

Suzuki Reactions with Stable Organic Radicals – Synthesis of Biphenyls Substituted with Nitronyl-Nitroxide Radicals

Christophe Stroh,^[a] Marcel Mayor,^{*[a,b]} and Carsten von Hänisch^[a]

Keywords: C–C Coupling / Radicals / Magnetic properties / Nitronyl nitroxide

The synthesis of biphenyls substituted with nitronyl-nitroxide organic radicals is described. To investigate the Suzuki-type cross-coupling reaction conditions in the presence of the radical, a model compound **1** was prepared. The successful coupling was extended to cyano-functionalized, bi-phenylic, paramagnetic molecules. Both the *ortho*- and *meta*-

iodophenyl-nitronyl-nitroxide radicals were used to synthesize radicals **2** and **3**. The characterizations of the spin-labelled molecules obtained by this synthetic strategy include two X-ray crystal structures and magnetic measurements. (© Wiley-VCH Verlag GmbH & Co. KGaA, 69451 Weinheim, Germany, 2005)

Introduction

Stable organic radicals are intensively investigated due to particular features induced by the presence of an unpaired electron. The electronic properties of a large number of spin-labels and spin-probes have been studied in various environments,^[1a–1e] and the magnetic features of various radicals have been explored, giving rise to the fascinating field of molecular magnetism.^[2a–2d] Major advances involving the magnetic properties of molecules have been made with model compounds based on Ullman's nitronyl-nitroxide radicals^[3a–3b] since the discovery of the first purely organic magnet.^[4]

To study the intramolecular coupling between the spins of radicals, conjugated organic oligo- and polyradicals have been synthesized.^[5a–5e] Nitronyl-nitroxide diradicals and tri-radicals gave valuable results,^[6a–6d] and the spin density distribution in such systems has been mapped.^[7] Well suited for the preparation of multidimensional scaffolds, these radicals have been used as building blocks of linear, 2-D, 3-D or cyclic structures.^[8a–8f] Moreover, tailor-made molecules combining stable organic radicals with other functional subunits allow the investigation of the interaction between an unpaired electron spin and other electrons of different sources. For example, redox-active groups have been combined with radicals,^[9a–9b] and organic radicals bearing chromophores were prepared as magneto-optical systems^[10a–10d] and to study switching effects.^[11] However, in all these oligoradical investigations the spatial arrangement of the radical subunits and the molecular structures connecting these

paramagnetic subunits turned out to be of particular importance to tune the properties. Also, the intermolecular interaction of monoradicals in the solid state depends on both the spatial arrangement of the radical subunits and the molecular structure bearing these units.^[12] To control both key features by rational design, the synthesis of rigid molecular structures as scaffolds for functional building blocks is an elegant approach which has already been used in different research areas like light harvesting systems^[13a–13e] and molecular electronics.^[14a–14d] Many rigid organic scaffolds consisting of linked aromatic subunits, like shape persistent macrocycles, have been reported.^[15a–15d] The most prominent examples are acetylene- and directly-linked aromatic π systems, both synthetically based on metal-catalyzed coupling reactions like the Sonogashira reaction^[16] and the Suzuki reaction,^[17] respectively. While Sonogashira reactions have already been applied to arrange stable radicals within a molecular framework,^[18a–18d] to the best of our knowledge, Suzuki reactions with organic radicals have not yet been reported, even though biphenyl-based structures have been investigated.^[19a–19d] The combination of a Suzuki-type cross-coupling reaction and nitronyl-nitroxide radical building blocks enables the synthesis of spin-labelled oligophenylenes and may also lead to larger organic scaffolds containing paramagnetic subunits.

Here we report the first protocol for a Suzuki-type cross-coupling reaction in the presence of a nitronyl-nitroxide radical.

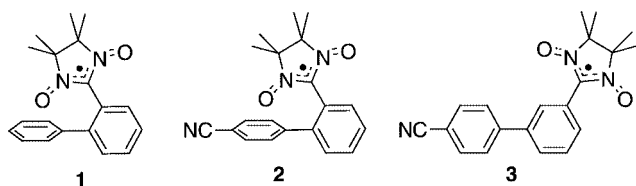
Results and Discussion

To investigate the compatibility of the nitronyl-nitroxide radical structure with the conditions of a Suzuki cross-coupling reaction, the model compounds **1–3** have been chosen as synthetic targets (Scheme 1). All three structures

[a] Institut für Nanotechnologie, Forschungszentrum Karlsruhe GmbH, Postfach 3640, 76021 Karlsruhe, Germany
Fax: +49-7247-82-5685
E-mail: marcel.mayor@int.fzk.de

[b] Department of Chemistry, University of Basel, St. Johannis-Ring 19, 4056 Basel, Switzerland

consist of a nitronyl-nitroxide radical subunit linked to a biphenyl core. Our synthetic strategy is to form the radical subunit first and subsequently assemble the biphenyl backbone by a Suzuki coupling. To profit from the possibility offered by this alternative strategy, compounds **2** and **3** with a cyano group at the peripheral ring as additional functionality have been synthesized. The cyano group is of particular interest because of its coordination features toward noble metal surfaces. Hence, compounds **2** and **3** enable the decoration of metallic substrates with stable organic radicals. Not only is the electronic interaction with the underlying surface of particular interest, but also the investigation of a spin probe at the end of a fixed molecular rod on a single-molecule level.

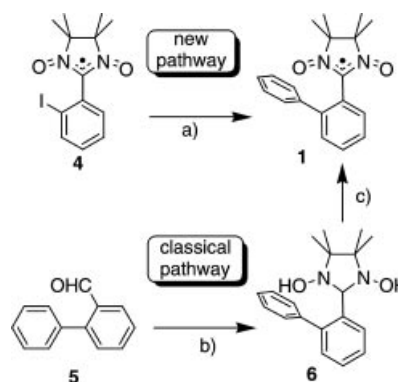


Scheme 1. Molecular structures of the *ortho*-nitronyl-nitroxide compounds **1** and **2** and of the *meta*-nitronyl-nitroxide compound **3**.

From a synthetic point of view, we further show that a halogen in the *ortho* position of a phenyl-nitronyl-nitroxide can be substituted, a finding that increases the feasible structural variety of the family of paramagnetic molecules.

