Direct C–C coupling of two Ni-salphen complexes to yield dinickel-disalphen complexes with symmetric and non-symmetric substitution-patterns†

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The synthesis of symmetric and non-symmetric 5,5′-linked disalphen Ni(II) complexes by the Suzuki-Miyaura-reaction is reported. Also, the synthesis and structural characterization of four Ni(II)-precursor complexes are presented. The 5-Br-substituted mononuclear complexes 4 and 5 are coupled to the pina-colborane substituted complexes 6 and 7 yielding the four dinuclear dinickel complexes 8–11 in good yields. The crystal structure of dinuclear complex 8 was obtained revealing a coplanar arrangement between the two salphen fragments. Electronic spectra as well as DFT-calculations on the ground states and excitation energies are reported and they reveal a small coupling between the electronically saturated Ni-salphen complexes.

Introduction

Oligonuclear salen-complexes gained a lot of attention recently, owing to their unique combination of an easy-to-modify non-innocent ligand with a very broad range of central metal-ions, ranging from alkali- over 3d metal- to lanthanide-ions.1,2 Due to this versatility this class of compounds has been investigated for a variety of applications and properties, including metal–organic frameworks,3,4 catalysis,5,6 and redox behavior.7–9 Furthermore, the unique properties of salen-complexes have led to their established role in the research on molecule-based magnetism.10–13 In a recent study, 5,5′-dibromo-salphen-cobalt(II)-molecules have been oligomerized on a gold-surface in an Ullmann-type coupling reaction under the formation of 5,5′-C-C-coupled oligomeric complex chains.14 These molecular chains exhibited a unique magnetic behavior, which is caused by the interaction of the magnetic orbitals of the cobalt atoms with the extended π-system of the ligand along the chain.15 Based on this result, an on-surface hetero-coupling strategy was developed to combine different salphen-building blocks yielding oligonuclear complexes for potential molecular spintronic devices.16

A variety of oligonuclear salen- and salophen-complexes are known in the literature, e.g. covalently linked oligosalen,13,17 fused salen-18–21 and macrocyclic complexes.22 Nevertheless, a direct synthetic approach yielding salen-dimers and -oligomers linked via a 5,5′-C-C bond has not been reported. As mentioned before, oligosalen-complexes with this particular bonding-pattern may exhibit a unique combination of properties and applications and thus their systematic investigation is of special interest.

For the directed synthesis of multinuclear linked salen complexes, a simple, standardized and versatile synthetic protocol is necessary. Keeping the maximum flexibility of the target compounds in mind, including unsymmetrical substitution patterns of the salen- and salophen ligands, the ideal approach would be a direct cross-coupling reaction of prefabricated building blocks. One example of a direct coupling reaction of two salen-complexes has been reported in the literature, exploiting the olefin-metathesis reaction,23 but only symmetric salen-complexes were achieved.

In this paper we present a method for the synthesis of symmetric and unsymmetric 5,5′-bonded dinuclear nickel-salphen-complexes by cross-coupling of mononuclear precursor-complex building blocks. In addition, the structural and electronic properties of the synthesized mono- and dinuclear nickel-complexes are investigated, especially regarding the effects of an unsymmetrical substitution-pattern and a potential electronic communication between the salphen moieties.

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‡Electronic supplementary information (ESI) available. CCDC 1053849, 1053735, 1053850, 1053745 and 1053865. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c5dt04612b

Cite this: Dalton Trans., 2016, 45, 7460–7468

Received 24th November 2015, Accepted 16th March 2016
DOI: 10.1039/c5dt04612b
www.rsc.org/dalton
Results and discussion

In order to synthesize C–C coupled Ni(II) disalophen complexes we employed the Suzuki-cross-coupling-reaction (Scheme 1) as a versatile method to covalently link two molecules.24,25 This method was chosen for its tolerance towards functional groups and its relatively mild reaction conditions, potentially allowing the introduction of reactive metal-centers and substituents. Also, the absence of bivalent highly Lewis-acidic metal ions during synthesis that could exchange with the coordinated nickel(II) ion is an advantage over other C–C cross-coupling reactions.

