This assumption may be validated by the McLachlan calculation, which shows that both atoms of a nitroxide function carry similar spin densities of the same sign.[18] Tyutyulkov et al.[19] studied the band structure of



4′

polynitroxide **3**, taking the nitroxide group as a "quasiatom", and demonstrated that there are degenerate NBMO's in the middle of a wide energy gap between bonding and antibonding MO's in a manner similar to the case of analogous hydrocarbons such as **1**.

Thus, **3** and polymers of **4** and **5**, should be persistent high-spin molecules. The J values in the order 170 cm^{-1} observed in this study should be compared with those of **1**. The latter is estimated to be much greater than 300 cm^{-1}. Whereas in diphenylcarbene, the lowest analogue of **1**, 24% of the π-spin is delocalized on each phenyl ring,[20] in diphenyl nitroxide 11% is delocalized on each ring.[18] The reduced degree of spin polarization in the π-network is considered to be responsible for the smaller exchange interaction in the nitroxides. Although **4** is persistent, the smaller J value suggests the difficulty in obtaining high-spin **3** and its analogues at ambient temperature in practice.

Experimental Section

Instrumentation and Measurements. ESR spectra were obtained on a Brucker ESP 300 X-band (9.4 GHz) spectrometer equipped with a Hewlett-Packard 5350B microwave frequency counter. The sample solution was degassed by a freeze–thaw–cycle method with use of an oil diffusion pump. The simulation of the ESR fine structures due to quartet **4** was carried out by using a program written by Itoh et al. on the basis of a perturbation treatment to third order in the fine-structure energy.[21] The $|E|/h\nu$ values greater than 0.0004 cm^{-1} gave split inner paired lines. Anisotropy in g values made slightly unsymmetrical center lines.

NMR spectra were measured on a JEOL GX-270 spectrometer at 270 MHz for ^{1}H in CDCl$_3$ solution. UV/vis and IR absorption spectra were measured on a JASCO UVIDEC 610C and Hitachi 270-30 spectrophotometer, respectively. Mass spectra (MS) were obtained on a JEOL JMS-D300 spectrometer. The relative intensities are shown in parentheses.

The magnetic susceptibility was measured by the Faraday method on an Oxford Instruments magnetic susceptibility system with a 7-T superconducting magnet. The powdery sample was fixed in a quartz cell with aid of a small amount of Nujol. The background data of the cell and the same amount of Nujol were measured separately and subtracted from the raw data. The diamagnetic contribution of the sample itself was estimated from Pascal's constants.

Materials. Dinitroxide **5** was synthesized according to the literature method.[6b]

3,5-Dibromo-*tert*-butylbenzene (6). **6** was synthesized from *p-tert*-butylaniline in a modified method of the preparation for 1,3,5-tribromobenzene from aniline.[22] Air streams carrying 19 g of bromine were introduced for 30 min to a solution of 5.38 g of *p-tert*-butylaniline and 3.3 mL of concentrated HCl(aq) in 160 mL of water. After it was stirred for 3 h, a dilute aqueous solution of $Na_2S_2O_3$ and $NaHCO_3$ and ether were added and the organic layer was separated, washed with water, dried over $MgSO_4$, concentrated under reduced pressure, and passed through a short column (SiO_2/CH_2Cl_2) to give a red oily product (9.28 g). To its solution in 50 mL of ethanol and 17 mL of benzene, 4.5 mL of concentrated H_2SO_4 and 4.5 g of $NaNO_2$ were added, and the mixture was refluxed for 3 h. After addition of ether, the organic layer was separated, washed, dried ($MgSO_4$), concentrated, and chromatographed on silica gel and hexane as an eluent to give 7.21 g of **6** as a slightly yellow oily product (69%): ^{1}H NMR δ 1.28 (s, 9 H), 7.43 (d, 2 H, J = 1.6 Hz), 7.47 (t, 1 H, J = 1.6 Hz); MS m/z 294, 292, 290 (M$^+$, 16, 33, 17, respectively), 227 (base).

