A Ditopic Phosphane-decorated Benzenedithiol as Scaffold for Di- and Trinuclear Complexes of Group-10 Metals and Gold


Dedicated to Professor Dr. Manfred Scheer on the Occasion of his 65th Birthday

Abstract. The ability of 3-(diphenylphosphinomethyl)-benzene-1,2-dithiol (pbdtH$_2$) to act as ditopic ligand was probed in reactions with selected group-10-metal complexes. Reactions with [(cod)PdCl$_2$] afforded a mixture of products identified as [Pd(pbdtH)$_2$], [Pd$_2$(μ$_2$-pbdt)$_2$] and [Pd$_3$(μ$_2$-pbdt)$_2$Cl$_2$]. The polynuclear complexes could be isolated after suitably adjusting the reaction conditions, and heating of a mixture in a microwave reactor effected partial conversion into a further complex [Pd$_3$(μ$_2$-pbdt)$_3$]. Reaction of pbdtH$_2$ with [Ni(H$_2$O)$_6$Cl$_2$] gave rise to a complex [Ni$_2$(μ$_2$-pbdt)$_2$], which was shown to undergo two reversible 1e– reduction steps. Reaction of [Pd(pbdtH)$_2$] with [Au(PPh$_3$)Cl] afforded heterotrinuclear [PdAu$_2$(μ$_2$-pbdt)$_2$(PPh$_3$)]. All complexes were characterized by analytical, spectroscopic and single-crystal X-ray diffraction studies. Their molecular structures confirm the ability of the pbdt$^-$ unit to support simultaneous P,S- and S,S-chelating coordination to two metal centers.

Introduction

Ditopic ligands possess multiple donor functions that are arranged to provide separate binding domains for two metal centers and enable the assembly of elaborate architectures from di- and multinuclear complexes with specific molecular geometries$^{[1]}$ to coordination polymers and more-dimensional framework structures.$^{[2]}$ We have previously reported on two trifunctional ligands with mixed P,O,O- (1)$^{[3]}$ and P,S,S-donor sets (2)$^{[4]}$ that are pre-organized to create two metal binding sites (see Scheme 1). In 1, the combination of “hard” and “soft” donor atoms inflicts different electronic preferences for both sites and enables predictable assembly of hetero-di- and multinuclear complexes through site-selective binding of “hard” and “soft” metal ions.$^{[5]}$ In phosphane-dithiol 2, all three donor units are electronically more similar, and this selectivity is lost as metal species like Pd$^{II}$ ions with a high affinity for P-donors may also readily address the sulfur atoms. Nonetheless, careful choice of the reaction conditions enabled us to access a first mononuclear complex 3$^{[4]}$ featuring two mono-anionic pbdtH$^-$ ligands in P,S-chelating coordination mode (Scheme 2). We report now on an extended study of the complexation behavior of 2, which reveals that the free ligand and its palladium complex 3 can also be used as scaffolds for the assembly of homo- or heterometallic complexes with two or three metal centers. Moreover, the synthesis of a platinum analogue of 3 is described.

Scheme 1. Ditopic ligands 1 and 2 (pbdtH$_2$ = phosphane-benzenedithiol).

Scheme 2. Synthesis of mononuclear complexes of composition [M(pbdtH)$_2$].

Results and Discussion

Syntheses

The reported selective outcome of the synthesis of 3 (Scheme 2) can be related to two decisive factors, viz. the use...
of a tailored precursor with a predisposition to react under successive displacement of the acac$^-$ units by new mono-anionic chelate ligands, and the maintenance of a metal-to-ligand ratio of 1:2 needed for exhaustive ligand exchange.$^{[14]}$

We found now that the reaction of two equivalents of 2 with [Pt(acac)$_2$] proceeds in a similar way to yield the analogous platinum complex 4 (Scheme 2), which was isolated in approx. 90% yield and characterized by analytical and spectroscopic data and a single-crystal X-ray diffraction study. The corresponding reaction of 2 with [Ni(acac)$_2$] was less selective and afforded, according to a $^{31}$P NMR spectroscopic assay, a mixture of several newly formed species, one of which was later on identified as a 2:2 complex composed of two metal cations and two dianionic pdbt$^{2-}$ ligands (see below). The identity of the other products remains unknown, even if their $^{31}$P NMR chemical shifts suggest addressing them likewise as nickel complexes. Remarkably, the 2:2 complex constituted, irrespective of the initial metal-to-ligand ratio, always the most abundant metal-containing product.