For the Suzuki-coupling the four precursor-complexes 4–7 were synthesized (Scheme 2). Complexes 4 and 5 bear one Br-substituent each, and in 6 and 7, pinacolborane groups are attached. The latter substituent was chosen over boronic acid for its higher stability and pH-neutrality, which is important regarding the acid-sensitivity of the imine-group in Schiff-base-ligands. The synthesis of the precursors was carried out following the procedure of Kleij et al. except for the choice of solvents.3

The mono-imines 1 and 2 (Scheme 2) were generated from ortho-diaminobenzene and selected salicylic aldehyde bearing one or two tert-butyl substituents.26 The mono-imine (1 or 2) was then added to a methanol solution of nickelacetate-tetrahydrate in the presence of triethylamine.27 Subsequent addition of a solution of either 5-bromosalicylaldehyde or 5-(pinacolboron)-salicylaldehyde (3) in THF yielded the corresponding unsymmetrically substituted nickel-salophen precursor complexes 4–7. Aldehyde 3 was synthesized in a modified literature-protocol from 5-bromosalicylaldehyde.28 All four precursor complexes were isolated in an analytically pure form in good to excellent yields of 76–99% (see the Experimental section). The Br-substituted complexes 4 and 5 were coupled to the pinacolborane derivatives 6 and 7 with yields given in Table 1.

The cross-coupling reaction was carried out using the complex tetrakistriphenylphosphine palladium(0) as a catalyst in the presence of potassium carbonate as a base. For the reaction, stock-solutions of the precursor-complexes (40 mmol L⁻¹) and the catalyst (10 mmol L⁻¹) in THF were prepared. Similar amounts of a Br-precursor and a BPIn-precursor complex were mixed in Schlenk-flasks and then treated with the catalyst complex and an aqueous solution of potassium carbonate. After 24 hours of stirring at 70 °C the products were isolated.

Crystallography

Of the four mononuclear complexes 4–7 and the dinuclear complex 8, single-crystals suitable for structure analysis could be obtained after crystallization from CHCl₃/n-hexane (4), THF/n-hexane (5–7) or pyridine/n-hexane (8). The structures of 7 and 8 are presented in Fig. 1. For crystallographic information see Table S1 in the ESI.† Selected bond-lengths are listed in Table S2† along with structural data retrieved from DFT-calculations. In all five complexes the nickel-atom is four coordinate with Ni–N distances from 1.8505(15) Å in 7 to 1.8624(26) Å in 4 and Ni–O distances from 1.8315(13) Å in 7 to 1.8501(22) Å in 4. These geometry parameters are in accordance with those found in the literature (see Fig. S1†).29

Remarkably, the Ni–N1 and Ni–O1 bonds are slightly longer

| Table 1 | Numbers and yields of the coupling-products. The Br-carrying coupling components are in columns, and the pinacolborane in rows |
|---------|-----------------------------------------------------|
|         | 4                     | 5                     |
| 6        | 8, 56%                | 9, 66%                |
| 7        | 10, 66%               | 11, 93%               |

Scheme 1 Suzuki-cross-coupling of two nickel-salophens. R1, R2: 5-‘Bu, 3,5-di‘Bu.

Scheme 2 Two-step synthesis of the nickel-salophen precursors. o-PDA = ortho-diaminobenzene.
than the corresponding Ni–N2 and Ni–O2 distances with differences ranging from 1.07 pm (6) to 0.43 pm (4) for the Ni–O distances and from 0.07 pm (6) to 0.97 pm (7) for the Ni–N bonds. Although this difference is well within the margin of error for compounds 4, 6 and 8, the fact that this trend is observed in all five crystal structures as well as reproduced by the DFT calculations makes this observation significant and raises the question of the strength of a substituent influence.

The electron-donating character (+I-effect) of the tBu-substituents as opposed to the electron-withdrawing substituents (bromine: −I-effect, boron: −M-effect) and the resulting shift of the electron density appear to be the cause.

The structure of the dinuclear complex 8 exhibits a crystallographic center of inversion on the phenyl–phenyl axis and thus the alignment of the phenyl rings is coplanar in the solid state. This conformation is presumably enforced by crystal-packing effects, since the ordering in the crystal is dominated by shifted stacks of salophen-complexes. In these stacks, the C–C-bond of each dimer is sandwiched between two planar salophen units with a distance of 3.57 Å.