***N*-(3-Bromo-5-*tert*-butylphenyl)-*N*-*tert*-butylhydroxyamine (7).** To a solution of 3.36 g of **6** in 20 mL of tetrahydrofuran (THF), 14.9 mL of *tert*-butyllithium pentane solution (1.7 N) was added at −78 °C under argon, and the mixture was gradually warmed to 0 °C for 30 min. A solution of 1.3 g of 2-methyl-2-nitrosopropane dimer in 10 mL of THF was added to it at −78 °C, and the mixture was gradually warmed again to room temperature for 1 h. After addition of a dilute aqueous solution of NH_4Cl and ether, the organic layer was separated, washed with water, dried over $MgSO_4$, concentrated under reduced pressure, and chromatographed (SiO_2/hexane/CH_2Cl_2 (hexane:CH_2Cl_2 = 1:1)) to give 2.26 g of **7** as orange solids (66%): mp 73–76 °C; ^{1}H NMR δ 1.16 (s, 9 H), 1.21 (s, 9 H), 6.95 (s, 1 H), 7.19 (s, 1 H), 7.19 (s, 1 H), 7.29 (s, 1 H), 8.28 (br s, 1 H); MS m/z 301, 299 (M$^+$, 2), 57 (base); IR (KBr disc) ν_{O-H} 3248 cm^{-1}.

***N*-(3-Bromo-5-*tert*-butylphenyl)-*N*-(*tert*-butyldimethylsiloxy)-*N*-*tert*-butylamine (8).** The hydroxyl group in **7** was silylated according to the method exploited by Corey.[7] A solution of 2.26 g of **7**, 1.28 g of imidazole, and 2.3 g of *tert*-butylchlorodimethylsilane in 6 mL of *N,N*-dimethylformamide was stirred at 50–60 °C for 12 h. After dilution with hexane and water, the organic layer was separated, washed with water several times, dried ($MgSO_4$), concentrated, and chromatographed on silica gel and CH_2Cl_2 as an eluent to give quantitatively 3.12 g of **8**: mp 58–66 °C; ^{1}H NMR δ −0.12 (br s, 6 H), 0.91 (s, 9 H), 1.08 (s, 9 H), 1.27 (s, 9 H), 7.2 (br, 3 H); MS m/z 415, 413 (M$^+$, 0.5), 57 (base).

Bis[3-*tert*-butyl-5-[*N*-(*tert*-butyldimethylsiloxy)-*tert*-butylamino]phenyl] Nitroxide (9). To a solution of 1.32 g of **8** in 7 mL of THF, 3.9 mL of *tert*-butyllithium pentane solution (1.7 N) was added at −78 °C under argon, and the mixture was warmed to room temperature for 15 min. Cooled again to −78 °C, 0.21 mL of *n*-pentyl nitrite was added to it, and the mixture was gradually warmed to room temperature and stirred for 1 h. After aqueous workup in a similar manner as described

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for the preparation of **7**, the concentrated residue was chromatographed on silica gel and hexane/CH_2Cl_2 (3:1) as an eluent to give 437 mg of **9** as a red viscous oil (39%): ESR (CH_2Cl_2, 25 °C) $g = 2.0053$, $a_{N(-O\cdot)} = 10.4$ G, $a_{H(arom)} = 1.8$ G; MS m/z calcd for $C_{40}H_{72}N_3O_3Si_2$ 698.5112, found 698.5134 (0.5), 57 (base).

Bis[3-*tert*-butyl-5-(*N*-hydroxy-*tert*-butylamino)phenyl] Nitroxide (10). A solution of 97.5 mg of **9** and 97 mg of tetrabutylammonium fluoride trihydrate in 5 mL of THF was stirred at 0 °C for 15 min and at room temperature for 15 min under argon. After aqueous workup as described above, the organic layer was chromatographed on silica gel and CH_2Cl_2 to give 37 mg of **10** as a red viscous oil (55%): ESR (benzene, 25 °C) $g = 2.0057$, $a_{N(-O\cdot)} = 9.9$ G, $a_{H(arom)} = 1.9$ G; IR (KBr disc) ν_{O-H} 3268 cm^{-1}; MS m/z 526 (M^+, 0.5), 57 (base).