Attempts to use 3 as metallo-ligand for the assembly of homo-dinuclear complexes remained unsuccessful, but formation of a heterotrinuclear product was achieved upon reaction with two equivalents of [(Ph$_3$P)AuCl] in the presence of triethylamine as acid scavenger in a solvent mixture (THF/dmso 95:5) in the presence of triethylamine as acid scavenger.

Analysis of the $^{31}$P NMR spectroscopic data of the crude reaction mixture allowed us to identify one of the minor constituents as complex 3. Observing that this complex became a single-crystal X-ray diffraction study as the expected 2:2 complex 6 (Scheme 4).

The transformation proceeded readily at ambient temperature and afforded (according to a $^{31}$P NMR spectroscopic assay) a mixture of three metal complexes that precipitated eventually from the reaction mixture. The main product was isolated in pure form and 48 % yield through repeated fractional recrystallization and identified by analytical and spectroscopic data and a single-crystal X-ray diffraction study as the expected 2:2 complex 6 (Scheme 4).

Facing the failure of a stepwise synthesis of a homo-dinuclear complex that would exploit the full capacity of the pdbt$^{2-}$ unit as ditopic ligand, we decided to approach the target compound in a single stage via self-assembly of the free phosphane-dithiol with suitable monometallic precursors. Anticipating that this strategy should benefit from using a metal-to-ligand ratio of 2:2 and a precursor with an enhanced tolerance to the binding of chelate ligands in different charge states, we investigated the reaction of equimolar amounts of 2 and [(cod)PdCl$_2$] in the presence of a suitable acid scavenger (KOrBu or a tertiary amine such as Et$_3$N or pyridine). The

Analysis of the $^{31}$P NMR spectroscopic data of the crude product mixture allowed us to identify one of the minor constituents as complex 3. Observing that this complex became a single-crystal X-ray diffraction study as the expected 2:2 complex 6 (Scheme 4).


Scheme 4. Formation of homo-di- and trinuclear complexes 6–9 from 2 and [(cod)PdCl$_2$] or [Ni(H$_2$O)$_6$Cl$_2$], respectively.

Reaction of 2 and an equimolar amount of [Ni(H$_2$O)$_6$Cl$_2$] in the presence of KOrBu afforded the nickel-analogue 8 of complex 6 (Scheme 4), whereas treatment with [(cod)PdCl$_2$] produced only ill-defined, paramagnetic solids which could not be further analyzed. It should be noted that the reaction of [Ni(H$_2$O)$_6$Cl$_2$] with two equivalents of 2 was likewise unselective and yielded a mixture in which, as in the aforementioned reaction of 2 with [Ni(acac)$_2$], 8 was identified spectroscopically as a dominant component. Separation of the product mixture or isolation of any other component remained unfeasible.
An intriguing result was observed when the crude product of a reaction of 2 with [cod]PdCl₂ in the presence of pyridine, which contained complexes 3 and 6 as the only species detectable by ³¹P NMR spectroscopy, was dissolved in THF and heated to 170 °C in a microwave reactor. A ³¹P NMR assay revealed that the molar fraction of 3 had been greatly reduced and a new product had formed, which serendipitously separated in crystalline form when the reaction mixture was allowed to cool down to ambient temperature. The ¹H and ³¹P NMR spectroscopic data of this species bear close similarity with those of 6, but a single-crystal X-ray diffraction study revealed the presence of a complex 9 with a trimeric rather than a dimeric structure (Scheme 4). While this species could not be generated by simple heating of solutions of pure 6, its formation was also observed upon microwave irradiation of THF/pyridine solutions containing 7 besides 2 and/or 3, respectively. We assume therefore that the trinuclear core is formed via base-induced condensation of 7 with excess ligand under more forcing conditions. Interestingly, this reaction requires that one of the chelate ligands on the central palladium switches from S,S- to P,S-coordination and reverses thus the isomerization observed during the formation of 5.

**Crystallographic Studies**

The molecular structures of complexes 4–7 and 9 established from single-crystal X-ray diffraction studies are displayed in Figure 1, Figure 2, Figure 3, Figure 4, and Figure 5, and selected metric parameters are compiled in Table 1 and Table 2. A listing of crystallographic data and a plot of the molecular structure of 8 are given as Supporting Information.