The synthesis of radical **1** is displayed in Scheme 2. The iodophenyl-nitronyl-nitroxide **4** and phenylboronic acid react with each other in the presence of catalytic $\text{Pd}(\text{PPh}_3)_4$ and excess K_2CO_3 (aq.) in a toluene/MeOH (1:1) solvent mixture at 80 °C. Despite very similar R_f values and colors of both the starting compound **4** and the product **1**, silica gel chromatography allowed us to isolate **1** as a pink solid in 43% yield. To compare synthetic strategies and to further corroborate the structure of **1**, it was also synthesized by the classical synthetic strategy described by Ullman. A multiple condensation of *N,N'*-dihydroxy-2,3-diamino-2,3-dimethylbutane (DHA)^[20] with the aldehyde-functionalized biphenyl **5** in MeOH gave the intermediate compound **6**. Oxidation with NaIO_4 in a biphasic mixture gave the desired product **1**. For this two-step reaction sequence, an overall yield of 27% was obtained after purification by column chromatography. The isolated compound **1** synthesized by both strategies displayed identical characterization data and properties. The 43% yield of this alternative strategy is rather moderate or even poor. However, the reaction pathway is of particular interest for target compounds bearing functional groups that are not sensitive under the conditions of the classical Ullman reaction, like aldehydes. To compare the overall yields, the synthetic steps (Scheme 3) leading to 2-iodophenyl-nitronyl-nitroxide **4** have to be considered also. Starting with commercial 2-iodobenzaldehyde, 1,3-dihydroxy-2-(2-iodophenyl)-4,4,5,5-tetramethylimidazolidine **7** was obtained by a multiple condensation with DHA in 88% yield. Subsequent oxidation of **7** with NaIO_4 in a biphasic mixture afforded **4** with a yield of 68%. The 26% overall

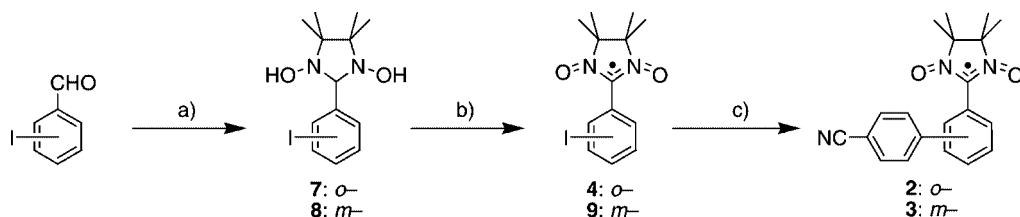
yield of the alternative reaction pathway over the three steps is in the same domain as the synthesis based on the classical Ullman reaction. Considering the yield of 91% for the synthesis of biphenyl-2-carboxaldehyde **5**, the overall yield for **1** by the classical reaction pathway drops to 25%. Hence, concerning the overall yield, both strategies are comparable, at least for the selected target compound. The loss in yield during the Suzuki reaction is most likely due to decomposition of the nitronyl-nitroxide radical subunit at higher temperature. Both the temperature and the duration of the reaction may be reduced by careful choice of the catalyst and the solvent, which might lead to further increase in the yield for the synthetic strategy; however, the focus of this work was to demonstrate the feasibility of the synthetic concept and to isolate and characterize the desired target compounds in excellent purity for subsequent applications in nanoscale physical devices and experiments.



Scheme 2. Two synthetic strategies for the synthesis of the biphenyl-nitronyl-nitroxide conjugated radical **1**. New pathway: a) phenylboronic acid, $\text{Pd}(\text{PPh}_3)_4$, Na_2CO_3 (aq.), Tol/MeOH, 1:1, 80 °C, 2 h, 43%. Classical pathway: b) DHA, MeOH, room temperature, 4 d, 73%. c) NaIO_4 , $\text{CH}_2\text{Cl}_2/\text{H}_2\text{O}$, 1 h, 37%.

To corroborate the structure of **1**, single crystals suitable for X-ray analysis were grown by slow diffusion of hexane into a solution of **1** in CH_2Cl_2 . The solid-state structure of **1** is discussed below and displayed in Figure 2.

To investigate the versatility of this alternative strategy, both starting compounds have been varied. As displayed in Scheme 3, 4-cyanophenylboronic acid was used instead of phenylboronic acid to synthesize **2** and **3**. For the synthesis of **3**, 3-iodophenyl-nitronyl-nitroxide **9** was synthesized in a comparable reaction sequence as described above for **4**. Commercial 3-iodobenzaldehyde was converted by condensation with DHA to 1,3-dihydroxy-2-(3-iodophenyl)-4,4,5,5-tetramethylimidazolidine **8** in 94% yield. Oxidation with NaIO_4 gave **9** in a 96% yield. For the synthesis of both compounds **2** and **3**, a similar Suzuki coupling protocol as described above for **1** has been applied. The reactions were monitored by thin-layer chromatography (TLC) and were quenched with excess cold water after 2 to 2.5 h at 80 °C. The desired compounds were isolated by flash chromatography as a pink solid in 40% yield for **2** and as violet microcrystals in 44% yield for **3**.



Scheme 3. Synthesis of the substituted phenyl-nitronyl-nitroxide conjugated radicals **2** and **3** and their precursors **4**, **7**, **8** and **9**. a) DHA, MeOH, room temperature, 3–5 d, 88% for **7** and 94% for **8**. b) NaIO₄, CH₂Cl₂/H₂O, 2 h, 68% for **4** and 96% for **9**. c) Cyanophenylboronic acid, Pd(PPh₃)₄, Na₂CO₃ (aq.), Tol/MeOH, 1:1, 80 °C, 2–2.5 h, 40% for **2** and 44% for **3**.

The structure of **3** was also confirmed by X-ray analysis. Single crystals suitable for X-ray analysis were prepared by slow diffusion of hexane into a solution of **3** in CH₂Cl₂.

In addition to the X-ray structures of **1** and **3**, radicals **1**–**3** prepared by the Suzuki-type cross-coupling reaction were characterized by MALDI-TOF spectrometry, FT-IR and UV/Vis spectroscopy, and elemental analysis. Furthermore, the purity of the samples was investigated by SQUID techniques.

The MALDI-TOF spectra of all three compounds **1**–**3** are very comparable and typical for structures bearing nitronyl-nitroxide radical subunits. An intense signal for the ionized molecule is followed by the signal arising from the molecule having lost one oxygen atom. A third intense signal, arising from the loss of both oxygen atoms, is also observed for all three compounds.

The IR spectra of all three compounds display comparable features, again pointing at the presence of the nitronyl-nitroxide substructure. All three samples display the characteristic ν_{NO} vibration band at 1367 cm⁻¹ for **1**, 1369 cm⁻¹ for **2**, and 1363 cm⁻¹ for **3**. In addition, compounds **2** and **3** display the characteristic $\nu_{\text{C}\equiv\text{N}}$ vibration band at 2226 cm⁻¹ of the cyano group.

