



HAL
open science

Synthesis and Catalytic Use of Polar Phosphinoferrocene Amidosulfonates Bearing Bulky Substituents at the Ferrocene Backbone

Petr Vosáhlo, Léa Radal, Marine Labonde, Ivana Císařová, Julien Roger, Nadine Pirio, Jean- Cyrille Hierso, Petr Štěpnička

► **To cite this version:**

Petr Vosáhlo, Léa Radal, Marine Labonde, Ivana Císařová, Julien Roger, et al.. Synthesis and Catalytic Use of Polar Phosphinoferrocene Amidosulfonates Bearing Bulky Substituents at the Ferrocene Backbone. *Organometallics*, 2021, 40 (12), pp.1934-1944. 10.1021/acs.organomet.1c00244 . hal-03467878

HAL Id: hal-03467878

<https://hal.science/hal-03467878>

Submitted on 6 Dec 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Lorsqu'un écrit scientifique issu d'une activité de recherche financée au moins pour moitié par des dotations de l'État, des collectivités territoriales ou des établissements publics, par des subventions d'agences de financement nationales ou par des fonds de l'Union européenne est publié dans un périodique paraissant au moins une fois par an, son auteur dispose, même après avoir accordé des droits exclusifs à un éditeur, du droit de mettre à disposition gratuitement dans un format ouvert, par voie numérique, sous réserve de l'accord des éventuels coauteurs, la version finale de son manuscrit acceptée pour publication, dès lors que l'éditeur met lui-même celle-ci gratuitement à disposition par voie numérique ou, à défaut, à l'expiration d'un délai courant à compter de la date de la première publication. Ce délai est au maximum de six mois pour une publication dans le domaine des sciences, de la technique et de la médecine et de douze mois dans celui des sciences humaines et sociales.

Synthesis and Catalytic Use of Polar Phosphinoferrocene Amidosulfonates Bearing Bulky Substituents at the Ferrocene Backbone

Petr Vosáhlo,^a Léa Radal,^b Marine Labonde,^b Ivana Císařová,^a Julien Roger,^b Nadine Pirio,^b Jean-Cyrille Hierso,^{b*} and Petr Štěpnička^{a*}

^a Department of Inorganic Chemistry, Faculty of Science, Charles University, Hlavova 2030, 128 40 Prague, Czech Republic; ^b Institut de Chimie Moléculaire de l'Université de Bourgogne (ICMUB) UMR CNRS 6302, Université Bourgogne Franche-Comté (UBFC), 9 avenue Alain Savary, 21078 Dijon, France

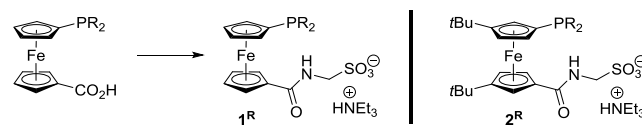
ABSTRACT: Anionic phosphinoferrocene amidosulfonates bearing sterically demanding *t*-butyl substituents in positions 3 and 3' of the ferrocene scaffold, viz. *rac*-(Et₃NH)[Fe(η⁵-*t*BuC₅H₃PR₂)(η⁵-*t*BuC₅H₃C(O)NHCH₂SO₃)] (R = phenyl and cyclohexyl) were synthesized by amidation of the corresponding phosphinocarboxylic acids, [Fe(η⁵-*t*BuC₅H₃PR₂)(η⁵-*t*BuC₅H₃CO₂H)]. These ditopic polar phosphinoferrocenes and their non-*t*-butylated analogues have been used as ligands to prepare zwitterionic (η³-allyl)palladium(II) complexes [Pd(η³-C₃H₅){Fe(η⁵-R'C₅H₃PR₂)(η⁵-R'C₅H₃C(O)NHCH₂SO₃)}] (R' = H, *t*Bu, R = Ph, Cy). Depending on the isolation procedure and crystallization conditions, some complexes were isolated in two isomeric forms which differed by the coordination of the amidosulfonate pendant group, where either amide or sulfonated oxygen ligated the Pd(II) centre. The preference for coordination of the amide or sulfonate oxygen atoms has been explained by interplay of electrostatic and solvation effects and further supported by DFT calculations. The (η³-allyl)Pd(II) complexes have been applied as defined pre-catalysts for Pd-catalysed C-H arylation of unprotected indole with aryl iodides in polar solvents. Under the optimized reaction conditions at 100°C in water, C₂-arylation proceeded selectively with various aryl iodides to produce the respective 2-arylindoles in acceptable yields at low catalyst loading (1 mol.% Pd) and in the absence of any phase transfer agent. The catalyst possessing *t*-butyl groups at the ferrocene core and an electron-rich dicyclohexylphosphino group exhibited the best catalytic performance.

INTRODUCTION

Homogeneous catalysis by transition metal complexes relies on the development of suitable supporting ligands.¹ Phosphines are particularly attractive due to their tuneable steric and electronic properties that can be used to control the course of catalytic processes² by means of substituent modification and by incorporation of additional functional groups.³ The introduction of polar hydrophilic substituents into the ligands is of particular practical importance, as it allows for the transfer of catalytic reactions from purely organic solvents to more innocuous aqueous media.⁴ Although numerous polar groups have been used as solubilizing moieties for phosphine ligands (e.g., charged ammonium, guanidium and carboxylate fragments), sulfonated phosphines remain the most successful ligands for aqueous catalysis. However, their practical success is partially compromised by challenging synthesis, as synthetic methods for introducing phosphine and sulfonate moieties are often incompatible due to the sensitivity of the phosphine groups towards oxidation.⁴

To alleviate these problems, we have recently devised an alternative approach based on amide coupling reactions⁵ between phosphinocarboxylic acids and aminosulfonic acids, producing functional amidophosphine ligands **1**^R (Scheme 1, left; R = Ph, Cy).^{6,7} These coupling reactions proceed with good to excellent yields, employ stable, safe, and readily accessible starting materials, and typically produce pure crystalline products.⁸ Utilizing this approach, we synthesized several phosphinoferrocene amidosulfonates, which proved to be useful ligands for catalytic reactions in aqueous systems.⁹ Notably, even a single amidosulfonate tag was sufficient to overcome the hydrophobicity of phosphinoferrocene ligands, which limits their applications in aqueous catalysis.¹⁰

Scheme 1. Phosphinoferrocene Amidosulfonates **1**^R and **2**^R



In this paper, we report the synthesis of new

phosphinoferrrocene amidosulfonate ligands $\mathbf{2}^R$ containing bulky *t*-butyl substituents at the ferrocene scaffold (Scheme 1, right; R = Ph, Cy). We have already shown that the introduction of sterically demanding *t*-butyl substituents to the ferrocene scaffold hinders rotation of the ferrocene cyclopentadienyls, thereby resulting in sterically locked conformations.¹¹ Such conformations are beneficial for catalysis,¹² partly because of preorganized strong interactions between the donor atoms.¹³ The aliphatic substituents also increase electron density at the ferrocene unit and at the attached phosphorus atom, and provide steric protection for the phosphine moiety and the ligated, catalytically active metal centre. Furthermore, aliphatic substituents render the phosphinoferrrocene fragment more hydrophobic and can direct the ligated metal centres towards the organic components of the reaction system, typically the organic reagents. The hydrophilic amidosulfonate tags, meanwhile, can stabilize dispersions formed in water.^{4c,14} In this study, the effect of the additional auxiliary substituents was investigated in the challenging Pd-catalysed C-H arylation of unprotected indoles performed in water, using Pd-allyl complexes stabilized with ligands $\mathbf{1}^R$ and $\mathbf{2}^R$ as the pre-catalysts.

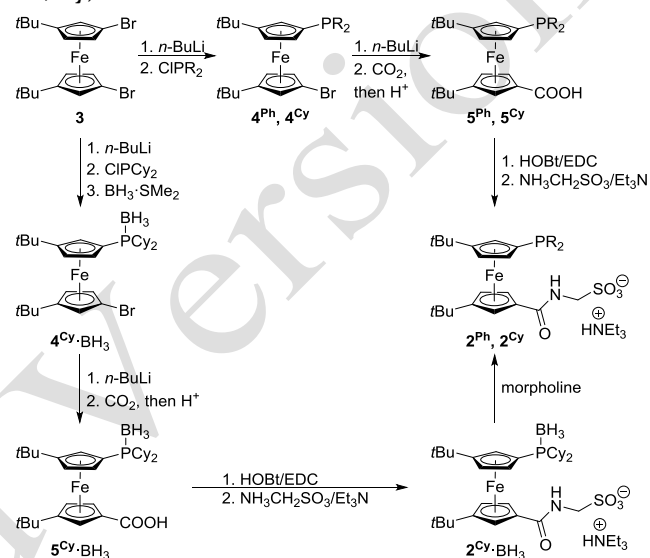
RESULTS AND DISCUSSION

Synthesis of Polar Phosphinoferrrocenes and Their (η^3 -Allyl)palladium Complexes. The synthesis of planar-chiral but racemic phosphinoferrrocene amidosulfonates $\mathbf{2}^R$, where R = Ph or cyclohexyl (Cy), was performed analogously to the synthesis of compounds $\mathbf{1}^R$ lacking the *t*-butyl substituents (Scheme 2). The respective starting materials, phosphinocarboxylic acids $\mathbf{5}^R$, were obtained in two steps by sequential lithiation/functionalization of racemic 1,1'-dibromo-3,3'-di-*t*-butylferrocene ($\mathbf{3}$)¹⁵ via phosphine-bromides $\mathbf{4}^R$. Subsequent amidation producing compounds $\mathbf{2}^{\text{Ph}}$ and $\mathbf{2}^{\text{Cy}}$ was achieved by treating acids $\mathbf{5}^{\text{Ph}}$ and $\mathbf{5}^{\text{Cy}}$ successively with 1-hydroxybenzotriazole (HOBT), 1-ethyl-3-[3-dimethylamino]propyl]carbodiimide (EDC), and aminomethanesulfonic acid in triethylamine/acetonitrile.^{9c} This procedure furnished better yields of the coupling products, typically *ca.* 95% yield after chromatography than the method used previously to prepare $\mathbf{1}^{\text{Ph}}$,⁶ in which the starting acids were converted to pentafluorophenyl esters that were subsequently reacted with aminomethanesulfonic acid and triethylamine.