Table 1. Selected distances /Å and angles /° for complexes 4–6. The two columns displayed for complex 6 denote the parameters of two crystallographically independent specimens in the asymmetric unit. Numbers in parentheses denote estimated standard deviations.

<table>
<thead>
<tr>
<th>Complex</th>
<th>M–P</th>
<th>M–S₈</th>
<th>M–S₉</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.282(15)</td>
<td>2.2652(16)</td>
<td>2.271(2)</td>
</tr>
<tr>
<td>5</td>
<td>2.2440(17)</td>
<td>2.2633(16)</td>
<td>2.319(2)</td>
</tr>
<tr>
<td>6</td>
<td>2.3323(14)</td>
<td>2.2861(15)</td>
<td>2.333(2)</td>
</tr>
</tbody>
</table>

**Table 2.** Selected distances /Å and angles /° for complexes 7–9. Numbers in parentheses denote estimated standard deviations.

<table>
<thead>
<tr>
<th>Complex</th>
<th>M–P</th>
<th>M–Cl</th>
<th>M–S₈</th>
<th>M–S₉</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>2.253(2)</td>
<td>2.325(2)</td>
<td>2.300(2)</td>
<td>2.393(5)</td>
</tr>
<tr>
<td>8</td>
<td>2.263(2)</td>
<td>2.330(2)</td>
<td>2.453(2)</td>
<td>2.439(2)</td>
</tr>
<tr>
<td>9</td>
<td>2.301(2)</td>
<td>2.299(2)</td>
<td>3.072(1)</td>
<td>3.9113(3)</td>
</tr>
</tbody>
</table>

The crystals of 4 are isotypic with those of the previously published [4] palladium complex 3. Complexes 6 and 8 (two modifications) crystallize as solvates with different solvent molecules (THF, CH₂Cl₂) and are not isotypic. All crystals comprise clearly separated molecular complexes which lack any specific intermolecular interactions and exhibit square-planar coordination geometry at all group-10 metal centers. The M–P distances (see Table 1 and Table 2) display no peculiarities and are close matches of the standard distance (Pd–P 2.278 ± 0.050 Å[7]) in palladium phosphate complexes. Analysis of the features of the di thiolene units reveals that all C–S bonds are essentially single bonds (C–S 1.75–1.79 Å) and the six-membered rings retain fully aromatic character, suggesting that all ligands adopt the lowest conceivable charge state and can be adequately described as benzene-dithiolates.

The molecular structure of complex 4 is centrosymmetric (as imposed by crystallographic C₁₁ symmetry) and characterized by a square-planar coordination arrangement at platinum and a trans arrangement of the two bidentate, P,S-bound ligands (Figure 1). The chelate rings adopt a boat conformation, and the bite angle of the bidentate ligand [P–Pt–S 91.88(5)°] comes close to the ideal value of 90°. Based on the observation that solution ¹H NMR spectra of 4 display, like those of 3,[4] a single set of signals suggests that the trans arrangement persists in solution, which contrasts the behavior of analogous complexes[5] derived from the P,O,O-based ligand H₂[PO]₂.

The palladium atom in heterometallic complex 5 is coordinated by one P,S- and one S,S-bound chelate ligands which exhibit essentially identical bite angles [S1–Pd1–S2B.
Figure 1. Representation of the molecular structure of complex 4 in the crystal. For clarity, hydrogen atoms (except those of thiol groups) and a solvent molecule (DMF) are omitted and the carbon framework of the ligands drawn using a wire model. Thermal ellipsoids are drawn at the 50% probability level.

89.21(7)°, S1A–Pd1–P1A 88.10(6)°] and create a slightly distorted square planar PS₃ coordination sphere (Figure 2).

Figure 2. Representation of the molecular structure of complex 5 in the crystal. For clarity, hydrogen atoms and solvent molecules (CHCl₃, EtOAc) are omitted and the carbon framework of the ligands drawn using a wire model. Thermal ellipsoids are drawn at the 50% probability level.

The remaining phosphane and thiolate moieties bind to a gold atom, which attains thus a quasi-linear [P1B–Au2–S2A 164.11(6)°] coordination sphere. The sulfur atoms of the ligand acting as a P,S-donor to palladium connect to the second gold atom, which carries an additional PPh₃. The inequality of the Au–S distances [Au1–S1A 2.4013(15) Å, Au1–S2A 2.5877(15) Å] suggests describing the metal coordination environment in terms of a dicoordinate primary unit (P1C···Au1···S1A) perturbed by a secondary interaction with a second sulfur atom (Au1···S2A). As a consequence of this perturbation, the primary unit is visibly bent [P1C–Au1–S1A 149.79(5)°] and the resulting arrangements intermediate between T- and Y-shaped. The Au1–Au2 distance of 3.0648(4) Å qualifies as a medium strong, semi-supported aurophilic interaction,[8] the presence of which may explain the preference for the observed unsymmetrical molecular structure over an alternative more symmetrical configuration.