Considerable differences in the UV/Vis spectra of the three radicals can be detected by the bare eye. While the two *ortho* nitronyl-nitroxide functionalized biphenyls **1** and **2** are pink, the *meta* nitronyl-nitroxide functionalized biphenyl **3** is violet. In the UV/Vis spectra the longest wavelength absorption of **3** is considerably bathochromically shifted (≈ 25 nm) relative to **1** and **2** (Figure 1). In the two latter compounds, the nitronyl-nitroxide subunit and the peripheral phenyl ring are connected at the central phenyl ring

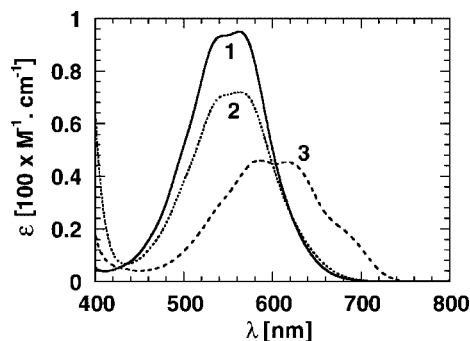


Figure 1. UV/Vis spectra of the three radicals in CH₂Cl₂ solution at 293 K and concentrations of 9.15×10^{-4} , 2.60×10^{-4} and 3.05×10^{-4} M for **1**, **2**, and **3**, respectively.

in the *ortho* position. This results in an increased steric repulsion which twists these two delocalized electronic subunits out of the plane of the central phenyl ring. The torsion angle between the nitronyl-nitroxide unit and the central phenyl ring is increased, and the π systems are separated. In contrast, the *meta*-substitution pattern of compound **3** puts both subunits at a considerably larger distance, and as a consequence, the arrangement of the central benzene ring and the nitronyl-nitroxide structure is flat, which results in a chromophore delocalized over both systems. This interpretation is further supported by the solid-state structures of **1** and **3**.

In the solid-state structure of **1**, the nitronyl-nitroxide moiety shows bond lengths as typically found for such radicals (NO = 1.29 Å, CN = 1.35 Å) (Figure 2). However, the mean plane of the radical makes a larger dihedral angle with the plane of the adjacent phenyl ring than generally observed (ca. 69.9°). As already mentioned above, this is due to the steric hindrance of the *ortho* substituent. Interestingly, the dihedral angle between the phenyl rings is 46.3° and is affected less by the radical subunit in the *ortho* position. Although the structural proximity of the radical oxygen and H atoms of the external phenyl ring may suggest an intramolecular H bond, the distance of 3.17 Å [O(1)⋯H–C(15)] is too large for such an interaction.

Close examination of the crystal packing shows an anti-parallel stacked arrangement of two neighboring radicals with a shortest distance above the van der Waals distance

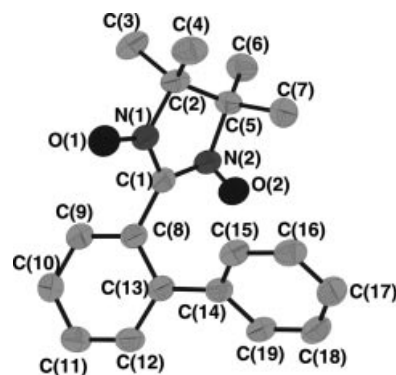


Figure 2. ORTEP view of the molecular structure of radical **1**. Selected bond lengths [pm] and bond angles [°]: O(1)–N(1) 128.8(2), N(2)–O(2) 128.6(2), N(2)–C(1) 134.7(2), N(1)–C(1) 135.2(2), C(8)–C(1) 148.5(2), N(2)–C(1)–C(8)–C(13) 71.5, N(1)–C(1)–C(8)–C(9) 68.3, C(8)–C(13)–C(14)–C(15) 46.7, C(12)–C(13)–C(14)–C(19) 46.0.

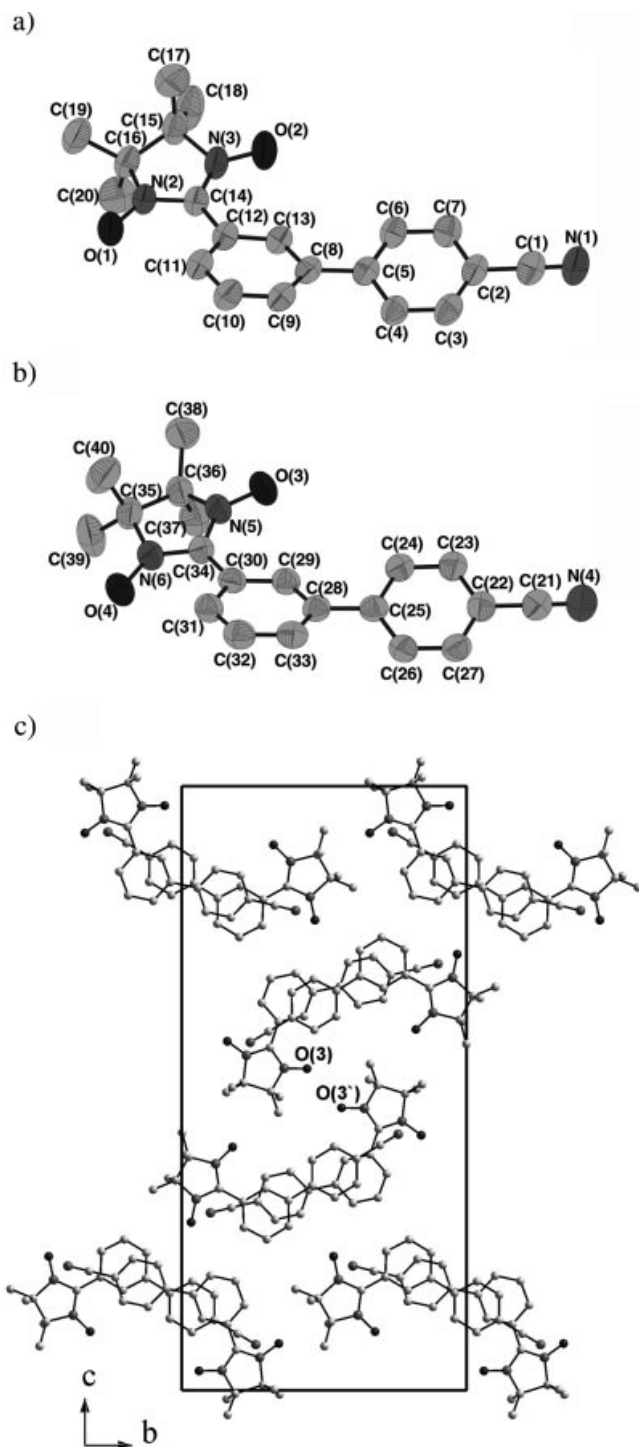


Figure 3. a) and b) ORTEP view of the two molecular structures of radical **3**. Selected bond lengths [pm] and bond angles [°]: N(2)–O(1) 129.2(3), N(3)–O(2) 129.5(3), C(14)–N(3) 136.1(4), C(14)–N(2) 136.4(4), C(12)–C(14) 147.4(4), C(5)–C(8) 150.3(4), C(1)–C(2) 145.6(5), C(1)–N(1) 115.8(4), N(3)–C(14)–C(12)–C(13) 14.6, N(2)–C(14)–C(12)–C(11) 12.9, C(13)–C(8)–C(5)–C(6) 19.3, C(9)–C(8)–C(5)–C(4) 19.6 and N(5)–O(3) 129.7(3), N(6)–O(4) 129.8(3), C(34)–N(5) 136.2(4), C(34)–N(6) 136.4(4), C(30)–C(34) 146.0(5), C(25)–C(28) 150.8(4), C(21)–C(22) 145.7(5), C(21)–N(4) 116.9(4), N(5)–C(34)–C(30)–C(29) 21.1, N(6)–C(34)–C(30)–C(31) 22.2, C(29)–C(28)–C(25)–C(24) 26.0, C(33)–C(28)–C(25)–C(26) 25.8. c) Packing of radical **3** showing the isolated pairs.