Amide $\mathbf{2}^{\text{Cy}}$ was also synthesized in its P-protected form (Scheme 2), $\mathbf{2}^{\text{Cy}}\cdot\text{BH}_3$. In this case, the amidation was performed with the protected acid $\mathbf{5}^{\text{Cy}}\cdot\text{BH}_3$, obtained from $\mathbf{4}^{\text{Cy}}\cdot\text{BH}_3$.¹⁶ Deprotection was achieved by heating $\mathbf{2}^{\text{Cy}}\cdot\text{BH}_3$

in freshly distilled morpholine (65°C/16 h),¹⁷ providing $\mathbf{2}^{\text{Cy}}$ in 66% yield after chromatography and crystallization. Although this route employs air-stable and easier-to-handle protected intermediates, it provides a lower overall yield of $\mathbf{2}^{\text{Cy}}$ than the shorter route, making use of unprotected intermediates (13% vs. 38%).

Scheme 2. Synthesis of Phosphinoferrrocenes $\mathbf{2}^R$ (R = Ph, Cy)^a



^a HOBT = 1-hydroxybenzotriazole, EDC = 1-ethyl-3-[3-dimethylamino]propyl]carbodiimide

Compounds $\mathbf{2}^{\text{Ph}}$ and $\mathbf{2}^{\text{Cy}}$ were purified by chromatography and crystallization from ethyl acetate, which removed minor amounts of the respective phosphine oxides. The compounds are orange crystalline materials, stable over extended periods, especially when stored under an inert atmosphere. In solution, they undergo slow oxidation under ambient conditions.

Polar ferrocenes $\mathbf{2}^{\text{Ph}}$ and $\mathbf{2}^{\text{Cy}}$ and all reaction intermediates were characterized by NMR and IR spectroscopy, ESI mass spectrometry, and elemental analysis. The solid-state structures of $\mathbf{2}^{\text{Ph}}$ and $\mathbf{2}^{\text{Cy}}\cdot\text{BH}_3$ were determined by single-crystal X-ray diffraction analysis (Figure 1 and Table 1; additional structural diagrams are available as Supporting Information).

The molecular structure of $\mathbf{2}^{\text{Ph}}$ (Figure 1) is similar to the structures of $\mathbf{1}^{\text{Ph}}$ and $\mathbf{1}^{\text{Cy}}$ reported earlier.^{6,9c} It comprises a regular ferrocene moiety, showing similar Fe-C distances and negligible tilting. The functional substituents at positions 1 and 1' depart by 20° from an eclipsed arrangement.

Lorsqu'un écrit scientifique issu d'une activité de recherche financée au moins pour moitié par des dotations de l'État, des collectivités territoriales ou des établissements publics, par des subventions d'agences de financement nationales ou par des fonds de l'Union européenne est publié dans un périodique paraissant au moins une fois par an, son auteur dispose, même après avoir accordé des droits exclusifs à un éditeur, du droit de mettre à disposition gratuitement dans un format ouvert, par voie numérique, sous réserve de l'accord des éventuels coauteurs, la version finale de son manuscrit acceptée pour publication, dès lors que l'éditeur met lui-même celle-ci gratuitement à disposition par voie numérique ou, à défaut, à l'expiration d'un délai courant à compter de la date de la première publication. Ce délai est au maximum de six mois pour une publication dans le domaine des sciences, de la technique et de la médecine et de douze mois dans celui des sciences humaines et sociales.

The amide moiety is rotated by $16.5(3)^\circ$ with respect to its bonding cyclopentadienyl ring so that the nitrogen atom is inclined towards the ferrocene unit. In the crystal, the ions constituting the structure of 2^{Ph} assemble into closed arrays (Figure 1). Specifically, two amidosulfonate anions forming an enantiomeric pair are linked into dimers located around crystallographic inversion centres by pairs of $\text{N1-H1N}\cdots\text{O3}$ hydrogen bonds, and these dimers further serve as H-bond acceptors for two adjacent Et_3NH^+ cations, with the latter acting as bifurcated H-bond donors ($\text{N2-H2N}\cdots\text{O2}/\text{N2-H2N}\cdots\text{O4}$).

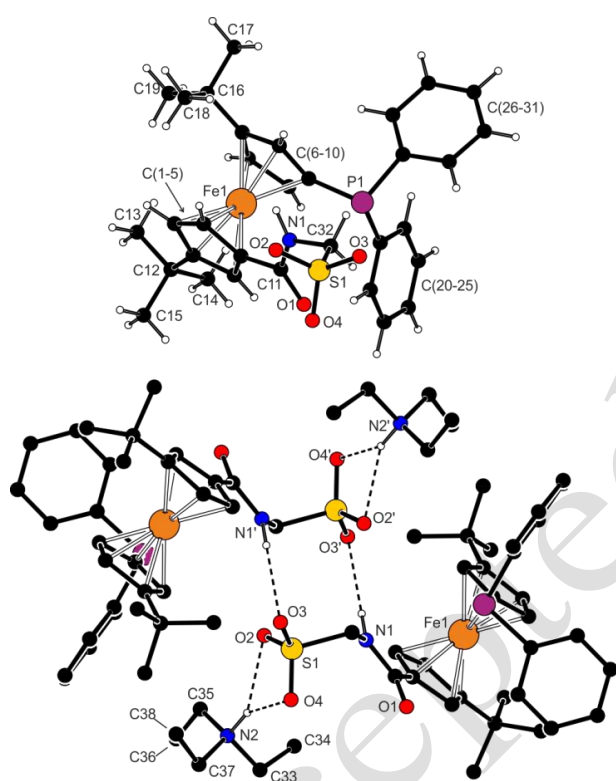


Figure 1. (top) View of the amidosulfonate anion in the structure of 2^{Ph} and (bottom) simplified packing diagram for the same compound. Hydrogen bond parameters: $\text{N1}\cdots\text{O3} = 3.289(3)$ Å, $\text{N2}\cdots\text{O2} = 3.096(3)$ Å, and $\text{N2}\cdots\text{O4} = 2.794(3)$ Å. Note: only one position of the disordered atom C37 is shown for clarity.

Table 1. Selected distances and angles for 2^{Ph} and $2^{\text{Cy}}\cdot\text{BH}_3$ (in Å and deg)

Parameter ^a	2^{Ph}	$2^{\text{Cy}}\cdot\text{BH}_3$ (mol 1/mol 2) ^b
Fe-C (range)	2.045(2)- 2.080(2)	2.037(5)-2.081(4)/2.033(5)- 2.085(4)
tilt	1.3(1)	4.2(3)/3.9(3)
τ	19.9(2)	54.5(3)/-55.2(3)

$\text{C11}=\text{O1}$	1.227(3)	1.226(6)/1.227(6)
$\text{C11}-\text{N1}$	1.361(3)	1.360(6)/1.363(6)
$\text{N1}-\text{C11}=\text{O1}$	122.9(2)	123.6(5)/123.4(5)
$\text{S1}-\text{O}$	1.442(2)- 1.461(2)	1.453(4)-1.464(3)/1.449(3)- 1.464(3)
$\text{C32}-\text{S1}$	1.804(2)	1.792(4)/1.797(4)

^a Definitions: tilt is the dihedral angle between the least-squares cyclopentadienyl planes; τ stands for the torsion angle $\text{C1}-\text{Cg1}-\text{Cg2}-\text{C6}$, where Cg1 and Cg2 denote the centroids of the cyclopentadienyl rings C(1-5) and C(6-10), respectively. ^b Data for two structurally independent molecules. Further parameters: $\text{P1}-\text{B1} = 1.919(6)/1.924(6)$ Å.

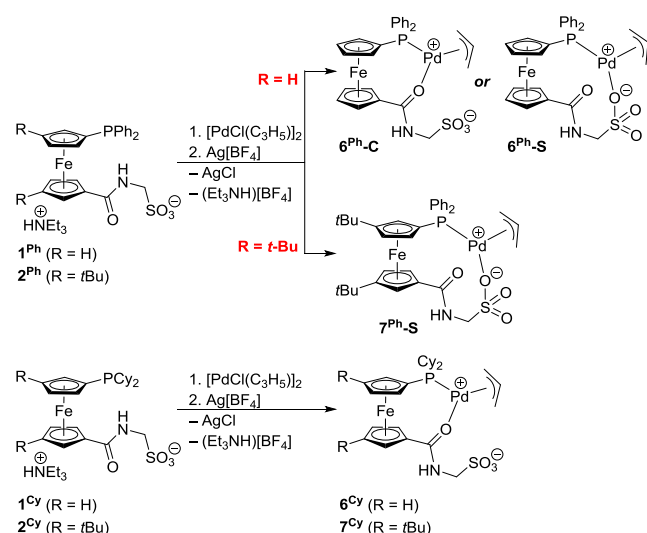
Compound $2^{\text{Cy}}\cdot\text{BH}_3$ crystallizes with two structurally independent but essentially identical molecules (see Supporting Information). Its molecular structure is similar to 2^{Ph} . However, the ferrocene units adopt a more opened conformation (*i.e.*, their substituents are more distant; see τ angles in Table 1), and the amide planes depart more from an arrangement coplanar with their parent cyclopentadienyl ring (dihedral angles: $34.0(6)/35.5(6)^\circ$; in this case, the nitrogen atoms are diverted from the ferrocene unit). The crystal assembly of $2^{\text{Cy}}\cdot\text{BH}_3$ is virtually identical to that of 2^{Ph} .

To examine the catalytic properties of 1^{R} and 2^{R} , we used these hydrophilic ligands to prepare zwitterionic Pd(allyl) complexes applicable as defined pre-catalysts (Scheme 3).