The C–C distance between the 6-membered rings in complex 8 is found to be 1.483(3) Å and corresponds to an elongated double-bond between the phenyl ring fragments. This is in accordance with reported structures of biphenyls in the solid state, where the repulsion between the two 6-membered rings leads to a long C–C bond. The salophen-units in 8 take an anti-conformation in the solid state.

Spectroscopic characterization and DFT-studies
All four precursor-complexes and the coupling-products 9/10 and 11 were subjected to NMR-analysis. Due to the poor solubility of the dinuclear compounds, 13C and correlation spectra (COSY, HMBC, HSQC) were recorded only for the mononuclear compounds with the consequence that an unambiguous assignment of most of the signals was impossible for compounds 9/10 and 11. It catches the eye that the chemical shifts of the imine-protons at the tBu-side of the molecule are at lower field than the shifts of the protons at the Br/BPin-side. This permits the assignment of the imine-protons in the spectra of 9/10 and 11. The shift of the imine-protons is also a good indication of the asymmetric substitution-pattern in compound 9/10, since they are split into four clearly distinguishable singlets in the 1H-NMR spectra. For information on peak-assignment, please refer to the ESI (Table S4, Scheme S1†).

The UV/Vis spectra of complexes 4–10 were recorded in THF at room temperature and are depicted in Fig. 2. The data extracted from the spectra are listed in Table 2 and are in

Fig. 1 Top: molecular structure of 8, bottom: molecular structure of 7. Hydrogen atoms and solvent-molecules are omitted for clarity; ellipsoids are at 50% probability.
addition of one phenyl-ring results in a bathochromic shift of about 30 nm.33

This is less than that expected from shifts of conjugated polyphenyls, where the dinuclear complexes rather behave like two independent complex molecules, which is not expected based on the spectra of polyphenyls. This interpretation is further reinforced by the long phenyl–phenyl-bond of 1.4831 nm found in the crystal structure of 8 and a distortion of the coplanarity in the DFT-optimized gas-phase structure found by a torsion of the phenyl–phenyl-torsion-angle of roughly 36°. To clarify the nature of the electronic transitions, TD-DFT-calculations were performed (see Computational details),36 which were successfully employed on related complexes.15,37–39

In accord with the deconvoluted spectra the calculations revealed five absorptions with significant intensity in the recorded spectral region.

NTO-analyses were performed on the relevant electronic excitations40 (Fig. 3, 4, S5 and S6†). For the discussion of these results, the co-ordinate-system presented in Fig. 3 will be used.41 The lowest energy transition #1 appears to be an MLCT from a dπ orbital at the Ni-atom to the π-system of the ligand with a polarization in the x-direction.

The occupied NTO for transitions #1 and #2 has small coefficients at the 5′-Bu groups with opposite sign to the C6-phenyl torsion-angle of roughly 36°. To clarify the nature of the electronic transitions, TD-DFT-calculations were performed (see Computational details),36 which were successfully employed on related complexes.15,37–39

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The redox-behaviour of all four mononuclear compounds (4–7) and the tetra-tert-butyl substituted dinuclear complex (11) were investigated. All five substances exhibit two oxidation-steps in the positive potential range (Table 3) in accord with reported complexes.42,43

The cyclic voltammograms (Fig. 5) of complexes 5 and 7 show a redox-couple at $E_{1/2} = 568$ mV and 581 mV respectively. These redox-processes are quasi-reversible according to standard criteria.44,45 A second irreversible oxidation step is detected at $E_{ox} = 1167$ mV and $E_{ox} = 1192$ mV for compounds 5 and 7. For compounds 4 and 6 two irreversible oxidation steps each were found. The first oxidation steps of 4 and 6 occur at potentials of $E_{ox}(4.1) = 686$ mV and $E_{ox}(6.1) = 681$ mV, and the second steps occur at $E_{ox}(4.2) = 957$ mV and $E_{ox}(6.2) = 1005$ mV, respectively.

In the cyclic voltammogram of the dinuclear complex 11, two redox-processes were also observed. The first step at $E_{1/2} = 250$ mV is found to be quasi-reversible (see also Fig. S15 in the ESI†). The second oxidation occurs at a potential of $E_{ox} = 1159$ mV and is irreversible. However, due to the very poor solubility of complex 11, the response was very weak. Since most of the investigated redox-processes are not reversible, we have to limit ourselves to comparing the oxidation-potentials in the following discussion.