of 3.72 Å between the O1 atoms (N–O⋯O'–N' = 180.0°, O⋯O'–N' = 97.2°, C–N–O⋯O' = 88.2°); π stacking between the aromatic subunits is not observed.

The crystal structure of compound **3** contains two independent molecules, which are displayed individually in Figure 3a,b. Both show NO and CN bond lengths characteristic of such radicals (ca. 1.29–1.30 and 1.36 Å, respectively). However, one radical (Figure 3b) makes a dihedral mean angle of 21.6° with its adjacent phenyl ring, while this mean angle is only 13.7° in the second molecule (Figure 3a). Furthermore, the dihedral mean angle between the two phenyl rings is also larger in the first molecule than in the second (ca. 25.9° and 19.5°, respectively).

The packing of radical **3** is considerably different from the one found for **1**. π -Stacking of antiparallel molecules predominates, and the distances between the phenyl rings are nearly 3.5 Å. Interestingly, the distances between the nitrogen atom of the cyano group and the oxygen atoms of the radicals are between 3.36 and 3.90 Å. The formation of this crystal packing is probably based on dipole-dipole interactions between these polar molecules. Within these stackings, one out of two radicals shows a short contact with a neighboring radical (O(3)⋯O(3') = 3.58 Å) (Figure 3c).

The purity of compounds **1–3** is documented by their accurate elemental analysis. However, the nitronyl-nitroxide subunit as a stable organic radical allows us to confirm the purity of the sample by investigating the spin concentration

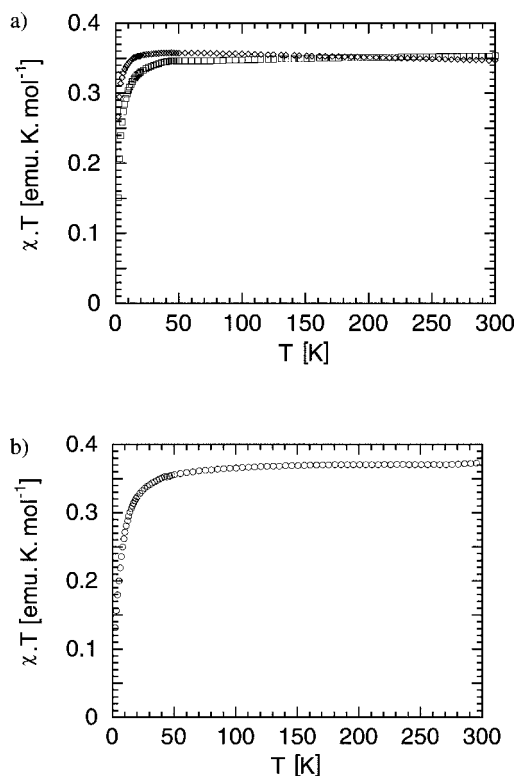


Figure 4. SQUID measurements from 300–2 K for the three radicals prepared by the new pathway; a) *ortho*-substituted compounds **1** (diamonds) and **2** (squares); b) *meta*-substituted compound **3** (circles).

of the compounds by SQUID measurements. Magnetic measurements were recorded on a SQUID susceptometer for all radicals on polycrystalline samples from 2–300 K. The corresponding magnetic behaviors versus temperature are reported in Figure 4a,b. At high temperature, the $\chi \cdot T$ versus T curves for all compounds are located near the expected value for one isolated $S = 1/2$ spin. The $\chi \cdot T$ products are 0.347, 0.353 and 0.373 $\text{emu} \cdot \text{K} \cdot \text{mol}^{-1}$ at 300 K for **1**, **2**, and **3** respectively. These values are consistent with an excellent spin concentration and high purity of the samples. By lowering the temperature, a decrease in the $\chi \cdot T$ products is observed for the three compounds at very low temperature, revealing the presence of very weak intermolecular antiferromagnetic interactions. Despite a small difference in the behavior of the *meta*-substituted derivative **3**, which shows a more rapid decrease in the $\chi \cdot T$ product than in the *ortho*-substituted radicals (Figure 4b), an interpretation of the origin of the change in the magnetic behaviors would be misleading in view of the complicated crystal packing of the molecules.^[12] Mean-field correction parameters θ of -0.9 , -1.6 and -3.3 K are obtained for **1**, **2** and **3**, respectively, by fitting the $1/\chi = f(T)$ curves with the Curie–Weiss law over the complete temperature range.

Conclusions

An alternative reaction pathway based on a Suzuki-type cross-coupling reaction in the presence of a nitronyl-nitroxide radical has been used for the first time. The significance of the synthetic strategy in the preparation of new functionalized paramagnetic molecules is demonstrated by the synthesis of three biphenylic structures containing a nitronyl-nitroxide subunit. These new compounds were fully characterized, two of them by X-ray crystal structures, and magnetic SQUID investigations corroborate their identity and purity by excellent spin concentrations.

The synthesis of various paramagnetic structures designed for physical experiments and investigations, like compounds containing surface anchor groups and paramagnetic molecular wires, will be further investigated in our research group. Moreover, the assembly of macromolecules containing several paramagnetic subunits may come within reach using this new strategy.