Following the procedure used to prepare 6^{Cy} ,^{9c} the ligands were first reacted with $[\text{Pd}(\mu\text{-Cl})(\eta^3\text{-C}_3\text{H}_5)_2]_2$ to give the nonisolated phosphine complexes $[\text{PdCl}(\eta^3\text{-C}_3\text{H}_5)(\text{L}-\kappa\text{P})]$ ($\text{L} = 1^{\text{R}}$ and 2^{R}), which were treated with $\text{Ag}[\text{BF}_4]$ to remove the Pd-bound halide. The resulting zwitterionic complexes were less water soluble than the original phosphinoferrocenes. This was advantageously used during their purification: the partitioning of the crude product between CH_2Cl_2 and water removed $(\text{Et}_3\text{NH})[\text{BF}_4]$ and the subsequent flash chromatography and crystallization furnished pure complexes 6^{R} and 7^{R} as air-stable solids.

Scheme 3. Synthesis of Allylpalladium(II) Complexes 6^{R} and 7^{R}

Lorsqu'un écrit scientifique issu d'une activité de recherche financée au moins pour moitié par des dotations de l'État, des collectivités territoriales ou des établissements publics, par des subventions d'agences de financement nationales ou par des fonds de l'Union européenne est publié dans un périodique paraissant au moins une fois par an, son auteur dispose, même après avoir accordé des droits exclusifs à un éditeur, du droit de mettre à disposition gratuitement dans un format ouvert, par voie numérique, sous réserve de l'accord des éventuels coauteurs, la version finale de son manuscrit acceptée pour publication, dès lors que l'éditeur met lui-même celle-ci gratuitement à disposition par voie numérique ou, à défaut, à l'expiration d'un délai courant à compter de la date de la première publication. Ce délai est au maximum de six mois pour une publication dans le domaine des sciences, de la technique et de la médecine et de douze mois dans celui des sciences humaines et sociales.



The ligands bearing dicyclohexylphosphine groups produced complexes 6^{Cy} (reported compound^{9c}) and 7^{Cy} , wherein the amide oxygen completed the coordination sphere of Pd(II) (*N.B.* for 7^{Cy} , the same product resulted upon crystallization from CHCl_3 /hexane and CH_2Cl_2 + methanol/hexane). Conversely, depending on the crystallization conditions, complex 6^{Ph} was isolated in two coordinative isomeric forms, where either the amide oxygen or the sulfonate oxygen coordinated to palladium (henceforth distinguished as $6^{\text{Ph-C}}$ and $6^{\text{Ph-S}}$). Whereas $6^{\text{Ph-C}}$ containing a smaller and more rigid P,O-chelate ring was reproducibly obtained from the CH_2Cl_2 + methanol/hexane mixture, the isomeric complex $6^{\text{Ph-S}}$ featuring a charge-supported O \rightarrow Pd interaction resulted from crystallization with the CHCl_3 /hexane mixture. Apparently, polar solvents that better solvate the charged sulfonate group favour the formation of $6^{\text{Ph-C}}$, whereas using a less polar solvent mixture leads to the preferential formation of $6^{\text{Ph-S}}$. The analogous complex featuring 2^{Ph} was isolated only as a $7^{\text{Ph-S}}$ isomer when employing either CHCl_3 /ethyl acetate or CH_2Cl_2 + methanol/hexane mixtures for crystallization. The complexes were structurally authenticated by spectroscopic methods and by X-ray diffraction analysis (*vide infra*).

The formation of isomers differing by the coordination of the pendant amidosulfonate moiety was analysed by DFT. In particular, the differences in the Gibbs energy of the C- and S-isomers, $\Delta G = G_{\text{S}} - G_{\text{C}}$, at 298 K (Table 2) suggested that the isomer with the sulfonate-bound amidophosphine ligand is favoured for 7^{Ph} in both CHCl_3 and methanol. Conversely, the C-isomer is preferred for 7^{Cy} , in line with the experimental results. For complex 6^{Ph} , both isomers can be isolated depending on the crystallization conditions. The calculations favoured the $6^{\text{Ph-S}}$ isomer in

CHCl_3 as the less polar solvent and revealed a slight preference for the $6^{\text{Ph-C}}$ isomer in methanol, again in accordance with the experimental observations. Although the PCM approach¹⁸ used for modelling the solvation effects has limitations for properly accounting for H-bonding interactions, which seems to stabilize the C-isomers *via* solvation of the uncoordinated sulfonate moiety, our DFT results are consistent with the general experimental trends.

Table 2. Gibbs energy differences computed in CHCl_3 and methanol (PCM) between the S- and C-isomers of 6^{Ph} , 7^{Ph} , and 7^{Cy}

Complex	$\Delta G^{298} = G_{\text{S}}^{298} - G_{\text{C}}^{298}$ [kcal mol ⁻¹] ^a		
	vacuum	CHCl_3	methanol
6^{Ph}	-12.83	-4.60	0.028
7^{Ph}	-14.09	-6.19	-1.46
7^{Cy}	2.84	4.05	8.87

^a Differences in Gibbs free energies at 298 K. A negative ΔG value indicates that the S-isomer is energetically favoured over the C-isomer; see Experimental for details. Full computational data are available in the Supporting Information.

Consistent with the solid-state results, the solution NMR spectra of 6^{R} and 7^{R} displayed markedly broad signals with significant temperature dependence. This indicated a net fluxionality of the complexes in solution, attributed to ligand shuttling (amide vs. sulfonate coordination) and rotation of the Pd-bound allyl moiety. FTIR spectra of the isomeric complexes were quite similar, differing mostly in band intensities. Nonetheless, some diagnostic differences could be observed in the region of carbon stretching modes (see Figure S1).

The structures of $6^{\text{Ph-C}} \cdot \text{CH}_2\text{Cl}_2 \cdot \text{MeOH}$ and $6^{\text{Ph-S}} \cdot 1.5\text{CHCl}_3$ are displayed in Figure 2; the structures of solvated 7^{Ph} and 7^{Cy} are reported in the Supporting Information, which also provides additional structural diagrams. As stated above, $6^{\text{Ph-C}} \cdot \text{CH}_2\text{Cl}_2 \cdot \text{MeOH}$ and $6^{\text{Ph-S}} \cdot 1.5\text{CHCl}_3$ differ in coordination of the amidosulfonate moiety. When comparing the molecular structures of $6^{\text{Ph-C}}$ and $6^{\text{Ph-S}}$ (Table 3), differences in the conformation of the 1,1'-disubstituted ferrocene units can be observed, with the pendant functions approximately 10° closer in $6^{\text{Ph-S}}$. Twisting of the amide moiety in $6^{\text{Ph-C}}$ facilitates coordination of the amide oxygen O₁, while in $6^{\text{Ph-S}}$, it brings the sulfonate group to the vicinity of the palladium atom (the dihedral angles of the amide plane and ring C(1-5) are 21.6(3)° for $6^{\text{Ph-C}}$ and 8.8(2)° in the opposite sense for $6^{\text{Ph-S}}$). In addition, coordination of O₂ requires rotation of the sulfonate

group along the pivotal C₃₂-S₁ bond. Despite these structural changes, the arrangement of the amidosulfonate chain remains similar (*cf.* the torsion angles C₁₁-N₁-C₃₂-S₁ of 99.0(3)° in **6^{Ph}-C** and 95.4(2)° in **6^{Ph}-S**). The difference in the ligand bite angles, P₁-Pd₁-O₁ vs. P₁-Pd₁-O₂, is also small (*ca.* 5°).

Another notable feature is the positioning of the amide oxygen O₁ above the palladium atom in the molecule of **6^{Ph}-S** (Pd₁...O₁ = 2.888(1) Å; the angle between the Pd₁...O₁ interconnection and the {Pd₁,P₁,O₂} plane is 77.88(5)°), pointing to a possible "axial" interaction.¹⁹ No such contact is detected in the structure of **6^{Ph}-C**, where the shortest intramolecular distances between Pd₁ and sulfonate oxygen atoms exceed 5 Å. The allyl moiety in both structures is disordered over two positions that are approximately mirror images with respect to the {Pd₁, O_n, P₁} plane (*n* = 1 or 2).

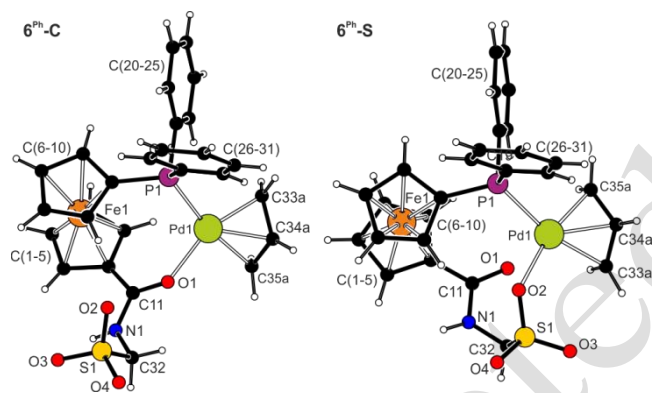


Figure 2. Views of the complex molecules in the structures of **6^{Ph}-C**·CH₂Cl₂·MeOH and **6^{Ph}-S**·1.5CHCl₃.

Table 3. Selected distances and angles for **6^{Ph}-C·CH₂Cl₂·MeOH and **6^{Ph}-S**·1.5CHCl₃ (in Å and deg)**

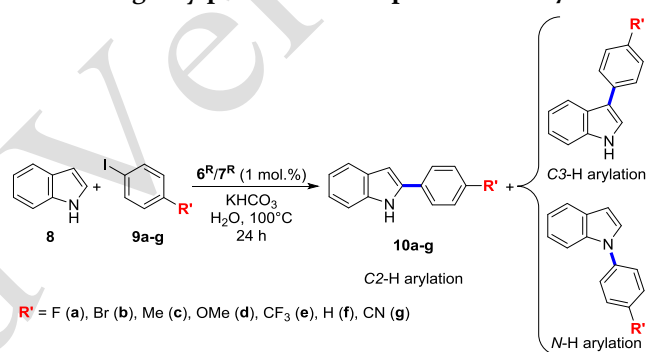
Parameter ^a	6^{Ph}-C (Y = O ₁)	6^{Ph}-S (Y = O ₂)
Pd ₁ -P ₁	2.3086(7)	2.3189(7)
Pd ₁ -Y	2.123(2)	2.165(1)
P ₁ -Pd-Y	101.11(6)	96.16(3)
Fe ₁ -C	2.018(3)-2.075(3)	2.024(2)-2.065(2)
tilt	5.0(2)	4.3(1)
τ	59.3(2)	49.4(1)
C ₁₁ =O ₁	1.257(3)	1.232(2)
C ₁₁ -N ₁	1.336(4)	1.357(2)
N ₁ -C ₁₁ =O ₁	120.4(2)	122.6(2)
S ₁ -O ₂ /3/4	1.443(2)/1.466(2)/1.448(2)	1.478(1)/1.451(1)/1.449(2)

3) 1)

^a Parameters are defined as for the free ligand; see footnote to Table 1.