Complexes 6–8 contain two (6, 8, Figure 3) or three (7, Figure 4) group-10 metals framed by two phosphane-dithiolate ligands, each of which acts as S,S-chelating donor to one and as P,S-chelating donor to a second metal atom. The metal coordination spheres are square planar and pairwise share a common edge. The geometrical constraints of the rigid ligands prevent a coplanar arrangement and impose a folded (6, 8) or half-pipe shaped (7) alignment with fold angles between adjacent planes of 58.6(1)° to 62.8(1)°. Even if this configuration instigates rather close metal-metal contacts [Pd–Pd 3.0718(9) to 3.0946(9) Å in 6, 7; Ni–Ni 2.9391(3) / 2.9240(5) Å in 8], a closer look at the observable distortions in the local coordination spheres gives no indication for a significant attractive interaction. Altogether, the structural features of 8, including the fold angle between the two metal coordination planes and the short intermetallic distance, match those of the known complex [Ni₂(PPh₃)₂(μ₂-SCH₂CH₂S)₂].[9]

Figure 3. Representation of one of the two crystallographically independent molecules of complex 6 in the crystal. For clarity, hydrogen atoms and a solvent molecule (THF) are omitted and the carbon framework of the ligands drawn using a wire model. Thermal ellipsoids are drawn at the 50% probability level.

Figure 4. Molecular structure of complex 7 in the crystal (top) and reduced plot showing the trinuclear core with the first ligand sphere from a different view angle (bottom). For clarity, hydrogen atoms and a solvent molecule (DMSO) are omitted and the carbon framework of the ligands drawn using a wire model. Thermal ellipsoids are drawn at the 50% probability level.

The central palladium atom in 7 exhibits a distinct displacement from its S₄-coordinate plane away from the terminal metal centers, but it cannot be decided if this feature points to a repulsive interaction or is simply enforced by geometrical constraints or the binding preferences of the sulfur atoms. Further noteworthy features of 7 are the transoid orientation of
the chlorido and phosphate ligands on the terminal and the orientation of the benzenedithiolato-units on the central metal atoms, which altogether create a bowl-shaped conformation of the whole assembly. Worth mentioning is also the pronounced elongation of the Pd–S distances between the terminal metal centers and the sulfur atoms in trans-position of the phosphane ligand, which exceed all other Pd–S distances in the complexes studied by approx. 10 pm.

Complex 9 contains, like 6 and 8, \( \mu_2 \)-bridging phosphenedithiolate units which act as bidentate S,S-donors to one and as P,S-donors to a second metal center. In contrast to the dimeric complexes, the coordination spheres of adjacent metal atoms share common corners rather than edges, resulting in a trinuclear framework arranged around a central Pd$_3$S$_3$ six-membered ring (Figure 5). This ring adopts a strongly distorted boat conformation in which two sulfur are situated on one and the third one on the other side of a reference planed defined by the three metal atoms. As a consequence of this alignment, the whole assembly lacks any higher symmetry. The metal coordination environments display larger deviations from ideal planarity than in the dinuclear complexes. The $^1$H NMR spectroscopic data indicate that the non-planar alignment of the trinuclear core is dynamically averaged in solution to give an assembly with effective $C_3$-symmetry.

Even if attempts to identifying the reaction products by spectro-electrochemistry gave no conclusive results, these observations rule out that a reversible dithiolene redox chemistry involving oxidation of the benzenedithiolato to dithiosemiquinone and dithioquinone units takes place.

The cyclic voltammogram of 7 displayed further an irreversible reduction wave at a peak potential of –1.67 V (Figure S3). Nickel complex 8 was found to undergo two reductions (Figure 6), the first of which \( (E_{1/2} = -1.507 \text{ V vs. Fc/Fc}^+ ) \) was reversible \( (i_{pa}/i_{pc} = 0.94) \) while the second one \( (E_{1/2} = -2.054 \text{ V vs. Fc/Fc}^+ ) \) was only partially reversible \( (i_{pa}/i_{pc} = 0.75) \).