Experimental Section

General Remarks: 2-Iodobenzaldehyde and 3-iodobenzaldehyde were purchased from Aldrich. *N,N'*-Dihydroxy-2,3-diamino-2,3-dimethyl-butane was synthesized by following a reported method.^[20] All cross-coupling reactions were carried out under oxygen-free conditions. Characterizations were performed with the following instruments: melting points—Büchi B 540 (open capillaries, uncorrected values); UV/Vis—Varian Cary 500 Scan spectrophotometer; IR—Perkin–Elmer Spectrum GX FT-IR system; MALDI-TOF—PerSeptive Biosystems Voyager-DETMPRO; elemental analyses—CE Instruments Flash EA 1112 series. Magnetic susceptibilities were measured on polycrystalline materials for **1** and **3** and on a powder for **2** with a Quantum Design MPMS superconducting

SQUID magnetometer operating at a field strength of 0.5 T. The data were corrected for the magnetization of the sample holder contribution, and diamagnetism of the molecules was estimated from Pascal's constants.^[21]

Biphenyl-2-carboxaldehyde (5): Compound **5** was obtained as a white solid (91%) from 2-iodobenzaldehyde and phenylboronic acid by a standard procedure using $\text{Pd}(\text{PPh}_3)_4$ and Na_2CO_3 (aq.) in DMF and after purification by chromatography on SiO_2 (hexane/ Et_2O , 9:1).^[22] ^1H NMR (CDCl_3): δ = 10.01 (d, 4J = 0.9 Hz, 1 H, CHO), 8.05 (dd, 3J = 7.5, 4J = 1.2 Hz, 1 H, Ar), 7.7 (dt, 3J = 7.5, 4J = 1.2 Hz, 1 H, Ar), 7.55–7.39 (m, 7 H, Ar) ppm.

General Procedure for the Synthesis of Dihydroxyimidazolidine Intermediates: The corresponding iodobenzaldehyde (gram scale) and *N,N'*-dihydroxy-2,3-diamino-2,3-dimethyl-butane (ca. 1.5 equiv.) in MeOH (30 mL) were stirred at room temperature in the dark for 3 to 5 d. The solution volume was reduced by half, and the white precipitate was filtered and washed with MeOH, to give the title compound.

Compound 7: White solid. Isolated yield: 88%. R_f = 0.41 (SiO_2 , $\text{CH}_2\text{Cl}_2/2\%\text{MeOH}$). M.p.: 196–199 °C (dec.). ^1H NMR [$(\text{CD}_3)_2\text{SO}$]: δ = 7.79 (d, 3J = 7.8 Hz, 1 H, Ar), 7.63 (d, 3J = 7.8 Hz, 1 H, Ar), 7.60 (s, 2 H, OH), 7.39 (t, 3J = 7.5 Hz, 1 H, Ar), 7.02 (t, 3J = 7.8 Hz, 1 H, Ar), 4.94 (s, 1 H), 1.07 (s, 12 H, Me) ppm. $^{13}\text{C}\{^1\text{H}\}$ NMR [$(\text{CD}_3)_2\text{SO}$]: δ = 143.7, 139.3, 131.7, 130.4, 128.6, 103.3, 92.6, 67.1, 24.9, 18.6 ppm. IR (KBr): $\tilde{\nu}$ = 3247, 2985, 2926, 1465, 1450, 1376, 1363, 1262, 1210, 1153, 1144, 1019, 1010, 917, 865, 752 cm^{-1} . MALDI-TOF (1,8,9-anthracenetriol): m/z (%) 362.7 $[\text{M}]^+$ (100), 346.7 $[\text{M} - \text{OH} + \text{H}]^+$ (12), 328.7 $[\text{M} - 2\text{OH}]^+$ (12). $\text{C}_{13}\text{H}_{19}\text{IN}_2\text{O}_2$ (362.21): calcd. C 43.11, H 5.29, N 7.73; found C 43.13, H 5.29, N 7.75.

Compound 8: White solid. Isolated yield: 94%. R_f = 0.38 (SiO_2 , $\text{CH}_2\text{Cl}_2/2\%\text{MeOH}$). M.p.: 158 °C (dec.). ^1H NMR [$(\text{CD}_3)_2\text{SO}$]: δ = 7.84 (m, 1 H, Ar + 2 H, OH), 7.63 (m, 1 H, Ar), 7.46 (m, 1 H, Ar), 7.14 (t, 3J = 7.8 Hz, 1 H, Ar), 4.45 (s, 1 H), 1.07 (s, 6 H, Me), 1.03 (s, 6 H, Me) ppm. $^{13}\text{C}\{^1\text{H}\}$ NMR [$(\text{CD}_3)_2\text{SO}$]: δ = 144.8, 136.8, 135.9, 129.9, 128.1, 94.3, 89.6, 66.2, 24.4, 17.2 ppm. IR (KBr): $\tilde{\nu}$ = 3217, 2913, 1593, 1569, 1430, 1379, 1368, 1267, 1215, 1142, 1105, 995, 918, 899, 881, 816, 775, 690, 663, 507 cm^{-1} . MALDI-TOF (1,8,9-anthracenetriol): m/z (%) 362.7 $[\text{M}]^+$ (100), 344.7 $[\text{M} - \text{H}_2\text{O}]^+$ (10), 328.7 $[\text{M} - 2\text{OH}]^+$ (22). $\text{C}_{13}\text{H}_{19}\text{IN}_2\text{O}_2$ (362.21): calcd. C 43.11, H 5.29, N 7.73; found C 43.22, H 5.25, N 7.91.

General Procedure for the Synthesis of Nitronyl-nitroxides: The corresponding 1,3-dihydroxy-2-(iodophenyl)-4,4,5,5-tetramethylimidazolidine (1 to 2 g) in CH_2Cl_2 (1 to 2 L) and NaIO_4 (ca. 2 equiv.) in H_2O (1.0 L) were vigorously stirred for 2 h in the dark at room temperature. The organic layer was separated, washed with H_2O , and dried with MgSO_4 . The solvent was evaporated, and the crude solid was purified by chromatography (SiO_2 , CH_2Cl_2 to $\text{CH}_2\text{Cl}_2/1\text{--}2\%\text{MeOH}$). The radical was recrystallized twice from $\text{CH}_2\text{Cl}_2/\text{hexane}$ to give the pure compound.

Radical 4: Pink solid. Isolated yield: 68%. R_f = 0.26 (SiO_2 , $\text{CH}_2\text{Cl}_2/2\%\text{MeOH}$). M.p.: 165–167 °C. UV/Vis (CH_2Cl_2): λ_{max} (ϵ , $\text{M}^{-1}\text{cm}^{-1}$) = 546 (790), 329 (7310), 232 (11790) nm. IR (KBr): $\tilde{\nu}$ = 2987, 1457, 1404, 1368, 1220, 1164, 1138, 1022, 753, 667, 539 cm^{-1} . MALDI-TOF (1,8,9-anthracenetriol): m/z (%) 360.6 $[\text{M} + \text{H}]^+$ (100), 344.7 $[\text{M} - \text{O} + \text{H}]^+$ (95), 328.7 $[\text{M} - 2\text{O} + \text{H}]^+$ (25). $\text{C}_{13}\text{H}_{16}\text{IN}_2\text{O}_2$ (359.18): calcd. C 43.47, H 4.49, N 7.80; found C 43.40, H 4.32, N 7.74.