Catalytic Experiments. Arylindoles are recurring motifs in biologically active molecules and pharmaceuticals.²⁰ They have been prepared traditionally using cross-coupling strategies.²¹ However, the development of direct C-H arylation, while challenging because of the intrinsic strength of this bond, allows direct functionalization of indoles, thus enabling simple synthesis of aryl-substituted indoles in a more atom-economic process.²² We used this reaction to assess the properties of palladium catalysts supported by polar ligands **1^R** and **2^R** (Scheme 4).

Scheme 4. Direct C-H Arylation of Unprotected Indoles using Allylpalladium Complexes **6^R** and **7^R**



The arylation of unprotected indole **8** was performed in water using complexes **6^R** and **7^R** as defined pre-catalysts and various *para*-substituted iodoarenes as the arylating agents. Bromoarenes were found to be unreactive during preliminary reaction tests. The initial studies were conducted using 1 mol.% **7^{Ph}** for the reaction between **8** and 4-fluoro-1-iodobenzene (**9a**, Scheme 4). As shown in Table 4, the arylation proceeded with a high selectivity, producing nearly exclusively (>99%) C₂-arylated product **10a**. We, however, take note of the challenges associated with this coupling reaction in biphasic conditions (see Experimental) since, despite our efforts, the best yields of arylated indoles were limited to *ca.* 50%. As anticipated, the solvent played a crucial role. The use of classical organic solvents such as toluene, DMF, AcOH, or dioxane (Table 4, entries 1-3 and 8) or alcohols (entries 6 and 7) and their more innocuous alternatives (ethylene carbonate and methyl cyclopentyl ether, entries 4 and 5) provided less than 5% conversion. We observed a 20% conversion using a 1:1 mixture of dioxane and water, albeit with a slight loss of selectivity (entry 9). Pleasingly, the use of pure water resulted in a better 25% conversion and full selectivity (entry 10). Gradually increasing the amount of catalyst **7^{Ph}** up to 5 mol.% (entries 11 and 12) allowed us

Lorsqu'un écrit scientifique issu d'une activité de recherche financée au moins pour moitié par des dotations de l'État, des collectivités territoriales ou des établissements publics, par des subventions d'agences de financement nationales ou par des fonds de l'Union européenne est publié dans un périodique paraissant au moins une fois par an, son auteur dispose, même après avoir accordé des droits exclusifs à un éditeur, du droit de mettre à disposition gratuitement dans un format ouvert, par voie numérique, sous réserve de l'accord des éventuels coauteurs, la version finale de son manuscrit acceptée pour publication, dès lors que l'éditeur met lui-même celle-ci gratuitement à disposition par voie numérique ou, à défaut, à l'expiration d'un délai courant à compter de la date de la première publication. Ce délai est au maximum de six mois pour une publication dans le domaine des sciences, de la technique et de la médecine et de douze mois dans celui des sciences humaines et sociales.

to improve this yield to 40% while conserving the C2 selectivity. Various bases other than KHCO₃ were also tested, albeit with detrimental effects on either selectivity or on conversion, as illustrated for K₂CO₃ and KOAc (entries 13 and 14).

Table 4. Screening of Conditions for the Pd-Catalysed Indole C₂-H Arylation Yielding 2(4-Fluorophenyl)indole (10a)^a

Entry	Catalyst	Solvent	Base	Yield of 10a (%)
1	7 ^{Ph} (1%)	toluene	KHCO ₃	<1
2	7 ^{Ph} (1%)	DMF	KHCO ₃	<1
3	7 ^{Ph} (1%)	AcOH	KHCO ₃	<2
4	7 ^{Ph} (1%)	ethylene carbonate	KHCO ₃	<2
5	7 ^{Ph} (1%)	MeOC ₅ H ₉	KHCO ₃	<2
6	7 ^{Ph} (1%)	EtOH	KHCO ₃	<5
7	7 ^{Ph} (1%)	<i>t</i> -amyl alcohol	KHCO ₃	<5
8	7 ^{Ph} (1%)	dioxane	KHCO ₃	<5
9	7 ^{Ph} (1%)	dioxane/H ₂ O ^b	KHCO ₃	20 ^c
10	7 ^{Ph} (1%)	H ₂ O	KHCO ₃	25
11	7 ^{Ph} (3%)	H ₂ O	KHCO ₃	29
12	7 ^{Ph} (5%)	H ₂ O	KHCO ₃	40
13	7 ^{Ph} (1%)	H ₂ O	K ₂ CO ₃	15 ^c
14	7 ^{Ph} (1%)	H ₂ O	KOAc	11

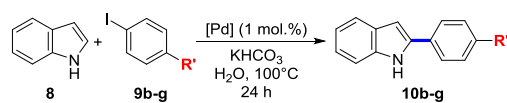
^a Conditions: 0.5 mmol of **8**, 0.6 mmol **9a**, 1.5 mmol of base, 2 mL solvent at 100°C for 24 h; yields from standardized ¹H NMR spectra and duplicate experiments. MeOC₅H₉ = methyl cyclopentyl ether. ^b 1:1 (v/v) mixture. ^c Partial loss of selectivity was observed with the formation of ca. 5% of the C₃-arylated isomer.

Based on these results, we used water as the solvent and KHCO₃ as the base for subsequent experiments aimed at comparing the activity (at 1 mol.%) of palladium complexes **6^R** and **7^R** in the coupling of **8** with functionalized iodoarenes **9b-g** to give arylindoles **10b-g** (Table 5). When using the simple allylpalladium(II) complex [PdCl(η³-C₃H₅)₂]₂ in the absence of any ligand (entry 1) or with the "classical" tertiary phosphine ligands PPh₃ and *in situ* deprotected PCy₃ (entries 2 and 3), the arylation of **8** using 4-bromo-1-iodobenzene (**9b**) occurred only marginally. The comparison of the results achieved with palladium complexes stabilized by the polar phosphinoferrrocene amidosulfonate ligands with (**7^R**) or without (**6^R**) the *t*Bu groups revealed that the activity practically doubled when *t*Bu groups were present (entries 4-7). The presence

of dicyclohexylphosphino groups was also beneficial, and complex **7^{Cy}** provided **10b** in the best, albeit still modest yield of 19%. This general trend was confirmed for the reactions producing *p*-tolyl derivative **10c**, since **7^{Cy}** provided 48% yield of this aryl indole (entry 11), while **7^{Ph}** achieved only 31% yield (entry 10), and the non-*t*-butylated counterparts **6^{Cy}** and **6^{Ph}** were found to be ineffective (entries 8 and 9).

Considering these results, the most active catalyst **7^{Cy}** was utilized in reaction tests employing iodoarenes **9d-g** with different substituents. Thus, compounds **10d** and **10e**, incorporating the 4-methoxyphenyl and 4-(trifluoromethyl)phenyl moieties, were obtained in 47% and 40% yields (entries 12 and 13). The reaction of unsubstituted iodobenzene **9f** proceeded with a lower conversion (36% of **10f**, entry 14), whereas arylation with its electron-poor cyano derivative **9g** (15% of **10g**, entry 15) was more difficult. Surprisingly, catalyst **7^{Cy}** showed a higher efficiency for electron-rich iodoarenes, which is rather unusual.^{22b} Increasing the reaction time and the amount of catalysts had only marginal effects on the yield of the arylation product.

Table 5. Palladium-Catalysed C₂-H Arylation of Indole using Substituted Iodoarenes 9b-g^a



R' = Br (b), Me (c), OMe (d), CF₃ (e), H (f), CN (g)

Entry	Catalyst	R'	Product	Yield (%)
1	[PdCl(C ₃ H ₅) ₂] ₂	Br	10b	<2
2	[PdCl(C ₃ H ₅) ₂]/PPh ₃	Br	10b	<5
3	[PdCl(C ₃ H ₅) ₂]/PCy ₃ HBf ₄	Br	10b	<5
4	6^{Ph}	Br	10b	6
5	6^{Cy}	Br	10b	12
6	7^{Ph}	Br	10b	14
7	7^{Cy}	Br	10b	19
8	6^{Ph}	Me	10c	<5
9	6^{Cy}	Me	10c	7
10	7^{Ph}	Me	10c	31
11	7^{Cy}	Me	10c	48
12	7^{Cy}	OMe	10d	47
13	7^{Cy}	CF ₃	10e	40
14	7^{Cy}	H	10f	36

Lorsqu'un écrit scientifique issu d'une activité de recherche financée au moins pour moitié par des dotations de l'État, des collectivités territoriales ou des établissements publics, par des subventions d'agences de financement nationales ou par des fonds de l'Union européenne est publié dans un périodique paraissant au moins une fois par an, son auteur dispose, même après avoir accordé des droits exclusifs à un éditeur, du droit de mettre à disposition gratuitement dans un format ouvert, par voie numérique, sous réserve de l'accord des éventuels coauteurs, la version finale de son manuscrit acceptée pour publication, dès lors que l'éditeur met lui-même celle-ci gratuitement à disposition par voie numérique ou, à défaut, à l'expiration d'un délai courant à compter de la date de la première publication. Ce délai est au maximum de six mois pour une publication dans le domaine des sciences, de la technique et de la médecine et de douze mois dans celui des sciences humaines et sociales.

15 ⁷Cy CN 10g 15^b

^a For conditions, see Table 3. The yields are from standardized ¹H NMR spectra and duplicate experiments. ^b A loss of selectivity was observed with the formation of ca. 10% of arylated C₃ isomer.