**Table 3** Redox waves of compounds 4–7 and 11 at a scan rate of 100 mV s$^{-1}$ as referenced to Fc$^+/\text{Fc}$

|   | 4   | 5   | 6   | 7   | 11  |
|---|-----|-----|-----|-----|-----|
| $E_{ox}$ | 686 | 624 | 681 | 616 | 272 |
| $E_{red}$ | $-a$ | 512 | $-a$ | 545 | 219 |
| $E_{1/2}$ | $-b$ | 568 | $-b$ | 581 | 250 |
| $E_{ox}$ | 957 | 1167$^a$ | 1005 | 1192 | 1159 |

$^a$No corresponding reduction signal was detected. $^b$Since no corresponding reduction signal was detected, $E_{1/2}$ could not be determined. Potentials are given in mV.

**Electrochemistry**

The redox-behaviour of all four mononuclear compounds (4–7) and the tetra-tert-butyl substituted dinuclear complex (11) were
According to the literature, the two abovementioned redox-processes are located at the ligand.\(^1\)\(^{21,42,43}\) For the mononuclear compounds, the potential of the first oxidation depends mainly on the number of \(^7\)Bu-substituents whereas the nature of the other substituent (Br or BP\(\text{Pin}\)) has only a minor influence. This is to be expected, since the addition of a substituent with a +I influence like the tert-butyl group should shift the oxidation to a more negative potential. This finding is in accord with the results from the electronic spectra. There, a redshift of the first absorption-band for species 5 and 7 is attributed to a higher energy of the highest occupied state due to the second \(^7\)Bu-substituent. The first redox-process found for the dinuclear compound 11 occurs at the considerably more negative potential of \(E_{\text{ox}}(11.1) = 272\) mV. Keeping in mind that the oxidation is located on the ligand, it may be assumed that for 11 the biphenyl-part of the molecule gets oxidized. This is in accordance with the electronic spectra, where the first electronic transition originates from the highest occupied state with a large coefficient on the biphenyl-bridge. DFT-calculations further reinforce this interpretation: the optimized structure of 11 has a torsion angle of 36° at the biphenyl-bond whereas the structure of the hypothetical cation \(11^+\) is twisted by only 18°, indicating a considerable change in electron density at the biphenyl-unit upon oxidation. Also, the calculated spin-density of the monocation clearly indicates that the first oxidation step takes place at the biphenyl bridge (Fig. S7?).

All the second oxidation-processes in the observed complexes 4–7 and 11 are irreversible. Since compounds 4–7 contain rather reactive substituents (Br and BP\(\text{Pin}\)) it can be assumed that at potentials as strong as +1 V, chemical reactions take place.

Conclusions

We presented the first method to synthesize dinuclear salophen-complexes with an unsymmetric substitution pattern by cross-coupling mononuclear salophen building blocks. This method yields a new type of biphenyl-bridged dinuclear salophen complex. The precursor-complexes 4–7 were hitherto unknown, and to the best of our knowledge, compounds 6 and 7 are the first examples of boronate-substituted salophen complexes. Complexes 4–7 were cross-coupled yielding the disalophens 8–11 in good yields.

The complexes were fully characterized including the determination of the crystal structures. Due to the unsymmetrical substitution patterns the mononuclear complexes experience the influence of combined substituent-effects (+M, −M, +I, −I). The substituent effects on the electronic structures of the compounds have been investigated by a combination of X-ray crystallography, cyclic voltammetry and NMR- and UV/Vis-spectroscopy. The experimental results were further evaluated in DFT-calculations. Electronic transitions were further assigned by NTO analyses. From these investigations it can be deduced that the tert-butyl substituents have a large influence on optical properties and oxidation potentials due to a shift of the high-lying occupied states towards higher energies. The influence of a Br- as well as a pinacolborane substituent is rather small for the excitation spectra as well as the oxidation potentials. However, the substituents have a large influence on the reversibility of the redox potentials as well as the reactivity of these complexes.