Bis[3-*tert*-butyl-5-(*N*-oxy-*tert*-butylamino)phenyl] Nitroxide (4). To a solution of 33 mg of **10** in 2 mL of ether, a large excess amount (ca. 100 mg) of freshly prepared Ag_2O was added, and the mixture was stirred for 30 min at room temperature. The mixture was filtered with Celite, and the filtrate was chromatographed (alumina/CH_2Cl_2) to give 26 mg of **4** as orange solids (80%): mp 120–123 °C (from hexane); ESR (solid, 25 °C) $g = 2.0055$; (benzene, 25 °C) $g = 2.0058$, $\Delta H_{pp} = 14$ G; MS m/z calcd for $C_{28}H_{42}N_3O_3$ 468.3226, found 468.3243 (1), 57 (base); UV/vis λ 370 nm (sh, ϵ 1900), 430 (sh, 1500), 520 (sh, 410).

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Diels–Alder Reactions in Aqueous Solutions. Enforced Hydrophobic Interactions between Diene and Dienophile

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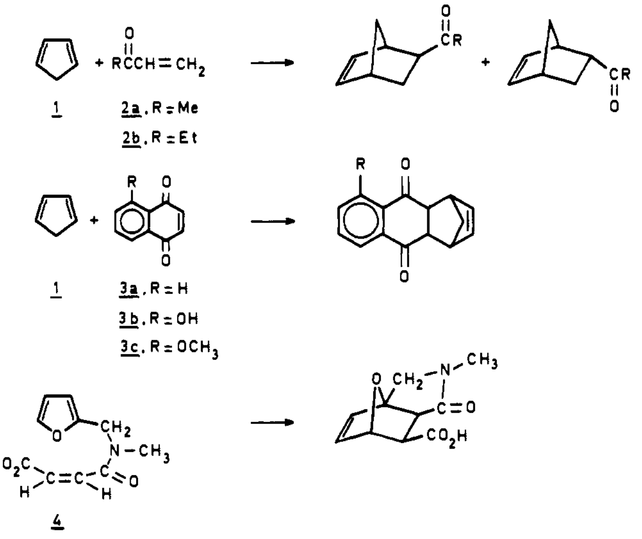
Abstract: Second-order rate constants and isobaric activation parameters for the intermolecular Diels–Alder reactions of cyclopentadiene with alkyl vinyl ketones (**2a**,**b**) and 5-substituted-1,4-naphthoquinones (**3a–c**) as well as for the intramolecular Diels–Alder reaction of *N*-furfuryl-*N*-methylmaleamic acid (**4**) were determined in water, monohydric alcohols, and highly aqueous solutions containing monohydric alcohols and other organic cosolvents. The intermolecular as well as the intramolecular Diels–Alder reaction are characterized by large rate accelerations upon going from an organic solvent to water as the reaction medium. A model for solvation effects on rate constants for Diels–Alder reactions in aqueous solutions is developed. The typical, huge rate enhancements for Diels–Alder reactions in water and in highly aqueous binary mixtures are significantly sensitive to substituent effects and are discussed in terms of enforced pairwise hydrophobic interactions between diene and dienophile.

Introduction

For a wide range of solvent systems, both the rate constants and stereoselectivities of Diels–Alder reactions are only moderately sensitive to changes in the nature of the reaction medium.[1] However, the pioneering work of Breslow et al.[2] has shown that Diels–Alder reactions are dramatically accelerated in aqueous solutions. Other studies also revealed curious rate effects on different types of cycloaddition reactions in water.[3-7] Recently, Grieco et al.[8] reported a large rate enhancement for a Diels–Alder reaction in diethyl ether containing 5 M lithium perchlorate. The large rate accelerations have been tentatively explained in terms of hydrophobic packing of diene and dienophile,[2] aggregation processes[3c] and the high internal pressure of water.[8-10]

Chart I



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