CONCLUSION

In this paper, we describe the synthesis of two new phosphiniferrocene ligands possessing hydrophilic amidosulfonate pendants and *t*-butyl substituents that limit the overall molecular mobility. Together with their analogues, which lack the *t*-butyl substituents, these compounds were used to prepare zwitterionic (η^3 -allyl)Pd(II) complexes. The formation of isomers differing by the coordination of the pendant amidosulfonate was noted, controlled by crystallization conditions. This behaviour, confirmed by the results of DFT calculations, underlines the hybrid nature of ligands **1**^R and **2**^R, wherein the soft phosphine moiety forms a stronger bond to Pd(II) than the hard oxygen donors, which in turn results in fluxional coordination. As defined pre-catalysts, the allylpalladium complexes mediate direct C–H arylation of indole with aryl iodides. Of note is the fairly low catalyst amount (1 mol.%), high C₂ selectivity, and the absence of the use of an additional phase-transfer agent in this catalytic system.

EXPERIMENTAL SECTION

Materials and Methods. All reactions were performed under an argon or nitrogen atmosphere by using standard Schlenk techniques. Racemic 1,1'-dibromo-3,3'-di-*t*-butylferrocene (**3**), **4**^{Ph,15}, **4**^{Cy}.BH₃, **5**^{Cy}.BH₃, **5**^{Ph,16}, **1**^{Ph,6}, and **1**^{Cy,9c} were prepared as previously reported. Anhydrous THF and dichloromethane were obtained from a Puresolv MD5 solvent purification system. Solvents used for chromatography and crystallizations were of reagent grade and were employed without additional purification. NMR spectra were recorded at 25°C on a Varian UNITY Inova 400, Bruker Avance 500 and 600 spectrometers. Chemical shifts (δ /ppm) are given relative to internal tetramethylsilane or, alternatively, to residual signals of the deuterated solvents (¹H and ¹³C NMR), and to external, 85% aqueous H₃PO₄ (³¹P NMR). FTIR spectra were recorded on a Nicolet 6700 spectrometer in the range of 400–4000 cm⁻¹. ESI mass spectra were obtained with a Bruker Compact Q-TOF spectrometer. Elemental analyses were performed using a Perkin-Elmer PE 2400 CHN analyser or a Thermo Electron Flash EA 1112 Series.

Synthesis of **4^{Cy}.** Under an argon atmosphere, racemic 1,1'-dibromo-3,3'-di-*t*-butylferrocene (**3**; 0.912 g, 2.0 mmol) was dissolved in dry THF (10 mL) in an oven-dried, two-necked reaction flask equipped with a stirring bar and an argon inlet. The solution was cooled with an acetone/liquid nitrogen bath to approximately –80°C before *n*-butyllithium (0.80 mL of 2.5 M in hexanes, 2.0 mmol) was introduced, whereupon the initially yellow solution turned orange-red. The mixture was stirred and

cooled for 30 min, and then neat ClPCy₂ (0.49 mL, 2.2 mmol) was added dropwise. The resulting mixture was stirred at –80°C for another 30 min and then gradually warmed to room temperature over 90 min. The crude reaction mixture was concentrated under reduced pressure, and the red oily residue was partitioned between dichloromethane and water (10 mL each). The organic phase was washed with brine, dried over magnesium sulfate and evaporated, leaving an orange oil, which was taken up with degassed pentane and transferred onto the top of a silica gel column packed in the same solvent. The first yellow band, removed by pentane and containing mostly bromo- and 1,1'-dibromo-3,3'-di-*t*-butylferrocene (80 mg), was discarded, and the second major orange band eluted by degassed pentane/dichloromethane (4:1) was collected and evaporated, providing pure **4**^{Cy} as a yellow orange foam. Yield: 828 mg (72%).

¹H NMR (500 MHz, CDCl₃): δ = 4.29 (dd, *J* = 2.4, 1.3 Hz, 1 H, Cp), 4.15–4.13 (m, 1 H, Cp), 4.12 (t, *J* = 1.5 Hz, 1 H, Cp), 4.03 (dd, *J* = 2.4, 1.5 Hz, 1 H, Cp), 3.92 (dd, *J* = 2.5, 1.5 Hz, 1 H, Cp), 3.79 (q, *J* = 1.4 Hz, 1 H, Cp), 2.00–1.63 (br m, 12 H, Cy), 1.41–0.99 (br m, 10 H, Cy), 1.27 (s, 9 H, *t*Bu), 1.22 (s, 9 H, *t*Bu) ppm. ¹³C{¹H} NMR (126 MHz, CDCl₃): δ = 105.06 (d, *J* = 2 Hz, C^{ipso}-*t*Bu of Cp), 101.20 (C^{ipso}-*t*Bu of Cp), 78.83 (d, *J* = 19 Hz, C^{ipso}-P of Cp), 78.71 (C^{ipso}-Br), 73.10 (d, *J* = 14 Hz, CH of Cp), 72.73 (d, *J* = 7 Hz, CH of Cp), 70.06 (CH of Cp), 69.45 (d, *J* = 2 Hz, CH of Cp), 68.56 (CH of Cp), 64.58 (CH of Cp), 33.86 (d, *J* = 13 Hz, Cy), 33.38 (d, *J* = 12 Hz, Cy), 31.83 (d, *J* = 2 Hz, CH₃ of *t*Bu), 31.78 (CH₃ of *t*Bu), 31.68 (C^{ipso} *t*Bu), 31.56 (C^{ipso} *t*Bu), 30.95 (Cy), 30.81 (d, *J* = 14 Hz, Cy), 30.71 (d, *J* = 10 Hz, Cy), 30.70 (Cy), 30.48 (d, *J* = 10 Hz, Cy), 27.57 (d, *J* = 11 Hz, Cy), 27.50 (d, *J* = 10 Hz, Cy), 27.47 (Cy), 26.75 (Cy), 26.63 (Cy) ppm. ³¹P{¹H} NMR (202 MHz, CDCl₃): δ = –8.8 (s) ppm. FTIR (ATR diamond): ν_{max} = 2953 m, 2917 vs, 2847 s, 1480 m, 1461 m, 1446 m, 1381 m, 1358 m, 1297 w, 1276 m, 1197 w, 1174 m, 1074 w, 1045 m, 1022 w, 997 w, 917 s, 902, w, 879 s, 843 s, 801 m, 747 w, 675 w, 630 w, 594 w, 550 w, 530 w, 514 s, 497 vs, 478 s, 445 m, 429 m cm⁻¹. Anal. Calc. for C₃₀H₄₆BrFeP (573.4): C 62.84, H 8.09%. Found: C 63.09, H 7.92%. ESI-MS: *m/z* 573 ([M + H]⁺).

Synthesis of **5^{Cy}.** Compound **4**^{Cy} (0.470 g, 0.82 mmol) was dissolved in dry THF (10 mL) under an argon atmosphere. The solution was cooled in an acetone/liquid nitrogen bath to –80°C, and *n*-butyllithium (0.56 mL of 1.6 M in hexanes, 0.90 mmol) was added with continuous stirring. The yellow solution turned orange-red after the addition. The resulting mixture was stirred at –80°C for an additional 30 min before a stream of carbon dioxide was passed through the mixture, first at –80°C for 2.5 h and then at room temperature for 30 min. Then, the reaction mixture was diluted with dichloromethane (5 mL) and concentrated under reduced pressure. The oily residue was diluted by degassed CH₂Cl₂/MeOH (20:1) and transferred onto the top of a silica gel column packed with the same solvent. The first, minor yellow band was discarded and the following, major red band was collected and evaporated to afford acid **5**^{Cy} as a red-orange solid. Yield: 326 mg (74%).

¹H NMR (400 MHz, DMSO-*d*₆): δ = 12.07 (br s, 1 H, COOH), 4.59 (br s, 1 H, Cp), 4.35 (br s, 1 H, Cp), 4.21 (br s, 1 H, Cp), 4.09 (br s, 1 H, Cp), 4.05 (br s, 1 H, Cp), 3.88 (br s, 1 H, Cp), 1.95–1.53 (br m, 12 H, Cy), 1.38–0.76 (br m, 10 H, Cy), 1.22 (s, 9 H, *t*Bu), 1.20 (s, 9 H, *t*Bu) ppm. ¹³C{¹H} NMR (101 MHz, DMSO-*d*₆): δ = 172.16 (COOH), 104.67 (C^{ipso}-*t*Bu of Cp), 104.20 (d, *J* = 3 Hz, C^{ipso}-*t*Bu of Cp), 77.41 (d, *J* = 21 Hz, C^{ipso}-P of Cp), 71.46 (C^{ipso}-COOH of Cp),

71.01 (br s, CH of Cp), 70.07 (CH of Cp), 69.99 (d, $J \approx 14$ Hz, CH of Cp), 69.09 (CH of Cp), 68.00 (CH of Cp), 67.70 (CH of Cp), 32.84 (d, $J = 13$ Hz, Cy), 32.79 (d, $J = 13$ Hz, Cy), 31.54 (d, $J = 3$ Hz, CH₃ of *t*Bu), 31.26 (CH₃ of *t*Bu), 31.03 (C^{ipso} of *t*Bu), 30.89 (C^{ipso} of *t*Bu), 30.40 (2 \times Cy), 30.27 (d, $J = 8$ Hz, Cy), 29.96 (d, $J = 13$ Hz, Cy), 26.79 (Cy), 26.69 (2 \times Cy), 26.60 (Cy), 26.19 (Cy), 26.06 (Cy) ppm. ³¹P{¹H} NMR (162 MHz, DMSO-*d*₆): $\delta = -10.2$ (s) ppm. The signal due to the corresponding phosphine oxide appears at δ_P 45.2 (s). FTIR (ATR diamond): $\nu_{\max} = 2957$ m, 2918 m, 2850 m, 1666 vs (CO), 1489 m, 1479 m, 1464 m, 1446 m, 1390 w, 1366 m, 1339 w, 1313 m, 1263 s, 1173 m, 1070 w, 1039 m, 1022 w, 996 w, 968 m, 939 m, 917 m, 885 w, 852 m, 827 m, 818 m, 783 w, 753 m, 676 w, 630 w, 614 m, 564 m, 532 m, 512 m, 499 s, 479 m, 441 m cm⁻¹. Anal. Calc. for C₃₁H₄₇FePO₂ (538.5): C 69.14, H 8.80%. Found: C 69.05, H 8.60%. ESI-MS: m/z 539 ([M + H]⁺).

