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Synthesis of zwitterionic phosphapalladacycles: unusual reactivity pattern of six-membered P,N-chelates

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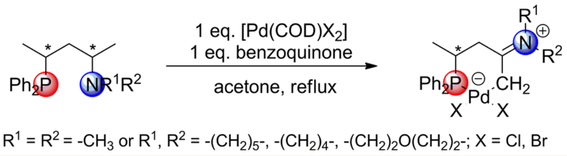
Supporting Information

ABSTRACT: A cyclometalation motif has been discovered in the unprecedented reaction of Pd(II) precursors with simple pentane-2,4-diyl based aminoalkyl-phosphines. The unique six-membered zwitterionic palladacycles can easily be synthesized in the presence of 1 molar equiv of oxidant in high yields in a pure form. A comparison between the analogous ligands of different tether lengths revealed that the formation of the zwitterionic palladacycles is the exclusive privilege of the six-membered rings.



$R^1 = R^2 = -CH_3$ or $R^1, R^2 = -(CH_2)_5-, -(CH_2)_4-, -(CH_2)_2O(CH_2)_2-$; X = Cl, Br

Heterobidentate ligands containing a combination of exclusively phosphorus and nitrogen donor atoms are widely studied due to their diverse coordination behavior and exceptional catalytic properties.[1] Generally, their unique catalytic features are attributed to the interplay of the steric and electronic effects of their P and N donor-atoms at the metal center. Indeed, the most frequent κ^2-P,N coordination mode of bidentate P,N systems ensures successful stereoelectronic communication between the substrate and the catalyst.[2] In several cases, however, P,C chelation becomes preponderant over P,N coordination, e.g., palladacycles can form due to the rather unusual bonding interactions of palladium with an ipso carbon atom of an aromatic ring (e.g., Figure 1, **A**, Pd complex of the chiral ligand MAP).[3] Of particular interest are P,N-ligated complexes where the preliminary CH activation of the ligand at the transition-metal center results in the formation of P,C-metallacycles.[4] These types of reactions offer themselves for mechanistic examinations, which can make significant contribution to the development of highly efficient catalytic systems.[5] Moreover, cyclopalladated complexes have shown extremely high activity and selectivity in a number of catalytic transformations.[6] Surprisingly, cyclometalated complexes of simple alkanediyl-based P,N ligands are extremely rare.[4c] Furthermore, to the best of our knowledge there is no example for the formation of zwitterionic metallacycles by the sp^3 CH activation of a P,N ligand. However, the synthesis and catalytic application of zwitterionic metal complexes exhibiting reversed polarity, i.e. with a formal negative charge on the transition metal, are of crucial importance.[7] They may have unique catalytic features, as they are able to accelerate oxidative addition owing to the electron-rich metalate moiety (Figure 1, **A**−**D**).[3b,8] Zwitterionic palladate type complexes reported recently usually contain an imidazole (e.g., Figure 1, **B**−**D**) or triazole unit as the positively charged moiety.[8,9]

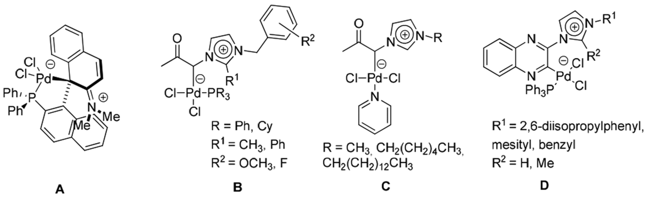


Figure 1. Examples of zwitterionic palladate type complexes synthesized from MAP (**A**) and several imidazole derivatives (**B**−**D**).

Herein we present evidence that the reaction of alkanediyl-based P,N systems with Pd(II) can lead to the formation of unique zwitterionic palladate type complexes with a κ^2-P,C coordination. Furthermore, we report on a facile synthetic methodology for the preparation of these zwitterionic palladacycles. In order to shed light on the possible CH_2 linkage effects in the unusual complex formation reaction, we extended our studies to P,N ligands of different tether length.