The separation of cathodic and anionic peak potentials (213 and 226 mV for the first and second reduction step) indicates that the electron transfer is kinetically hindered, presumably because it is associated with a change in the complex geometry. Attempts to characterize the reduction products by UV/Vis and EPR spectroelectrochemistry gave no conclusive results. However, since the pbdt-ligand in 8 adopts already its lowest charge state and further reduction seems unlikely, we assume that both reduction steps are metal-centered and can be described by the processes displayed in Scheme 5. This view was confirmed by the results of DFT calculations at the CPCM-B3LYP/def2-TZVP/J-D3BJ level on complexes \([\text{Ni}_2(\text{pbdt})_2]^q\) \( (q = 1+/0/–1/–2) \). Energy optimization of the structure of neutral \([\text{Ni}_2(\text{pbdt})_2] (8) \) resulted in metrics that are in good agreement with the experimental data and support the description as a complex containing two Ni$^{II}$ centers and two dithiolato ligands pbdt$^{2–}$, as expected. The structural parameters of \([\text{Ni}_2(\text{pbdt})_2]^1\) differ, apart from a slight elongation of the Ni–Ni distance from 3.112 Å to 3.145 Å, not significantly from those of neutral 8, but the calculated electron and spin density distribution (Table S2 and Figure S5, Supporting Information) suggest that the oxidation is primarily ligand-centered. Complex \([\text{Ni}_2(\text{pbdt})_2]^1\) arising from one-electron reduction of 8 contains one nickel center, which still retains similar Ni-P/S distances as in 8, while the distances around the second nickel are noticeably elongated (Table S2, Supporting Information).

**Figure 5.** Representation of the molecular structure of complex 9 in the crystal. For clarity, hydrogen atoms are omitted and the carbon framework of the ligands drawn using a wire model. Thermal ellipsoids are drawn at the 50 % probability level.

**Figure 6.** Cyclic voltammogram of complex 8 (conditions: scan rate 100 mV·s$^{-1}$ at 25 °C in anhydrous DMF with 0.1 m [NBu$_4$]PF$_6$ as conducting salt, glassy carbon working electrode; ferrocene (Fc) internal standard). The initial small redox waves centered around –0.75 V arise from a paramagnetic impurity which could not be removed even after repeated recrystallization.

In view of the known ability of benzodithiolene derivatives to act as redox active ligands,[10] we were also interested in studying the electron transfer behavior of the complexes prepared by cyclic voltammetry. Meaningful results were obtained for 4, the trinuclear palladium complex 7 and the dinuclear nickel complex 8. The cyclic voltammograms of all three complexes showed oxidation waves (at peak potentials between 0.5 to 0.8 V vs. Fe/Fc*, Figure S3, Supporting Information) but no complementary reduction events, presumably because the oxidation products were consumed by follow-up processes.

Electrochemical Studies
In connection with the localization of the spin density on this metal and the adjacent donor atoms (Figure S5), this feature is consistent with formation of a fully valence localized system, i.e., Ni²NiІ.

\[
\begin{align*}
[Ni^\text{II}Ni^\text{I}(\text{pdbt})_2]^2^- & -e^- & + e^- \\
[Ni^\text{II}Ni^\text{I}(\text{pdbt})_2]^- & -e^- & + e^- \\
[Ni^\text{II}Ni^\text{I}(\text{pdbt})_2] & -e^- & + e^- \\
\end{align*}
\]

Scheme 5. Postulated mechanism of the reduction of complex 8.

Computations on \([Ni_2(\text{pdbt})_2]^2-\) allowed us to identify two configurations that can be described as singlet \((S = 0)\) and triplet \((S = 1)\) states of a \(Ni^\text{II}Ni^\text{I}\) complex formed by antiferromagnetic or ferromagnetic coupling of the electron spins of two metal ions with formal \(d^9(s = \frac{1}{2})\)-electron count. The calculated spin density (Figure S6, Supporting Information) and the increase of the Ni–Ni distance \((3.175 \, \text{Å in } 1\) vs. \(3.112 \, \text{Å in neutral } 8\)) render the presence of a metal–metal bond in the singlet state unlikely. In regard of the very close energies (the triplet lies \(<0.1 \, \text{kcal-mol}^{-1}\) below the singlet state), safe assignment of the electronic ground state is currently unfeasible and requires further investigation. A reversible metal-centered reduction had previously also been established for a related mononuclear complex \([Ni(dfpp)(\text{bdt})]\) (dfpp = 1,1-bis-diphenylphosphinoferrocene, bdt = benzenedithiolate)\(^{[11]}\) and for dinickel complexes \([Ni_2(\text{NR}(CH_2(MeC_6H_2R')S)_2)_2]\)\(^{[12]}\) featuring structurally related N,S,S-coordinated amino-dithiolato ligands. The redox behavior of the latter complements that of 8 in that the amine-decorated dithiolato-ligands render oxidation toward higher oxidized forms electrochemically reversible, whereas the soft phosphine donors in 8 render further reduction of an initially formed \(Ni^\text{II}Ni^\text{I}\) complex to a \(Ni^\text{II}Ni^\text{I}\) complex (quasi)reversible.