Synthesis of 2^{Ph}. Under argon, acid 5^{Ph} (524.2 mg, 1.0 mmol) and 1-hydroxybenzotriazole (HOBt) (162.1 mg, 1.2 mmol) were suspended in a mixture of dry acetonitrile (19 mL) and triethylamine (1.3 mL). The mixture was cooled in an ice bath and treated with neat *N*-(3-dimethylaminopropyl)-*N'*-ethylcarbodiimide (EDC) (0.2 mL, 1.2 mmol). After stirring at 4°C for 30 min, solid aminomethanesulfonic acid (888.0 mg, 8.0 mmol) was added, and the mixture was stirred at room temperature for 24 h. Then, it was filtered using a 0.45 μ m PTFE syringe filter and evaporated. The obtained crude product was purified by chromatography over a silica gel column using dichloromethane/methanol/triethylamine (90:9:1) as the eluent. The second band was collected and evaporated to give compound 2^{Ph} as an orange solid. Yield: 686.3 mg (95%). Single crystals were obtained from CH₂Cl₂/AcOEt.

¹H NMR (400 MHz, CD₂Cl₂): $\delta = 9.86$ (br s, 1 H, HNEt₃), 7.63–7.55 (m, 2 H, Ph), 7.40–7.35 (m, 3 H, Ph), 7.27–7.16 (m, 5 H, Ph), 6.59 (m, 1 H, NHCO), 4.66 (dd, $J = 13.4$, 8.1 Hz, 1 H, CH₂), 4.58 (dd, $J = 2.6$, 1.4 Hz, 1 H, Cp), 4.37 (t, $J = 1.5$ Hz, 1 H, Cp), 4.20 (dd, $J = 2.4$, 1.5 Hz, 1 H, Cp), 4.18 (dd, $J = 2.6$, 1.5 Hz, 1 H, Cp), 4.15 (dt, $J = 2.8$, 1.5 Hz, 1 H, Cp), 4.14 (dd, $J = 13.4$, 4.8 Hz, 1 H, CH₂), 3.95 (dt, $J = 2.6$, 1.3 Hz, 1 H, Cp), 3.07 (dq, $J = 7.2$, 3.2 Hz, 6 H, CH₃CH₂N), 1.27 (t, $J = 1.3$ Hz, 9 H, CH₃CH₂N), 1.27 (s, 9 H, *t*Bu), 0.99 (s, 9 H, *t*Bu) ppm. ¹³C{¹H} NMR (101 MHz, CD₂Cl₂): $\delta = 170.0$ (CONH), 141.0 (d, $J_{PC} = 12$ Hz, C^{ipso} of Ph), 138.1 (d, $J_{PC} = 10$ Hz, C^{ipso} of Ph), 135.5 (d, $J = 22$ Hz, CH of Ph), 132.7 (d, $J = 19$ Hz, CH of Ph), 129.7 (CH^{para} of Ph), 128.9 (d, $J = 8$ Hz, CH of Ph), 128.6 (d, $J = 6$ Hz, CH of Ph), 128.4 (CH^{para} of Ph), 107.3 (d, $J = 6$ Hz, C^{ipso}-*t*Bu of Cp), 105.6 (C^{ipso}-*t*Bu of Cp), 76.1 (d, $J_{PC} = 7$ Hz, C^{ipso}-P of Cp), 75.5 (C^{ipso}-CONH of Cp), 73.6 (d, $J = 25$ Hz, CH of Cp), 71.7 (CH of Cp), 69.7 (CH of Cp), 69.05 (CH of Cp), 68.95 (CH of Cp), 67.2 (d, $J = 3$ Hz, CH of Cp), 56.1 (CH₂SO₃), 46.5 (CH₃CH₂N), 31.7 (CH of *t*Bu), 31.5 (CH of *t*Bu), 31.2 (C^{ipso} of *t*Bu), 30.7 (C^{ipso} of *t*Bu), 8.8 (CH₃CH₂N) ppm. ³¹P{¹H} NMR (162 MHz, CD₂Cl₂): $\delta = -18.4$ (s) ppm. FTIR (Nujol): $\nu_{\max} = 3335$ w (N-H), 3051 m (N-H), 2720 w, 2688 w, 2525 w, 2360 w, 2342 w, 1717 w, 1656 s (C=O), 1585 w, 1569 w, 1532 m, 1316 w, 1299 w, 1262 m, 1212 m, 1175 m (S=O), 1153 m (P-C), 1104 w, 1087 w, 1079 w, 1071 w, 1036 s (S=O), 971 w (P-C), 930 w, 918 w, 907 w, 895 w, 876 w, 864 w, 849 w, 830 w, 813 w, 766 w, 751 m, 743 m, 699 m, 675 w, 669 w, 626 w, 607 m, 539 m, 530 m, 514 m, 497 m, 479 m, 464 w, 442 m, 424 m, 411 m cm⁻¹. Anal. Calc. for C₃₈H₅₃N₃PO₄FeS (720.28): C 63.33, H 7.41, N 3.89%. Found: C 63.03, H 7.15, N 4.05%. ESI-MS: m/z 618 ([M - HNEt₃]⁻).

Synthesis of 2^{Cy}. An oven-dried, two-necked flask equipped with an argon inlet and stirring bar was charged with acid 5^{Cy} (619 mg, 1.15 mmol) and HOBt (212 mg, 1.38 mmol), flushed with argon, and sealed. The solids were dissolved by adding dry acetonitrile (20 mL) and degassed triethylamine (8 mL). The solution was cooled on ice, before neat EDC (0.24 mL, 1.38 mmol) was introduced, followed by solid aminomethanesulfonic acid (1.022 g, 9.20 mmol). The reaction mixture was stirred at room temperature for 24 h and then evaporated. The solid residue was taken up with a dichloromethane/methanol/triethylamine (95:4:1) mixture and transferred onto the top of a silica gel column. Elution with the same solvent mixture led to the development of a pale orange band, which was discarded, and a major orange band, which was collected and evaporated. The oily residue was dissolved in hot ethyl acetate (5 mL) and crystallized by cooling to 4°C. The separated orange crystalline solid was isolated by suction and dried under vacuum. Yield of 2^{Cy}: 596 mg (71%).

¹H NMR (400 MHz, DMSO-*d*₆): $\delta = 9.29$ (br s, 1 H, HNEt₃), 7.74 (dd, $J = 7.7$, 5.0 Hz, 1 H, NHCO), 4.86 (dd, $J = 2.6$, 1.4 Hz, 1 H, Cp), 4.55 (t, $J = 1.5$ Hz, 1 H, Cp), 4.26 (dd, $J = 13.0$, 7.6 Hz, 1 H, CHSO₃), 4.22 (dd, $J = 2.5$, 1.6 Hz, 1 H, Cp), 4.15 – 4.13 (m, 1 H, Cp), 4.00 (dd, $J = 2.5$, 1.6 Hz, 1 H, Cp), 3.84 (q, $J = 1.5$ Hz, 1 H, Cp), 3.79 (dd, $J = 13.0$, 4.9 Hz, 1 H, CHSO₃), 3.08 (q, $J = 7.3$ Hz, 6 H, CH₃CH₂N), 2.10 – 2.20 (m, 1 H, Cy), 1.95 – 0.85 (m, 20 H, Cy), 1.21 (s, 9 H, *t*Bu), 1.18 (t, $J = 7.3$ Hz, 9 H, CH₃CH₂N), 1.17 (s, 9 H, *t*Bu), 0.68 – 0.55 (m, 1 H, Cy) ppm. ¹³C{¹H} NMR (101 MHz, DMSO-*d*₆): $\delta = 168.45$ (CONH), 104.46 (d, $J = 4$ Hz, C^{ipso}-*t*Bu of Cp), 103.76 (C^{ipso}-*t*Bu of Cp), 76.11 (d, $J = 20$ Hz, C^{ipso}-P of Cp), 75.59 (C^{ipso}-CONH of Cp), 70.39 (d, $J = 20$ Hz, CH of Cp), 69.46 (CH of Cp), 69.30 (CH of Cp), 68.72 (CH of Cp), 67.50 (CH of Cp), 66.29 (CH of Cp), 55.50 (CH₂SO₃), 45.65 (CH₃CH₂N), 33.28 (d, $J = 15$ Hz, Cy), 32.38 (d, $J = 12$ Hz, Cy), 31.79 (d, $J = 3$ Hz, CH₃ of *t*Bu), 31.55 (C^{ipso} of *t*Bu), 31.50 (CH₃ of *t*Bu), 31.37 (C^{ipso} of *t*Bu), 30.73 (d, $J = 17$ Hz, Cy), 30.38 (Cy), 30.29 (Cy), 29.38 (d, $J = 10.5$ Hz, Cy), 28.69 (br s, Cy), 27.01 (d, $J = 4$ Hz, Cy), 26.89 (d, $J = 5$ Hz, Cy), 26.69 (d, $J = 8$ Hz, Cy), 26.62 (d, $J = 6$ Hz, Cy), 26.21 (Cy), 26.10 (Cy), 8.57 (CH₃CH₂N) ppm. ³¹P{¹H} NMR (162 MHz, DMSO-*d*₆): $\delta = -10.0$ (s) ppm. The signal of the respective phosphine oxide is observed at δ_P 45.2 (s). FTIR (ATR diamond): $\nu_{\max} = 3345$ w, 3082 w, 2915 m, 2848 m, 2696 w, 1651 m (CO), 1522 m, 1484 m, 1449 m, 390 w, 1363 w, 1313 w, 1256 m, 1233 m, 1209 m, 1163 s, 1075 w, 1035 s, 969 w, 930 w, 919 w, 897 w, 848 m, 814 w, 791 w, 772 w, 750 w, 669 w, 598 m, 532 m, 519 m, 487 m, 441 w cm⁻¹. Anal. Calc. for C₃₈H₆₅N₂FeO₄PS (732.8): C 62.28, H 8.94, N 3.82%. Found: C 61.90, H 8.68, N 3.65%. ESI-MS: m/z 630 ([M - HNEt₃]⁻).