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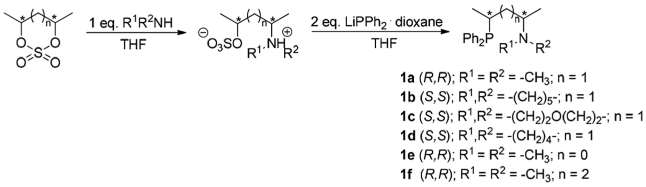
Chiral ligands **1a–f** (Scheme 1) were synthesized in an optically pure form according to literature methods (**1b–d**)[10] or to its slightly modified variant (**1a,e,f**).

Scheme 1. Synthesis of Alkanediyl-Based P,N Ligands



In order to investigate the coordination chemistry of the novel compounds, 1 equiv of chiral ligand **1a** was added to the suitably labile palladium precursor [Pd(COD)Cl_2] in CH_2Cl_2 as solvent. After 1 h of stirring the reaction mixture turned dark and palladium black appeared in the solution. Nevertheless, we were able to isolate a yellow complex (**2a**, 10% yield) from the reaction mixture that could be comprehensively characterized in both the solid and solution phases.

Crystals of **2a** suitable for X-ray structure analysis could be obtained by slow evaporation of the solvent from a dilute acetone solution of the complex. Strikingly, the X-ray structure revealed a six-membered palladium chelate with P,C_σ coordination (Figure 2). In contrast to compounds **1a–d**, pentane-2,4-diyl based P,N ligands with a secondary amino functionality form stable six-membered P,N chelates or 12-membered binuclear cycles with [Pd(COD)Cl_2], as was reported earlier.[11,12]

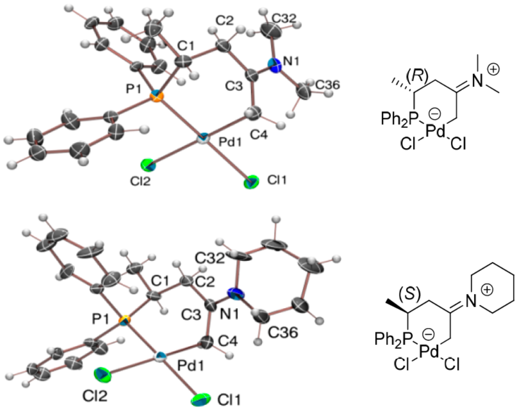


Figure 2. X-ray structures of complexes **2a** (top) and **2b** (bottom) crystallized from acetone: ORTEP views at the 50% probability level with a partial numbering scheme. Atom colors: gray, C; green, Cl; orange, P; violet, N; blue, Pd.

The palladium has a slightly distorted square planar geometry, and the chelate ring is stabilized in a boat conformation. The relatively long Pd1–C4 distance (2.079 Å), the wide Pd1–C4–C3 angle (101.53°), the pronounced double-bond character of the N1–C3 bond (1.324 Å), and the nearly full planarity at the nitrogen center support the iminium character of the ligand (Table 1). Furthermore, the torsion angle Pd1–C4–C3–N1 (94.2°) suggests a hyperconjugative orbital overlap between the π system of the iminium moiety and the Pd–C4 bond. This interaction might influence the geometry of the chelate ring and also stabilize the boat conformation.[13] Single crystals of **2a** were also obtained from a solution of the complex in chloroform that revealed the same structural characteristics found for the acetone solvate (see the Supporting Information).

Table 1. Selected Bond Lengths (Å) and Angles (deg) and Torsion Angles (deg) of Complexes 2a,b Crystallized from Acetone

	2a	2b
Pd1–Cl1	2.366(3)	2.369(5)
Pd1–Cl2	2.373(2)	2.370(5)
Pd1–P1	2.222(3)	2.219(5)
Pd1–C4	2.079(8)	2.06(2)
C3–N1	1.324(12)	1.31(3)
C3–N1–C32	124.2(10)	125(2)
C32–N1–C36	114.98(9)	108(2)
C3–N1–C36	120.9(8)	126(2)
Pd1–C4–C3	101.6(6)	101(1)
C2–C3–N1–C36	176.3(9)	174(2)
C4–C3–N1–C32	174(1)	174(2)
Pd1–C4–C3–N1	94.2(9)	98(2)