Radical 9: Violet solid. Isolated yield: 96%. R_f = 0.55 (SiO_2 , $\text{CH}_2\text{Cl}_2/2\%\text{MeOH}$). M.p.: 156–160 °C. UV/Vis (CH_2Cl_2): λ_{max} (ϵ ,

$\text{m}^{-1}\text{cm}^{-1}$) = 588 (440), 368 (15360), 272 (11820), 229 (17160) nm. IR (KBr): $\tilde{\nu}$ = 2981, 1553, 1477, 1445, 1415, 1371, 1360, 1294, 1209, 1164, 1130, 791, 684, 673, 543, 455 cm^{-1} . MALDI-TOF (1,8,9-anthracenetriol): m/z (%) 360.6 $[\text{M} + \text{H}]^+$ (37), 344.6 $[\text{M} - \text{O} + \text{H}]^+$ (100), 328.7 $[\text{M} - 2\text{O} + \text{H}]^+$ (22). $\text{C}_{13}\text{H}_{16}\text{N}_2\text{O}_2$ (359.18): calcd. C 43.47, H 4.49, N 7.80; found C 43.18, H 4.45, N 7.51.

Synthesis of 1 by the Classical Pathway: Aldehyde **5** (70.5 mg, 0.39 mmol) and *N,N'*-dihydroxy-2,3-diamino-2,3-dimethyl-butane (2 equiv.) in MeOH (3 mL) were stirred at room temperature in the dark for 4 d. The white precipitate was filtered and washed with MeOH to give 88.6 mg of the intermediate **6**.

Compound 6: White solid. Isolated yield: 73%. ^1H NMR $[(\text{CD}_3)_2\text{SO}]$: δ = 7.77–7.74 (m, 1 H), 7.50–7.30 (m, 9 H), 7.16–7.13 (m, 1 H), 4.84 (s, 1 H), 1.09 (s, 6 H, Me), 0.91 (s, 6 H, Me) ppm. $^{13}\text{C}\{^1\text{H}\}$ NMR $[(\text{CD}_3)_2\text{SO}]$: δ = 143.8, 141.6, 139.5, 131.2, 130.9, 130.1, 128.4, 127.8, 127.6, 127.5, 85.4, 66.8, 25.2, 18.4 ppm. $\text{C}_{19}\text{H}_{24}\text{N}_2\text{O}_2$ (312.41): calcd. C 73.05, H 7.74, N 8.97; found C 72.83, H 7.84, N 8.93.

Compound **6** (61.6 mg, 0.20 mmol) in CH_2Cl_2 (100 mL) and NaIO_4 (ca. 2 equiv.) in H_2O (100 mL) were vigorously stirred for 1 h in the dark at room temperature. The organic layer was separated, washed with H_2O , and dried with MgSO_4 . The solvent was evaporated, and the crude solid was purified by chromatography (SiO_2 , CH_2Cl_2 to $\text{CH}_2\text{Cl}_2/1\%$ MeCN) to give 37 mg of the target radical **1**.

Radical 1 (Classical Pathway): Pink solid. Isolated yield: 37%. R_f = 0.09 (SiO_2 , $\text{CH}_2\text{Cl}_2/3\%$ MeCN). UV/Vis (CH_2Cl_2): λ_{max} = 563, 324, 307, 237 (sh), 227 nm. IR (KBr): $\tilde{\nu}$ = 3434, 2982, 2930, 1638, 1600, 1474, 1451, 1403, 1365, 1220, 1165, 1135, 1073, 759, 704, 538, 455 cm^{-1} . MALDI-TOF (1,8,9-anthracenetriol): m/z (%) 310.8 $[\text{M} + \text{H}]^+$ (35), 294.8 $[\text{M} - \text{O} + \text{H}]^+$ (100), 278.8 $[\text{M} - 2\text{O} + \text{H}]^+$ (23).

General Procedure for the Suzuki-Type Cross-Coupling Reaction: Iodophenyl-nitronyl-nitroxide (100 to 300 mg) and phenylboronic acid or 4-cyanophenylboronic acid (ca. 1.5 equiv.) were dissolved in toluene/MeOH 1:1 (10 mm), and the solution was deoxygenated by bubbling with Ar. $\text{Pd}(\text{PPh}_3)_4$ (5 mol-%) was added under Ar, followed by a deoxygenated solution of Na_2CO_3 (ca. 7 equiv.) in H_2O (ca. 1.5 M). The mixture was heated at 80 °C for 2–2.5 h. H_2O (300 mL) was added, and the product was extracted with CH_2Cl_2 (500 mL). The organic phase was washed with H_2O (100 mL), dried with MgSO_4 , and the solvents were evaporated. The crude product was purified by chromatography (SiO_2 , $\text{CH}_2\text{Cl}_2/1$ –3% MeCN) to give the pure product.

Radical 1: Pink solid. Isolated yield: 43%. R_f = 0.09 (SiO_2 , $\text{CH}_2\text{Cl}_2/3\%$ MeCN). M.p.: 139–145 °C. UV/Vis (CH_2Cl_2): λ_{max} (ϵ , $\text{M}^{-1}\text{cm}^{-1}$) = 562 (950), 545 (sh, 930), 351 (sh, 5240), 324 (6620), 307 (6120), 237 (13180), 226 (13590) nm. IR (KBr): $\tilde{\nu}$ = 3516, 3057, 2998, 2942, 1631, 1481, 1472, 1449, 1441, 1403, 1389, 1367, 1218, 1168, 1137, 1010, 869, 850, 772, 765, 754, 705, 539, 459 cm^{-1} . MALDI-TOF (1,8,9-anthracenetriol): m/z (%) 310.9 $[\text{M} + \text{H}]^+$ (80), 294.9 $[\text{M} - \text{O} + \text{H}]^+$ (100), 278.9 $[\text{M} - 2\text{O} + \text{H}]^+$ (35). $\text{C}_{19}\text{H}_{21}\text{N}_2\text{O}_2$ (309.38): calcd. C 73.76, H 6.84, N 9.05; found C 73.81, H 6.46, N 8.98.

Radical 2: Pink solid. Isolated yield: 40%. R_f = 0.22 (SiO_2 , $\text{CH}_2\text{Cl}_2/6\%$ MeCN). M.p.: 170–175 °C. UV/Vis (CH_2Cl_2): λ_{max} (ϵ , $\text{M}^{-1}\text{cm}^{-1}$) = 564 (720), 321 (6250), 250 (18070) nm. IR (KBr): $\tilde{\nu}$ = 3443, 2991, 2226, 1608, 1476, 1448, 1403, 1369, 1217, 1170, 1135, 841, 760, 572 cm^{-1} . MALDI-TOF (1,8,9-anthracenetriol): m/z (%) 335.8 $[\text{M} + \text{H}]^+$ (75), 319.8 $[\text{M} - \text{O} + \text{H}]^+$ (100), 303.8 $[\text{M} - 2\text{O} + \text{H}]^+$ (25). $\text{C}_{20}\text{H}_{20}\text{N}_3\text{O}_2$ (M_r = 334.39): calcd. C 71.84, H 6.03, N 12.57; found C 71.56, H 6.16, N 12.44.