For complex 8 a crystal structure was recorded. It was found that the dinuclear complex 8 is coplanar in the solid state whereas in the DFT-optimized structure-calculations the complex fragments are rotated around the biphenyl axis. The evaluation of the electronic spectra revealed that the dinuclear compounds consist of two electronically weakly coupled salophen units. The filled metal and \(\pi\)-orbitals on the ligand appear to be the cause. From DFT-calculations it can be deduced that upon oxidation of the ligand or excitation from a filled ligand \(\pi\)-orbital with antibonding character with respect to the biphenyl bond the C–C bond is strengthened and the electronic coupling of the two complex fragments increases.

The very successful application of the Suzuki-cross-coupling to the synthesis of sp\(^2\)-sp\(^2\)-bonded dinuclear salophen complexes opens up the possibility of further exploration of this new class of molecules. Due to the mild conditions of the Suzuki coupling and the simple synthesis of precursor-complexes, this synthetic pathway should allow the fabrication of heterodinuclear complexes or compounds of even higher nuclearity. Research in this direction is currently being carried out by our workgroup.

Experimental section

General considerations

If not mentioned otherwise, all the reactions were performed under normal conditions without the exclusion of oxygen or moisture. The solvents used were of p.a. grade and used as received. Chemicals were purchased from either Sigma-Aldrich or MERCK and used as received.

X-ray crystallography was performed on a Bruker D8 diffractometer with a Bruker Apex 1 camera and an \(\text{I} \mu\text{S-Mo K} \alpha\) micro focus source (50 kV, 0.6 mA). Hydrogen-atoms were constrained at fixed positions and refined using the riding-model. A disorder at the pinacolborane-group in the structure of 6 has been treated by using a model consisting of two layers of the carbon-atoms of the pinacolborane-group. Various restraints and constraints were applied.

Infrared spectra were recorded using KBr discs on a Bruker Tensor T7 FT-IR-spectrometer.

The electronic spectra of solutions of compounds 4–10 in THF were recorded on a Varian Cary 50 spectrometer. Extinction coefficients were determined by a serial dilution with five concentrations. Due to low solubility, no meaningful data could be obtained for 11. For the Gaussian deconvolution of the spectra, the Origin 9.0g software-suite was employed.

NMR spectroscopy was carried out on a Bruker Avance 400 or a Fourier 300 instrument at room temperature with CDCl\(_3\) or DMSO-d6 as solvents and referenced to the solvent-signal.
The peaks were assigned according to the numbering-pattern presented in Scheme S1 in the ESI.†

Cyclic voltammetry was performed using a BASI C3 potentiostat. The setup consisted of a 3 mm GC working-electrode, a Pt counter-electrode and an Ag+/Ag reference-electrode using a Vycore-frit. Where possible, a 1 mM solution in DCM of the compound was measured with 0.1 M TBAP as the supporting electrolyte.

Synthesis of precursors and complexes

Synthesis of 5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-salicyaldehyde (3). Under the exclusion oxygen, 4-bromosalicyaldehyde (10.45 g, 35.77 mmol), bis(pinacolato)diboron (13.83 g, 54.46 mmol), sodium acetate (18.50 g, 136.1 mmol) and PEG600 (200 mL) were put into a flask and heated to 70 °C. After degassing the mixture for 20 min, tetrakis-triphenylphosphinepalladium(0) (1.44 g, 1.25 mmol) was added. The reaction mixture was then stirred for 24 h at 70 °C. After extraction with water/ethyl acetate the raw product was purified by column chromatography (PE/EE, silica gel) and recrystallization from hot n-heptane. A colourless, crystalline product (4.44 g, 17.9 mmol, yield: 50%) was obtained.

1H NMR (400 MHz, DMSO-d6, 25 °C): δ 11.09 (bs, 1H, OH), 10.27 (s, 1H, H7), 8.00 (d, 1H, JH16-H5 = 1.6 Hz, H3), 7.76 (dd, 1H, JH6-H5 = 8.3 Hz, JH3-H6 = 1.8 Hz, H5), 6.99 (d, 1H, JH16-H5 = 8.3 Hz, H6), 1.28 (s, 12H, H9).