Complex **2a** has very low solubility in organic solvents such as chloroform, dichloromethane, acetone, methanol, and THF. On the other hand, DMSO-d_6 offers complete solubility of the complex; therefore, it was the solvent of choice for NMR experiments. Compound **2a** showed a relatively simple ^1H NMR spectrum indicative of one species present in solution. Most importantly, the signal of the expected methyl protons in the ligand backbone adjacent to the nitrogen did not appear in the spectrum. Instead, two new diastereotopic methylene signals were detected at 3.46 and 2.78 ppm, respectively, indicating the presence of Pd–CH_2 protons. The ^{31}P signal of **2a** at 42.44 ppm is out of the range (21.6–27.6 ppm) found for six-membered [Pd(P,N)Cl_2] chelates with a pentane-2,4-diyl backbone.[12] Furthermore, on comparison of the $^{13}C\{^1H\}$ and ^{13}C DEPT NMR spectra a quaternary carbon signal (C=N) appeared at 184.81 ppm with a coupling constant of J(P,C) = 5.6 Hz. Additionally, the infrared spectrum of **2a** recorded in a KBr disk showed a very strong absorption band at 1591 cm^{-1} indicative of a C=N double bond.

The full agreement of both the solid- and solution-phase studies substantiates that compound **2a** is a zwitterionic iminium palladate type complex containing a Pd–C(sp^3) bond. This suggests that the reaction of the P,N compound with the metal precursor leads to the dehydrogenation of the ligand, furnishing two reducing equivalents (Pd(II) to Pd(0)), and to the coordination of the resulting enamine functionality in a η^1 fashion.[14] Although enamines are able to coordinate through the nitrogen donor[15] or through the π system of the carbon–carbon double bond,[16] complex **2a** should be considered as a metalated iminium compound with an M–C bond.[17]

To obtain more information on the reaction of ligand **1a** and [Pd(COD)Cl_2], it was carefully monitored by ^1H and ^{31}P NMR spectroscopy using CD_2Cl_2 as solvent. It has been observed that the formation of the corresponding six-membered P,N chelate takes place immediately, exhibiting a single line in the ^{31}P spectrum at 19.81 ppm. This complex then starts to decompose, and after 1 h a significant amount of new phosphorus species (ca. 20%) can be found in solution. This experiment indicates that the six-membered P,N chelate is an intermediate in the formation of **2a**.

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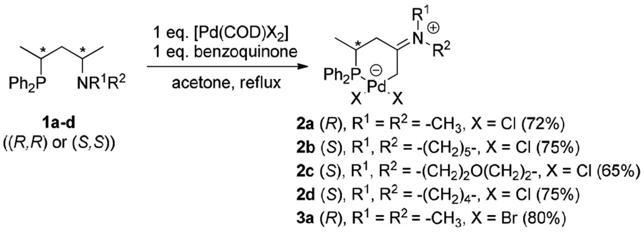
In order to prevent the formation of Pd(0), the reaction of ligands **1a–d** with [Pd(COD)X_2] (X = Cl, Br) was performed in acetone in the presence of 1 equiv of benzoquinone.[18] After 3 h of stirring at reflux temperature, the reaction mixtures were analyzed by ^{1}H NMR spectroscopy. The crude samples contained a 1:1:1 mixture of **2a**, hydroquinone, and cyclooctadiene, indicating the formation of the enamine complex as a result of the benzoquinone reduction. On the basis of this facile method, complexes **2a–d** and **3a** could readily be prepared as bright yellow solids in high yields (65–80%) without the formation of Pd black (Scheme 2). In addition, to our surprise, these complexes are stable in air and they are not moisture-sensitive.

Scheme 2. Synthesis of Zwitterionic Palladium Complexes 2a–d and 3a



According to ^{1}H, ^{31}P{^{1}H}, and ^{13}C{^{1}H} NMR spectroscopy, complexes **2a–d** and **3a** exhibit very similar characteristic coupling patterns and chemical shifts that are fully consistent with the zwitterionic iminium-palladate structure: i.e. with the Pd metal bearing a formal negative charge. The thorough NMR analysis also substantiated that all five six-membered chelates have the same boat conformation in solution, as deduced from the X-ray structure of **2a**. Moreover, crystals of **2b** suitable for X-ray analysis were grown by slow evaporation of the acetone solvent (its structure is shown in Figure 2). A comparison of the selected bond lengths, bond angles, and torsion angles of **2a**,**b** reveals that their structures are analogous (Table 1).