Synthesis of 2^{Cy}.BH₃. Compound 2^{Cy}.BH₃ was prepared similarly, starting from 5^{Cy}.BH₃ (1.10 g, 2.0 mmol) and HOBt (0.324 g, 2.4 mmol) in dry acetonitrile (38 mL) and triethylamine (2.6 mL). The suspension was cooled in an ice bath and treated with neat EDC (0.40 mL, 2.4 mmol). The mixture was stirred at 0°C for 30 min, and aminomethanesulfonic acid (1.78 g, 16.0 mmol) was added. The resultant mixture was stirred at room temperature for 24 h and filtered through a 0.45 μ m PTFE syringe filter, and the filtrate was evaporated. The crude product was purified by chromatography over silica gel and eluted with a dichloromethane/methanol/triethylamine mixture (90:9:1). The main second band was collected and evaporated, leaving 2^{Cy}.BH₃ as an

Lorsqu'un écrit scientifique issu d'une activité de recherche financée au moins pour moitié par des dotations de l'État, des collectivités territoriales ou des établissements publics, par des subventions d'agences de financement nationales ou par des fonds de l'Union européenne est publié dans un périodique paraissant au moins une fois par an, son auteur dispose, même après avoir accordé des droits exclusifs à un éditeur, du droit de mettre à disposition gratuitement dans un format ouvert, par voie numérique, sous réserve de l'accord des éventuels coauteurs, la version finale de son manuscrit acceptée pour publication, dès lors que l'éditeur met lui-même celle-ci gratuitement à disposition par voie numérique ou, à défaut, à l'expiration d'un délai courant à compter de la date de la première publication. Ce délai est au maximum de six mois pour une publication dans le domaine des sciences, de la technique et de la médecine et de douze mois dans celui des sciences humaines et sociales.

orange solid. Yield: 1.42 g (95%). Single crystals were obtained from $\text{CH}_2\text{Cl}_2/\text{AcOEt}$.

^1H NMR (400 MHz, CD_2Cl_2): δ = 6.62-6.58 (m, 1 H, NH), 4.75 (dd, J = 2.6, 1.4 Hz, 1 H, Cp), 4.67 (t, J = 1.5 Hz, 1 H, Cp), 4.58 (dd, J = 13.5, 7.5 Hz, 1 H, CH_2), 4.40-4.37 (m, 1 H, Cp), 4.35 (dd, J = 2.6, 1.6 Hz, 1 H, Cp), 4.31-4.29 (m, 1 H, Cp), 4.23 (dd, J = 13.5, 5.5 Hz, 1 H, CH_2), 4.10 (q, J = 1.5 Hz, 1 H, Cp), 3.90-3.35 (very br s, 1H, NH of HNEt_3), 3.01 (q, J = 7.3 Hz, 6 H, $\text{CH}_3\text{CH}_2\text{N}$), 1.99-1.61 (m, 12 H, Cy), 1.45-0.98 (m, 12 H, Cy), 1.29 (s, 9 H, *t*Bu), 1.26 (s, 9 H, *t*Bu), 1.25 (t, J = 7.3 Hz, 9 H, $\text{CH}_3\text{CH}_2\text{N}$), 0.85-0.12 (m, 3 H, BH_3) ppm. $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CD_2Cl_2): δ = 169.88 (CONH), 106.84 (d, J = 6 Hz, $\text{C}^{\text{ipso-tBu}}$ of Cp), 106.61 ($\text{C}^{\text{ipso-tBu}}$ of Cp), 76.05 ($\text{C}^{\text{ipso-CONH}}$ of Cp), 72.44 (d, J = 5 Hz, CH of Cp), 70.96 (d, J = 7 Hz, CH of Cp), 70.50 (d, J_{PC} = 55 Hz, $\text{C}^{\text{ipso-P}}$ of Cp), 69.93 (CH of Cp), 69.48 (CH of Cp), 69.06 (CH of Cp), 66.81 (CH of Cp), 56.17 (CH_2SO_3), 46.51 ($\text{CH}_3\text{CH}_2\text{N}$), 33.51 (d, J = 10 Hz, Cy), 33.18 (d, J = 10 Hz, Cy), 32.20 (CH of *t*Bu), 31.75 (CH of *t*Bu), 31.17 (C^{ipso} of *t*Bu), 31.03 (C^{ipso} of *t*Bu), 28.19 (Cy), 28.14 (Cy), 27.95 (Cy), 27.84 (Cy), 27.40 (d, J = 11 Hz, Cy), 27.39 (Cy), 27.27 (Cy), 27.21 (d, J = 12 Hz, Cy), 26.52 (Cy), 26.47 (Cy), 9.27 ($\text{CH}_3\text{CH}_2\text{N}$) ppm. $^{31}\text{P}\{^1\text{H}\}$ NMR (162 MHz, CD_2Cl_2): δ = 25.2 (br s) ppm. FTIR (Nujol): ν_{max} = 3412 m, 2377 m (borane), 2274 w, 1648 m (CO), 1540 m, 1263 m, 1202 m, 1178 m, 1062 m, 1038 m, 972 w, 931 w, 920 w, 903 w, 890 w, 853 w, 822 w, 755 w, 722 w, 670 w, 616 w, 596 w, 519 w, 473 w, 435 w cm^{-1} . Anal. Calc. for $\text{C}_{38}\text{H}_{68}\text{N}_2\text{BF}_4\text{FePO}_4\text{S}$ (746.7): C 61.13, H 9.18, N 3.75%. Found: C 61.07, H 9.35, N 3.35%. ESI-MS: m/z 644 ($[\text{M} - \text{HNEt}_3]^+$).

Deprotection of 2^{Cy}BH_3 . Compound 2^{Cy}BH_3 (691 mg, 1.0 mmol) was dissolved in morpholine (7 mL). The mixture was degassed by three freeze-pump-thaw cycles and then heated at 65°C for 16 h before evaporating under reduced pressure. The oily residue was transferred onto the top of a silica gel column packed in degassed $\text{CH}_2\text{Cl}_2/\text{MeOH}/\text{Et}_3\text{N}$ (100:5:5). A single orange band was eluted with degassed $\text{CH}_2\text{Cl}_2/\text{MeOH}$ (20:1) and evaporated. The gummy residue was crystallized from hot ethyl acetate (ca. 5 mL) to produce 2^{Cy} as an orange-red microcrystalline solid (487 mg, 66%).

Synthesis of 6^{Ph} . Solid $[\text{Pd}(\mu\text{-Cl})(\eta^3\text{-C}_3\text{H}_5)]_2$ (18.3 mg, 0.05 mmol) and 1^{Ph} (60.9 mg, 0.10 mmol) were dissolved in dry dichloromethane (5 mL). After stirring for 30 min, a solution of silver(I) tetrafluoroborate (19.4 mg, 0.10 mmol) in MeOH (1 mL) was added, causing immediate separation of an off-white precipitate (AgCl) and a colour change from orange to orange-brown. The resulting mixture was stirred for 1 h and filtered through a plug of Dicalite filter aid. The filtrate was evaporated and re-dissolved in dichloromethane (5 mL). The solution was washed three times with distilled water (5 mL each) to remove $\text{Et}_3\text{NH}[\text{BF}_4]$, dried over magnesium sulfate, and evaporated. The residue was taken up with dichloromethane/methanol (20:1) and filtered through a pad of silica gel to provide pure 6^{Ph} as an orange solid after evaporation. Crystallization by liquid-phase diffusion of pentane into a solution of the complex in $\text{CH}_2\text{Cl}_2/\text{MeOH}$ (20:1) gave orange crystals. Yield: 54 mg (82%). Crystals used for X-ray diffraction analysis were grown from chloroform/pentane.

^1H NMR (400 MHz, CDCl_3 , 25°C): δ = 7.49-7.36 (m, 10 H, Ph), 7.32 (t, J = 6.7 Hz, 1 H, NH), 5.78 (qi, J = 9.9 Hz, 1 H, C_3H_5), 5.60-5.00 (very br s, 1 H, C_3H_5), 5.00-4.30 (br s, 2 H of Cp and 1 H of C_3H_5), 4.84 (t, J = 1.9 Hz, 2 H, Cp), 4.49 (br s, 2 H, Cp), 4.21 (t, J =