Radical 3: Violet solid. Isolated yield: 44%. R_f = 0.43 (SiO_2 , $\text{CH}_2\text{Cl}_2/6\%$ MeCN). M.p.: 135–136 °C. UV/Vis (CH_2Cl_2): λ_{max} (ϵ , $\text{M}^{-1}\text{cm}^{-1}$) = 587 (460), 367 (11700), 271 (35790), 228 (11780) nm. IR (KBr): $\tilde{\nu}$ = 3439, 2988, 2226, 1608, 1452, 1422, 1405, 1386, 1363, 1308, 1278, 1214, 1167, 1135, 838, 793, 682, 539 cm^{-1} . MALDI-TOF (1,8,9-anthracenetriol): m/z (%) 335.9 $[\text{M} + \text{H}]^+$ (80), 319.9 $[\text{M} - \text{O} + \text{H}]^+$ (100), 303.9 $[\text{M} - 2\text{O} + \text{H}]^+$ (20). $\text{C}_{20}\text{H}_{20}\text{N}_3\text{O}_2$ (334.39): calcd. C 71.84, H 6.03, N 12.57; found C 71.81, H 5.66, N 12.26.

Crystal Data and Structure Refinement for 1 and 3: Data were collected at 200 K on a STOE-IPDS2 diffractometer with graphite-monochromated Mo- K_α radiation (λ = 0.71073 Å). The structures were solved by direct methods and refined by full-matrix least-squares analysis.

1: [$\text{C}_{19}\text{H}_{21}\text{N}_2\text{O}_2$]; M = 309.38, monoclinic, space group $P2_1/c$, a = 14.048(3) Å, b = 6.1625(12) Å, c = 19.408(4) Å, β = 98.95(3)°, V = 1659.7(6) Å³, Z = 4, D_c = 1.238 g/cm³, μ = 0.081 mm^{−1}. 5207 reflections measured, 2461 independent reflections, (R_{int} = 0.0458), 1861 independent reflections with $F_o > 4\sigma(F_o)$. 208 parameters (O, N, C refined anisotropically, H atoms calculated at ideal positions), R_1 = 0.0400, wR_2 = 0.1133 (all data), residual electron density: 0.148 e Å^{−3}.

3: [$\text{C}_{20}\text{H}_{20}\text{N}_3\text{O}_2$]; M = 334.39, monoclinic, space group $P2_1/n$, a = 7.1496(14) Å, b = 15.405(3) Å, c = 32.682(7) Å, β = 92.89(3)°, V = 3595.0(12) Å³, Z = 8, D_c = 1.236 g/cm³, μ = 0.082 mm^{−1}. 7420 reflections measured, 4540 independent reflections, (R_{int} = 0.0486), 2520 independent reflections with $F_o > 4\sigma(F_o)$. 451 parameters (O, N, C refined anisotropically, H atoms calculated at ideal positions), R_1 = 0.0513, wR_2 = 0.1415 (all data), residual electron density: 0.320 e Å^{−3}.

CCDC-260852 (**1**) and 260853 (**3**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Acknowledgments

We thank the Networkproject MOLMEM German Ministry of Education and Research (BMBF-FZK 13 N 8360) for financial support, the Alexander von Humboldt Foundation for a post-doctoral fellowship to C.S. and Alain Derory (IPCMS – Strasbourg) for magnetic measurements.

- [1] a) A. Okamoto, T. Inasaki, I. Saito, *Bioorg. Med. Chem. Lett.* **2004**, *14*, 3415–3418; b) A. Cerasi, E. Millo, M. F. Ottaviani, G. Damonte, M. Cangiotti, U. Benatti, L. Chiarantini, *Tetrahedron Lett.* **2003**, *44*, 8701–8704; c) A. T. Yordanov, K. Yamada, M. C. Krishna, A. Russo, J. Yoo, S. English, J. B. Mitchell, M. W. Brechbiel, *J. Med. Chem.* **2002**, *45*, 2283–2288; d) G. He, A. Samouilov, P. Kuppusamy, J. L. Zweier, *J. Magnet. Res.* **2001**, *148*, 155–164; e) P. P. Borbat, A. J. Costa-Filho, K. A. Earle, J. K. Moscicki, J. H. Freed, *Science* **2001**, *291*, 266–269.
- [2] a) P. M. Lahti, *Magnetic Properties of Organic Materials*, Marcel Dekker Inc., New York, **1999**; b) J. S. Miller, A. J. Epstein, *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 385–415; c) D. Gatteschi, *Adv. Mater.* **1994**, *6*, 635; d) A. L. Buchachenko, *Russ. Chem. Rev.* **1990**, *59*, 307–319.
- [3] a) E. F. Ullman, J. H. Osiecki, D. G. B. Boocock, R. Darcy, *J. Am. Chem. Soc.* **1972**, *94*, 7049–7059; b) J. H. Osiecki, E. F. Ullman, *J. Am. Chem. Soc.* **1968**, *90*, 1078–1079.