In order to shed light on the structural features promoting the dehydrogenation of the ligand, we compared the coordination properties of several analogous alkanediyl-based P,N systems with a tertiary amine functionality. In order to evaluate the effect of the chelate ring size, directly analogous alkanediyl-based aminoalkyl phosphines of different tether length (**1e**,**f**) have been synthesized (Scheme 1). Ligand **1e** (*n* = 0) formed a stable five-membered P,N chelate (**4e**) that can be proved by the characteristic chemical shifts and coupling patterns in its ^{1}H NMR spectrum. The yellow solid (**4f**) obtained with ligand **1f** (*n* = 2) revealed nine broad signals in its ^{31}P NMR spectrum at room temperature in $CDCl_3$, suggesting the presence of several species in dynamic equilibrium. These could arise from the different conformations of chelate species or from multinuclear complexes.[19] As the resonances of phosphorus in the ^{31}P spectrum as well as the ^{1}H NMR signals of the *N*-methyl protons in the major components are remarkably shifted with respect to those of the free ligand, it is reasonable to assume that both the N and P atoms are involved in coordination. Nevertheless, during complex formation no palladium black could be observed. Furthermore, complexes **4e**,**f** can be stored for days in dichloromethane without any change in their composition.

It is generally accepted that the stability of the chelate complexes follows the traditional order five- > six- > seven-membered chelate rings. This order is in good agreement with our experimental results: (i) ligand **1e** forms the expected five-membered P,N chelate ring, (ii) ligands **1a–d** initially also form six-membered P,N rings that are rapidly converted to P,C chelates, and (iii) the combined effect of the N atom's hemilability and the reduced stability of the seven-membered chelates results in the formation of a complex mixture in the case of ligand **1f**. It is also important to note that, in addition to the length of the P–N linker, the steric nature of the substituents on the nitrogen (tertiary vs secondary amine group) strongly affects the stability of a chelate ring.[20] Recently, it has also been demonstrated that the orientation of the C–H bond in an optimum position relative to the metal has a crucial role in CH-activation processes.[21]

Five-membered P,N chelates with secondary and tertiary amine functionalities as well as six-membered P,N chelates with secondary amine functionalities[11,12] are more stable than the six-membered P,N chelates formed by ligands **1a–d** bearing a tertiary amine moiety. This indicates that the formation of reactive free coordination sites is hampered in the former cases. Although the exact mechanism of the formation of complexes **2a–d** and **3a** is unclear, our findings indicate that (i) a suitably labile P,N-chelate and (ii) a properly tuned tether ensuring the proximity and the ideal orientation of the corresponding CH fragment are essential to initiate the activation.

In summary, we have presented a facile method for the synthesis of zwitterionic palladacycles. Five novel complexes were isolated and structurally characterized in the unusual reaction of [Pd(COD)Cl_2] and pentane-2,4-diyl based aminoalkyl phosphines. By addition of benzoquinone as an oxidant, **2a–d** and **3a** were readily obtained in high yield (65–80%). These complexes are stable in air and are not moisture-sensitive. The variation of the ligands' tether length as well as a change in their N substituent led to the conclusion that the formation of the zwitterionic palladacycles is the exclusive privilege of the pentane-2,4-diyl based systems with a tertiary amino functionality. We are currently expanding the scope of this ligand system in order to gain a closer look into the mechanism of the activation process as well as to apply the novel palladacycles in catalytic transformations.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.organomet.8b00224.

Experimental details and characterization data of the new compounds (PDF)

Cartesian coordinates for **2a_ac**, **2a_CHCl3** (**2a** crystallized from acetone and $CHCl_3$, respectively) and **2d** (XYZ)

Accession Codes

CCDC 1834437–1834439 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes

The authors declare no competing financial interest.

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