Conclusions

It was confirmed that phosphane-decorated benzenedithiol 2 qualifies as a compartmentalized ligand which can act as P,S-chelating ligand to one and S,S-chelating ligand to a second metal center. The lack of a pronounced site-selectivity in metal binding, which is a characteristic of the P,O,O-donor 1,\(^{[5]}\) favors the formation of homo-bi- and trimetallic complexes and enables easy metal-shifts between both binding pockets. The successful isolation of palladium complexes with different, even homologous (cf. 6 and 9), molecular structures (and the failure to obtain similar results on nickel and palladium complexes) reveals that specific addressing of individual target motifs is, even in the absence of a strong site-selectivity, not per se unfeasible, but depends very subtly on the nature of the metal involved. The observations made during the synthesis of 6–9 indicate that reaction kinetics seems to play a very important role, but further studies are certainly needed to draw a more detailed picture. The reversible reduction of di-nickel complex 8 stimulates further studies of the redox chemistry of multinuclear pdbt complexes in order to find out how the ability of the ligands to coerce two or more metal centers into close proximity can be used to create new cooperative reactivity.

Experimental Section

All manipulations were carried out in an atmosphere of dry argon or nitrogen using standard vacuum line techniques or in glove boxes. Solvents were dried prior to use by common procedures. Microwave syntheses were carried out using an Anton Paar Monowave 400 reactor. NMR spectra were recorded at 303 K on Bruker Avance 400 (\(^1\)H 400.1 MHz, \(^{31}\)P 161.9 MHz) or Avance 250 (\(^1\)H 250.1 MHz, \(^{31}\)P 101.2 MHz) spectrometers. \(^1\)H NMR chemical shifts were referenced to TMS using the signals of the residual protons or carbon atoms of the deuterated solvent (\(^1\)H: \(\delta(CDCl_3) = 7.24, \delta(CD_2Cl_2) = 5.32, \delta(D_2)\)DMSO) = 2.50) as secondary references. \(^{31}\)P NMR chemical shifts were referenced using the \(\Xi\)-scale\(^{[13]}\) with 85 % \(\text{H}_2\text{PO}_4\) (\(\Xi = 40.480747 \, \text{MHz}\)) as secondary reference. Coupling constants are given as absolute values. Signals of phenyl and benzene-dithiolato-substituents are denoted as Ph and bdt, respectively. (+)-ESI-mass spectra were recorded on a Bruker Daltonics MicroTOF Q instrument. Elemental analyses were obtained with an Elementar Micro Cube elemental analyzer. Cyclic voltammetry was performed on an EG&G Princeton Applied Research Potentiostat/Galvanostat Model 273A using a standard 3 electrode setup (glassy carbon working, platinum wire counter, silver wire reference), ferrocene was added during the final CV as an internal reference. The synthesis of 2 was carried out as described.\(^{[10]}\)

Crystal Structure Determinations: Single-crystal X-ray diffraction data were collected with a Bruker AXS Nanostar C diffractometer equipped with a Kappa APEX II Duo charge-coupled device (CCD) detector and a KRYO-FLEX cooling device at 100(2) K for \(6\)-THF and 130(2) K for \(4\)-DME, \(5\):(CH_2Cl_2, EtOAc), \(7\):DMSO, \(8\):(CH_2Cl_2, 8-THF), and 9 using Mo-K\(\alpha\) radiation (\(\lambda = 0.71073 \, \text{Å}\)) for all samples. Crystals were selected under Paratone-N oil, mounted on nylon loops, and immediately placed in a cold stream of \(N_2\). The structures were solved by direct methods (SHELXS\(^{[14]}\)) and refined with a full-matrix least-squares scheme on \(F^2\) (SHELXL\(^{[15]}\)). Numerical or semi-empirical absorption corrections from equivalents were applied for all structures. Non-hydrogen atoms were refined anisotropically (disordered atoms isotropically). One disordered solvent molecule (ethyl acetate) in the crystal structure \(5\):(CH_2Cl_2,EtOAc) and two disordered solvent molecules (CH_2Cl_2) in the crystal structure of \(9\):2CH_2Cl_2 were removed using the SQUEEZE routine in the program Platon.\(^{[16]}\) \(6\)-THF was refined as an inversion twin, and for \(8\):CH_2Cl_2 an extinction correction was applied.

Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Centre, CCDC, 12 Union Road, Cambridge CB21EZ, UK. Copies of the data can be obtained free of charge on quoting the depository numbers CCDC-1972321 (\(4\)-2DME), CCDC-1972325 (\(5\):(CH_2Cl_2, EtOAc), CCDC-1972324 (\(6\)-THF), CCDC-1972339 (\(7\):DMSO), CCDC-1972322 (\(8\):(CH_2Cl_2), CCDC-1972323 (\(8\)-THF), and CCDC-1972326 (\(9\):(CH_2Cl_2)) (Fax: +44-1223-336-033; E-Mail: deposit@ccdc.cam.ac.uk, http://www.ccdc.cam.ac.uk)

Complex 4: A solution of Pt(acac)_2 (45 mg, 0.15 mmol) and 2 (100 mg, 0.30 mmol) in THF (10 mL) was agitated in an ultrasound
bath until a yellow solid precipitated. The reaction mixture was stirred overnight. The precipitate formed was collected by filtration, washed with THF (3 x 10 mL) and dried in vacuo. Yield 104 mg (89%). \textsuperscript{1}H NMR (\textit{d}_{2}DMSO): \( \delta = 3.84 \) (br. \( J_{HH} = 7.2 \) Hz, 2 H, bdt), 7.03 (dd, \( J_{HH} = 7.6 \) Hz, 2 H, bdt), 7.34 (dd, \( J_{HH} = 7.6 \) Hz, 2 H, bdt), 7.43–7.61 (m, 6 H, Ph), 7.79–7.95 (m, 4 H, Ph). \textsuperscript{31}P\textsuperscript{1}H NMR (\textit{d}_{2}DMSO): \( \delta = 57.6 \) (s, \( J_{PP} = 2892 \) Hz). (+)–\textsuperscript{1}H NMR: 896.04 [MNa +]. \( \text{C}_{21}H_{17}Na_{2}P_{5}S_{10} \) (873.95 g mol\(^{-1}\)) : calcd. C 46.73 H 3.15 S 8.91 %, found C 46.73 H 3.16 S 8.92 %. A clear solution formed immediately after stirring overnight, MeOH was added until a golden orange precipitate formed. The solids were collected by filtration and washed with MeOH and Et\(_2\)O (3 x 10 mL each). The crude product was recrystallized by layering a saturated solution in CHCl\(_3\) with ethyl acetate. Yield 115 mg (80%). \textsuperscript{1}H NMR (CDCl\(_3\)): \( \delta = 3.48 \) (m, 1 H, CH\(_2\)), 3.59 (d, \( J_{HH} = 12.0 \) Hz, 2 H, CH\(_2\)), 4.05 (m, 1 H, CH\(_2\)), 6.12 (d, \( J_{HH} = 7.7 \) Hz, 1 H, bdt), 6.35 (dd, \( J_{HH} = 7.7, J_{HP} = 7.6 \) Hz, 1 H, bdt), 6.88–7.09 (m, 4 H, bdt), 7.09–7.41 (m, 22 H, Ph), 7.43–7.67 (m, 10 H, Ph), 8.03 (br., 2 H, bdt), 7.11–7.30 (m, 4 H, Ph), 7.31–7.46 (m, 6 H, Ph), 7.48–7.63 (m, 6 H, Ph), 7.76–7.92 (m, 4 H, Ph). \textsuperscript{31}P\textsuperscript{1}H NMR (CDCl\(_3\)): \( \delta = 64.5 \) (s, \( J_{PP} = 7.7 \) Hz). 36.1 (s), 19.1 (d, \( J_{PP} = 7.7 \) Hz). \( \text{C}_{57}H_{45}Pt_{2}P_{2}S_{4} \) (1439.5 g mol\(^{-1}\)) : calcd. C 46.73 H 3.15 S 8.91 %, found C 46.72 H 3.16 S 8.98 %.}