- [4] M. Tamura, Y. Nakazawa, D. Shiomi, K. Nozawa, Y. Hosokoshi, M. Ishikawa, M. Takahashi, M. Kinoshita, *Chem. Phys. Lett.* **1991**, *186*, 401–404.
- [5] a) T. Sugawara, S. Bandow, K. Kimura, H. Iwamura, K. Itoh, *J. Am. Chem. Soc.* **1986**, *108*, 368–371; b) I. Fujita, Y. Teki, T. Takui, T. Kinoshita, K. Itoh, F. Miko, Y. Sawaki, H. Iwamura, A. Izuoka, T. Sugawara, *J. Am. Chem. Soc.* **1990**, *112*, 4074–4075; c) A. Rajca, J. Wongsriratanakul, S. Rajca, R. Cerny, *Angew. Chem. Int. Ed.* **1998**, *37*, 1229–1232; d) H. Nishide, M. Miyasaka, E. Tsuchida, *Angew. Chem. Int. Ed.* **1998**, *37*, 2400–2402; e) A. Rajca, *Chem. Rev.* **1994**, *94*, 871–893.
- [6] a) L. Dulog, J. S. Kim, *Makromol. Chem.* **1989**, *190*, 2609–2614; b) P. Wautelet, J. Le Moigne, V. Videva, P. Turek, *J. Org. Chem.* **2003**, *68*, 8025–8036; c) L. Catala, J. Le Moigne, N. Kyrtsakas, P. Rey, J. J. Novoa, P. Turek, *Chem. Eur. J.* **2001**, *7*, 2466–2480; d) C. Stroh, M. Mayor, C. von Hänisch, P. Turek, *Chem. Commun.* **2004**, 2050–2051.
- [7] R. Ziessel, C. Stroh, H. Heise, F. H. Köhler, P. Turek, N. Claiser, M. Souhassou, C. Lecomte, *J. Am. Chem. Soc.* **2004**, *126*, 12604–12613.
- [8] a) A. Caneschi, D. Gatteschi, J. P. Renard, P. Rey, R. Sessoli, *Inorg. Chem.* **1989**, *28*, 1976–1980; b) A. Caneschi, D. Gatteschi, M. Chiara Melandri, P. Rey, R. Sessoli, *Inorg. Chem.* **1990**, *29*, 4228–4234; c) A. Caneschi, D. Gatteschi, J. Laugier, P. Rey, R. Sessoli, C. Zanchini, *J. Am. Chem. Soc.* **1988**, *110*, 2795–2799; d) E. V. Tretyakov, S. V. Fokin, G. V. Romanenko, V. I. Ovcharenko, *Polyhedron* **2003**, *22*, 1965–1972; e) K. Fegy, D. Luneau, E. Belorizky, M. Novac, J.-L. Tholence, C. Paulsen, T. Ohm, P. Rey, *Inorg. Chem.* **1998**, *37*, 4524–4532; f) D. Luneau, C. Stroh, J. Cano, R. Ziessel, *Inorg. Chem.* **2005**, *44*, 633–637.
- [9] a) G. Harada, T. Jin, A. Izuoka, M. M. Matsushita, T. Sugawara, *Tetrahedron Lett.* **2003**, *44*, 4415–4418; b) S. Hiraoka, T. Okamoto, M. Kozaki, D. Shiomi, K. Sato, T. Takui, K. Okada, *J. Am. Chem. Soc.* **2004**, *126*, 58–59.
- [10] a) N. V. Blough, D. J. Simpson, *J. Am. Chem. Soc.* **1988**, *110*, 1915–1917; b) S. E. Herbelin, N. V. Blough, *J. Phys. Chem. B* **1998**, *102*, 8170–8176; c) R. Ziessel, C. Stroh, *Org. Lett.* **2003**, *5*, 2397–2400; d) E. Lozinsky, V. V. Martin, T. A. Berezina, A. I. Shames, A. L. Weiss, G. I. Likhtenshtein, *J. Biochem. Biophys. Methods* **1999**, *38*, 29–42.
- [11] K. Takayama, K. Matsuda, M. Irie, *Chem. Eur. J.* **2003**, *9*, 5605–5609.
- [12] M. Deumal, J. Cirujeda, J. Veciana, J. J. Novoa, *Adv. Mater.* **1998**, *10*, 1461–1466.
- [13] a) Z. Xu, J. S. Moore, *Acta Polym.* **1994**, *45*, 83–87; b) A. Harriman, R. Ziessel, *Chem. Commun.* **1996**, 1707–1716; c) A. Elghayoury, A. Harriman, A. Khatyr, R. Ziessel, *Angew. Chem. Int. Ed.* **2000**, *39*, 185–189; d) D. Kuciauskas, P. A. Lidell, S. Lin, T. E. Johnson, S. J. Weghorn, J. S. Lindsey, A. L. Moore, T. A. Moore, D. Gust, *J. Am. Chem. Soc.* **1999**, *121*, 8604–8614; e) F. Barigelletti, L. Flamigni, V. Balzani, J.-P. Collin, J.-P. Sauvage, A. Sour, E. C. Constable, A. M. W. Cargill Thompson, *J. Am. Chem. Soc.* **1994**, *116*, 7692–7699.
- [14] a) M. Mayor, H. B. Weber, J. Reichert, M. Elbing, C. von Hänisch, D. Beckmann, M. Fischer, *Angew. Chem. Int. Ed.* **2003**, *42*, 5834–5838; b) J. E. Klare, G. S. Tulevski, K. Sugo, A. de Picciotto, K. A. White, C. Nuckolls, *J. Am. Chem. Soc.* **2003**, *125*, 6030–6031; c) M. Mayor, C. von Hänisch, H. B. Weber, J. Reichert, D. Beckmann, *Angew. Chem. Int. Ed.* **2002**, *41*, 1183–1186; d) S. M. Dirk, D. W. Price Jr, S. Chanteau, D. V. Kosynkin, J. M. Tour, *Tetrahedron* **2001**, *57*, 5109–5121.
- [15] a) C. Grave, A. D. Schlüter, *Eur. J. Org. Chem.* **2002**, 3075–3098; b) V. Prautzsch, S. Ibach, F. Vögtle, *J. Incl. Phenom. Macrocycl. Chem.* **1999**, *33*, 427–457; c) M. Mayor, C. Didschies, *Angew. Chem. Int. Ed.* **2003**, *42*, 3176–3179; d) M. Mayor, J.-M. Lehn, *J. Am. Chem. Soc.* **1999**, *121*, 11231–11232.
- [16] K. Sonogashira in *Metal-Catalyzed Cross-Coupling Reactions* (Eds.: F. Diederich, P. J. Stang), Wiley-VCH, Weinheim, **1998**, pp. 203–229.
- [17] A. Suzuki in *Metal-Catalyzed Cross-Coupling Reactions* (Eds.: F. Diederich, P. J. Stang), Wiley-VCH, Weinheim, **1998**, pp. 49–97.
- [18] a) F. M. Romero, R. Ziessel, A. De Cian, J. Fischer, P. Turek, *New J. Chem.* **1996**, *20*, 919–924; b) Y. Miura, T. Issiki, Y. Ushitani, Y. Teki, K. Itoh, *J. Mater. Chem.* **1996**, *6*, 1745–1750; c) C. Stroh, M. Mayor, C. von Hänisch, *Tetrahedron Lett.* **2004**, *45*, 9623–9626; d) F. M. Romero, R. Ziessel, *Tetrahedron Lett.* **1999**, *40*, 1895–1898.
- [19] a) H. Oka, T. Tamura, Y. Miura, Y. Teki, *J. Mater. Chem.* **1999**, *9*, 1227–1232; b) Y. Liao, C. Xie, P. M. Lahti, R. T. Weber, J. J. Jiang, D. P. Barr, *J. Org. Chem.* **1999**, *64*, 5176–5182; c) K. K. Anderson, D. A. Dougherty, *Adv. Mater.* **1998**, *10*, 688–692; d) D. A. Shultz, G. T. Farmer, *J. Org. Chem.* **1998**, *63*, 6254–6257.
- [20] M. Lamchen, T. W. Mittag, *J. Chem. Soc. (C)* **1966**, 2300–2303.
- [21] O. Kahn, *Molecular Magnetism*, Wiley-VCH, Weinheim, **1993**.
- [22] S. Chamoin, S. Houldsworth, C. G. Kruse, W. Iwema Bakker, V. Snieckus, *Tetrahedron Lett.* **1998**, *39*, 4179–4182.

Received: February 14, 2005
Published Online: July 12, 2005