General procedure for the preparation of mononuclear salophenato-nickel(II)-complexes

Equimolar amounts of the monomine (1 or 2) and nickel(II) acetate-tetrahydrate were combined in a flask and treated with 2 mL triethylamine. 15 mL of methanol were added afterwards. After five minutes of stirring, a solution of one aliquot of salicyaldehyde in 5 mL of tetrahydrofuran was added. The mixture was stirred overnight, the solvent removed in vacuo, and the residue suspended in methanol and then treated with water. The red precipitate was filtered off and washed with methanol and diethyl ether and dried in vacuo.

Synthesis of N-(5-tert-butylsalicylidene)-N′-(5-bromosalicylidene)phenylenediaminato nickel(II) (4). This substance was synthesized according to the general procedure for the preparation of salophenato-nickel(II)-complexes (v.s.). Monomine 1: 411 mg, 1.53 mmol, nickelacetate-tetrahydrate: 390 mg, 1.57 mmol, 5-bromosalicyaldehyde: 310 mg, 1.54 mmol. Yield: 721 mg, 1.28 mmol, 83.1%.

1H NMR (300 MHz, THF-d8, 25 °C): δ 8.62 (s, 1H, H7), 8.56 (s, 1H, H14), 8.00-7.94 (m, 2H, H9 + H12), 7.92 (d, 1H, JH16-H5 = 1.6 Hz, H5), 7.53 (dd, 1H, JH3-H6 = 8.7 Hz, JH3-H6 = 1.7 Hz, H3), 7.37 (s, 1H, H16), 7.35 (dd, 1H, JH16-H5 = 9.8 Hz, JH16-H5 = 2.6 Hz, H18), 7.24-7.17 (m, 2H, H10 + H11), 6.85 (d, 1H, JH16-H9 = 9.1 Hz, H19), 6.84 (d, 1H, JH2-H3 = 8.7 Hz, H2), 1.31 (s, 12H, H24), 1.29 (s, 9H, H22).

1C NMR (75 MHz, THF-d8, 25 °C): δ 169.8 (C1, C12), 166.3 (C1, C20), 155.9 (C14), 154.9 (C7), 142-144 (2C, C8 + C13), 141.1 (C19), 137.4 (C1, C3), 137.1 (C17), 135.3 (C5), 130.6 (C18), 128.1 (C10), 127.3 (C16), 127.2 (C11), 124.0 (C2), 122.4 (C6), 120.6 (C15), 116.0 (C9), 115.8 (C12), 106.0 (1C, C4), 36.3 (1C, C23), 34.7 (1C, C21), 31.4 (1C, C22), 29.7 (4C, C24).

MS (ESI+, HRMS) m/z 563.0871 [M + H]+ (calc.: 563.0843).

Elemental analysis: found: C 56.7, H 4.17, N 5.51, O 6.30 (calculated: C 56.7, H 4.20, N 5.63, O 6.30).
nickelacetate-tetrahydrate: 398 mg, 1.60 mmol, salicylaldehyde 3: 383 mg, 1.31 mmol. Yield: 695 mg, 1.31 mmol, 99.8%.

1H NMR (300 MHz, THF-d8, 25 °C): δ 6.87 (s, 1H, H7), 8.52 (s, 1H, H114), 7.95 (dd, 1H, JH1-H15 = 2.0 Hz, H5), 8.00–7.94 (m, 3H, H9 + H112), 7.55 (dd, 1H, JH2-H13 = 8.7 Hz, JH3-H15 = 1.8 Hz, C3), 7.39 (d, 1H, JH16-H18 = 2.6 Hz, H18), 7.23 (d, 1H, JH16-H18 = 2.6 Hz, H16), 7.26–7.20 (m, 2H, H10 + H11), 6.84 (d, 1H, JH2-H13 = 8.7 Hz, H2), 1.46 (s, 9H, H2), 1.30–1.32 (m, 21H, H22, H26).

13C NMR (75 MHz, THF-d8, 25 °C): δ 170.2 (C1), 165.6 (C20), 156.0 (C7), 155.8 (C14), 144.5 (C13), 144.0 (C8), 143.7 (C5), 141.3 (C19), 140.3 (C3), 137.2 (C17), 130.5 (C18), 127.8 (C16), 127.3 + 127.2 (C10 + C11), 122.0 (C4), 121.6 (C6), 121.4 (C2), 120.7 (C15), 115.9 + 115.7 (C9 + C12), 83.7 (C25), 36.3 (C23), 34.7 (C21), 31.5 (C24), 29.8 (C26), 25.1 (C22).