Complex 5: 

A second crop of crystals was obtained by storing the combined mother liquid and wash solvents. Yield 139 mg (48 %). A 31P NMR spectroscopic assay revealed that formation of 9 had occurred at the expense of 3. \textsuperscript{1}H NMR (CDCl\(_3\)): \( \delta = 1.82 \) (m, 4 H, THF), 3.68 (m, 4 H, THF), 3.90 (d, \( J_{HP} = 10.3 \) Hz, 6 H, CH\(_3\)), 5.33 (s, 2 H, CH\(_2\)), 6.36 (br. \( J_{HH} = 7.2 \) Hz, 3 H, bdt), 6.57 (ddd, \( J_{HH} = 7.9, J_{HP} = 7.2, J_{HP} = 0.5 \) Hz, 3 H, bdt), 6.81 (dd, \( J_{HP} = 7.9, J_{HH} = J_{HP} = 1.5 \) Hz, 3 H, bdt), 7.36 (m, 12 H, Ph), 7.44 (m, 6 H, Ph), 7.60 (m, 12 H, Ph). \textsuperscript{31}P\textsuperscript{1}H NMR (CDCl\(_3\)): \( \delta = 52.1 \) (s). \( \text{C}_{62}H_{56}P_{2}S_{8} \) (1491.58 g mol\(^{-1}\)) : calcd. C 49.92 H 3.74 S 12.90 %, found C 49.92 H 3.74 S 12.90 %.

Computational Studies: Density functional theory (DFT) calculations were performed with the ORCA program package\textsuperscript{19} using the B3LYP functional\textsuperscript{18} with the def2-TZVP and Weigend J auxiliary basis set\textsuperscript{19} and the RUCOSX approximation. Dispersion corrections were applied using Grimme’s D3BJ formalism.\textsuperscript{20} Geometry optimization was done with the TightSCF convergence option (1.0e-7 a.u.), and solvation in Me2S (no yield determined). A \textsuperscript{31}P NMR spectroscopic assay revealed that formation of 9 had occurred at the expense of 3. \textsuperscript{1}H NMR (CDCl\(_3\)): \( \delta = 1.82 \) (m, 4 H, THF), 3.68 (m, 4 H, THF), 3.90 (d, \( J_{HP} = 10.3 \) Hz, 6 H, CH\(_3\)), 5.33 (s, 2 H, CH\(_2\)), 6.36 (br. \( J_{HH} = 7.2 \) Hz, 3 H, bdt), 6.57 (ddd, \( J_{HH} = 7.9, J_{HP} = 7.2, J_{HP} = 0.5 \) Hz, 3 H, bdt), 6.81 (dd, \( J_{HP} = 7.9, J_{HH} = J_{HP} = 1.5 \) Hz, 3 H, bdt), 7.36 (m, 12 H, Ph), 7.44 (m, 6 H, Ph), 7.60 (m, 12 H, Ph). \textsuperscript{31}P\textsuperscript{1}H NMR (CDCl\(_3\)): \( \delta = 52.1 \) (s). \( \text{C}_{62}H_{56}P_{2}S_{8} \) (1491.58 g mol\(^{-1}\)) : calcd. C 49.92 H 3.74 S 12.90 %, found C 49.92 H 3.74 S 12.90 %.

Supporting Information (see footnote on the first page of this article): Crystallographic data for 4–9, graphical representations of the molecular structures of complexes 6 and 8, cyclic voltammetry data, computational results.

Acknowledgements

We thank Barbara Förtsch (Institut für Anorganische Chemie) for measuring elemental analyses and Martin Trinkner and Dr. Wolfgang Frey (both from Institut für Organische Chemie) for measuring ESI mass spectra and collecting X-ray data sets. M.R.R. gratefully acknowledges support by the State of Baden-Württemberg through bwHPC and the German Research Foundation (DFG) through grant no. INST 40/467–1 FUGG for access to the Justus cluster.

Keywords: P ligands; S ligands; Bridging ligands; Group-10 metals; Microwave assisted synthesis
References


Received: December 23, 2019
Published Online: ■

A Ditopic Phosphane-decorated Benzenedithiol as Scaffold for Di- and Trinuclear Complexes of Group-10 Metals and Gold