MS [FAB], HRMS m/z 611.2582 [M] (calculated: 611.2591).

Elemental analysis: found: C 66.81, H 6.76, N 4.58, O 10.5; calculated: C 66.81, H 6.76, N 4.58, O 10.5.

Procedure for the Suzuki-Miyaura-cross-coupling

Stock-solutions of the four precursors were prepared, each in 15 mL of absolute THF: 4: 306 mg, 0.602 mmol, 5: 334 mg, 0.592 mmol, 6: 330 mg, 0.595 mmol and 7: 366 mg, 0.599 mmol. A stock-solution of the catalyst Pd(PPh3)4 (310 mg, 0.268 mmol in 25 mL of THF) was also prepared. For the following reaction, 5 mL each of a Br-precursor-solution, a pinacolborane-precursor solution and the catalyst solution were put into a screw-cap flask, treated with 2 mL of a 2 M sodiumacetaldehyde solution, and then heated at 90 °C under argon. After 1 hour, the solution was cooled to room temperature and filtered over Celite and the filtrate was evaporated under vacuum. The residue was redissolved in hexane, filtered, washed with water, methanol and ethyl ether and dried in vacuo. The raw product was then dissolved in pyridine, filtered over Celite and crystallized by the addition of n-hexane. Yields: 4 + 6: 95 mg, 0.11 mmol, 56%; 4 + 7: 121 mg, 0.13 mmol, 66%; 5 + 6: 119 mg, 0.13 mmol, 66%; 5 + 7: 177 mg, 0.183 mmol 93%.

Due to very low solubility of all four coupling-products, only 1H-NMR-spectra could be obtained.

8: 1H NMR (300 MHz, DMSO-d6, 25 °C): δ 8.84 (s, 2H), 8.76 (s, 2H), 8.11–8.05 (m, 4H), 7.83 (d, JH1-H = 2.5 Hz, 2H), 7.64 (dd, JH1-H = 9.0 Hz, JH2-H = 2.6 Hz, 2H), 7.55 (d, JH1-H = 2.6 Hz, 2H), 7.43 (dd, JH1-H = 8.9 Hz, JH2-H = 2.7 Hz), 7.34–7.31 (m, 4H), 7.00 (d, JH1-H = 8.9 Hz), 6.88 (d, JH1-H = 9.0 Hz), 1.34 (s, 18H).

MS (MALDI+, DHB) m/z 911.3 [M + Na] (calculated: 911.3), 933.3 [M + Na+] (calculated: 933.2), 949.3 [M + K] (calculated: 949.2). For simulated isotope pattern match, see Fig. S15.†

Elemental analysis: found: C 69.2, H 6.00, N 5.66, O 6.72 (calculated: C 69.5, H 6.04, N 5.79, O 6.61).

Computational details

DFT-calculations were performed using the Gaussian09 software-package with the B3-LYP hybrid-functional and def2-TZVP basis for all atoms. The geometries were optimized using crystal structural data as the starting values, where available. To evaluate whether the optimized geometries are indeed the global energy-minimum, frequency analyses were carried out and checked for negative force constants. In the calculation for the putative coplanar structure 8C0, one imaginary frequency at 4i2 cm⁻¹ is observed and characterizes this state as a transition state. The corresponding normal mode represents torsion of the biphenylic bond.

Based on the optimized structures, TD-DFT-calculations were performed. Calculation of the first 25 and 30 states for the mono- and dinuclear compounds proved to sufficiently reproduce the experimental spectra. A shift in the spectra of compounds 6 and 7 of ca. 25 nm between the experimental and calculated transitions is observed. This is attributed to solvation effects, which were not taken into account in the calculations.

Acknowledgements

The DFG (SFB 668-TP4) is gratefully acknowledged for financial support. The Regionales Rechenzentrum as well as the Computing Cluster of the Inorganic Chemistry Institute are acknowledged for generous support and computing time. We thank Dr. Daniel Sieh for help with cyclic voltammetry measurements. We also thank Prof. Dr. Peter Burger for generous support and discussions. MHP wishes to thank the DFG funded Collaborative Research Center 3MET.de (TRR-88) for funding.

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