1.9 Hz, 2 H, Cp), 3.60-2.60 (very br s, 2 H, C_3H_5 or CH_2) ppm. ^1H NMR (400 MHz, CDCl_3 , 50°C): δ = 7.51-7.36 (m, 10 H, Ph), 7.06 (t, J = 6.7 Hz, 1 H, NH), 5.76 (qi, J = 9.9 Hz, 1 H, C_3H_5), 4.75 (t, J = 1.9 Hz, 2 H, Cp), 4.68 (br s, 2 H, C_3H_5 or Cp), 4.66 (br s, 2 H, C_3H_5 or Cp), 4.51 (br t, J = 1.8 Hz, 2 H, Cp), 4.35-3.09 (br s, 2 H, C_3H_5 or CH_2), 4.19 (t, J = 1.9 Hz, 2 H, Cp) ppm. At both temperatures, signals due to 2 hydrogen atoms of C_3H_5 and/or CH_2SO_3 were not observed due to extensive broadening. $^{31}\text{P}\{^1\text{H}\}$ NMR (161 MHz, CDCl_3 , 25°C): δ = 14.8 (s) ppm. FTIR of $6^{\text{Ph-C}}$ (DRIFTS, KBr): ν_{max} = 3312 w, 3233 w, 3088 w, 1641 m, 1596 m, 1541 m, 1480 w, 1436 m, 1402 w, 1387 w, 1314 w, 1257 m, 1228 m, 1220 m, 1185 m, 1154 s, 1099 w, 1074 w, 1044 m, 1035 w, 963 w, 912 w, 897 w, 844 w, 828 w, 751 m, 694 m, 611 m, 541 w, 532 m, 516 s, 490 m, 469 m, 450 m cm^{-1} . FTIR of $6^{\text{Ph-S}}$ (DRIFTS, KBr): ν_{max} = 3319 s, 3116 w, 300 w, 3085 w, 3057 m, 2955 m, 2871 w, 1641 s, 1586 w, 1538 m, 1532 m, 1481 w, 1456 w, 1435 m, 1402 w, 1388 w, 1379 w, 1363 w, 1312 m, 1258 s, 1214 m, 1155 vs, 1099 m, 1074 w, 1058 w, 1027 m, 1019 m, 911 w, 892 w, 869 w, 857 w, 823 w, 817 w, 747 m, 705 m, 694 m, 668 w, 626 w, 613 m, 590 w, 583 w, 552 w, 541 w, 528 m, 514 m, 494 m, 480 w, 469 m, 451 w, 439 m, 430 w cm^{-1} . Anal. Calc. for $\text{C}_{27}\text{H}_{26}\text{NFeO}_4\text{PPdS}\cdot 0.3\text{CH}_2\text{Cl}_2$ (679.28): C 48.27, H 3.95, N 2.06%. Found: C 48.34, H 4.03, N 2.12%. The amount of clathrated solvent was verified by NMR analysis (δ_{H} 5.30). HR ESI-MS calc. for $\text{C}_{27}\text{H}_{26}\text{NNaPO}_4\text{FeSPd}$ ($[\text{M} + \text{Na}]^+$): 675.9597, found: 675.9613.

Synthesis of 6^{Cy} . Compound 6^{Cy} was prepared similarly, using $[\text{Pd}(\mu\text{-Cl})(\eta^3\text{-C}_3\text{H}_5)]_2$ (17.5 mg, 0.048 mmol) and 1^{Cy} (59.5 mg, 0.096 mmol) in dry dichloromethane (5 mL) and $\text{Ag}[\text{BF}_4]$ (18.7 mg, 0.096 mmol) in MeOH (1 mL). Purification and crystallization as described above produced 6^{Cy} as an orange crystalline solid. Yield: 51 mg (80%).

^1H NMR (400 MHz, CDCl_3 , 25°C): δ = 7.87 (t, J = 6.7 Hz, 1 H, NH), 5.71 (qi, J = 9.9 Hz, 1 H, C_3H_5), 4.96 (br m, 2 H, Cp), 4.74 (br m, 2 H, Cp), 4.62 (br d, J = 6.6 Hz, 2 H, CH_2), 4.53 (br m, 2 H, Cp), 4.41 (br m, 2 H, Cp), 4.00-3.20 (very br s, 2 H, C_3H_5), 3.20-2.50 (very br s, 2 H, C_3H_5), 2.09-1.65 (m, 11 H, Cy), 1.41-1.09 (m, 11 H, Cy) ppm. $^{31}\text{P}\{^1\text{H}\}$ NMR (161 MHz, CDCl_3 , 25°C): δ = 27.3 (s) ppm. The data agree with those found in the literature.^{9c}

Synthesis of 7^{Ph} . Solids $[\text{Pd}(\mu\text{-Cl})(\eta^3\text{-C}_3\text{H}_5)]_2$ (56.0 mg, 0.15 mmol) and 2^{Ph} (216.2 mg, 0.30 mmol) were dissolved in dry dichloromethane (10 mL). After stirring for 30 min, a solution of $\text{Ag}[\text{BF}_4]$ (59.6 mg, 0.30 mmol) in MeOH (1.5 mL) was added, resulting in the separation of an off-white solid (AgCl) and a colour change from orange to orange-brown. The resulting mixture was stirred for 1 h and filtered through a cotton plug. The filtrate was evaporated and re-dissolved in dichloromethane (10 mL). The solution was washed three times with 10 mL of distilled water to remove $\text{Et}_3\text{NH}[\text{BF}_4]$, dried over magnesium sulfate, and evaporated. The residue was dissolved in dichloromethane/methanol (20:1) and filtered through a pad of silica gel. The filtrate was evaporated, and the residue was crystallized by dissolving in dichloromethane/methanol (20:1, 5 mL) and layering with pentane (ca. 15 mL). The crystals, which separated for several days, were filtered off and dried under vacuum to give 7^{Ph} as an orange crystalline solid. Yield: 196 mg (85%).

^1H NMR (400 MHz, CDCl_3 , 25°C): δ = 7.84-7.75 (m, 2 H, Ph), 7.53-7.47 (m, 3 H, Ph), 7.37-7.24 (m, 3 H, Ph), 7.06-6.98 (m, 2 H, Ph), 6.62 (dd, J = 10.8, 2.2 Hz, 1 H, NH), 5.79 (br s, 1 H, C_3H_5), 5.63 (br s, 1 H, Cp), 5.30 (dd, J = 13.6, 11.0 Hz, 1 H, C_3H_5), 4.77 (br s, 1 H, Cp), 4.71 (dd, J = 2.7, 1.4 Hz, 1 H, Cp), 4.27 (dd, J = 2.6, 1.8 Hz, 1 H,

Lorsqu'un écrit scientifique issu d'une activité de recherche financée au moins pour moitié par des dotations de l'État, des collectivités territoriales ou des établissements publics, par des subventions d'agences de financement nationales ou par des fonds de l'Union européenne est publié dans un périodique paraissant au moins une fois par an, son auteur dispose, même après avoir accordé des droits exclusifs à un éditeur, du droit de mettre à disposition gratuitement dans un format ouvert, par voie numérique, sous réserve de l'accord des éventuels coauteurs, la version finale de son manuscrit acceptée pour publication, dès lors que l'éditeur met lui-même celle-ci gratuitement à disposition par voie numérique ou, à défaut, à l'expiration d'un délai courant à compter de la date de la première publication. Ce délai est au maximum de six mois pour une publication dans le domaine des sciences, de la technique et de la médecine et de douze mois dans celui des sciences humaines et sociales.

Cp), 4.17 (dd, $J = 2.5, 1.6$ Hz, 1 H, Cp), 4.10-2.50 (very br s, 1 H, C_3H_5 or CH_2SO_3), 3.97 (dd, $J = 13.7, 2.6$ Hz, 1 H, C_3H_5), 3.72 (td, $J = 2.1, 1.4$ Hz, 1 H, Cp), 1.37 (s, 9 H, *t*Bu), 0.82 (s, 9 H, *t*Bu) ppm. 1H NMR (400 MHz, $CDCl_3$, 50°C): $\delta = 7.84$ -7.77 (m, 2 H, Ph), 7.51-7.47 (m, 3 H, Ph), 7.36-7.24 (m, 3 H, Ph), 7.06-6.99 (m, 2 H, Ph), 6.54 (dd, $J = 11.1, 2.1$ Hz, 1 H, NH), 5.78 (qi, $J = 9.8$ Hz, 1 H, C_3H_5), 5.64 (dt, $J = 3.0, 1.5$ Hz, 1 H, Cp), 5.27 (dd, $J = 13.6, 10.9$ Hz, 1 H, C_3H_5), 4.75 (br s, 1 H, Cp), 4.70 (dd, $J = 2.8, 1.4$ Hz, 1 H, Cp), 4.25 (dd, $J = 2.7, 1.7$ Hz, 1 H, Cp), 4.16 (dd, $J = 2.5, 1.6$ Hz, 1 H, Cp), 3.95 (dd, $J = 13.6, 2.6$ Hz, 1 H, C_3H_5), 3.73 (td, $J = 2.2, 1.4$ Hz, 1 H, Cp), 4.40 - 3.22 (very br s, 1 H, C_3H_5 or CH_2SO_3), 1.37 (s, 9 H, *t*Bu), 0.83 (s, 9 H, *t*Bu) ppm. At both temperatures, the signals of three hydrogen atoms from C_3H_5 and CH_2SO_3 could not be unequivocally identified due to extensive broadening. $^{31}P\{^1H\}$ NMR (161 MHz, $CDCl_3$, 25°C): $\delta = 14.2$ (s) ppm. FTIR (DRIFTS, KBr): $\nu_{max} = 3504$ w, 3441 w, 3339 w, 3097 w, 3058 w, 2963 m, 2905 w, 2867 w, 1643 m, 1526 m, 1482 m, 1459 w, 1435 m, 1400 w, 1365 m, 1314 w, 1270 m, 1258 s, 1214 w, 1179 m, 1150 vs, 1097 w, 1080 w, 1013 m, 973 w, 920 w, 856 w, 824 w, 750 m, 728 w, 704 w, 697 s, 616 w, 588 w, 560 w, 539 m, 524 m, 509 s, 493 m, 481 m, 440 w cm^{-1} . Anal. Calc. for $C_{35}H_{42}NFeO_4PPdS \cdot 0.8CH_2Cl_2$ (833.96): C 51.56, H 5.27, N 1.68%. Found: C 51.42, H 5.43, N 1.72%. The amount of residual solvent was confirmed by NMR analysis (δ_H 5.30). HR ESI-MS calc. for $C_{35}H_{42}FeNNaO_4PPdS$ ($[M + Na]^+$): 788.08486, found: 788.08674.

Synthesis of 7^{Cy} . Compound 7^{Cy} was prepared in an analogous manner starting from 2^{Cy} (219.9 mg, 0.30 mmol). Crystallization by dissolving the crude product in dichloromethane/methanol (20/1, 3 mL) and layering with pentane (10 mL) provided 7^{Cy} as an orange-red crystalline solid. Yield: 194 mg (83%).

1H NMR (400 MHz, $CDCl_3$, 25°C): $\delta = 6.99$ (br s, 1 H, NH), 5.70 (qi, $J = 9.5$ Hz, 1 H, C_3H_5), 5.26 (dt, $J = 2.8, 1.5$ Hz, 1 H, Cp), 5.13 (dd, $J = 13.6, 10.5$ Hz, 1 H, C_3H_5), 4.80 (br s, 1 H, Cp), 4.73 (br s, 1 H, Cp), 4.32 (dd, $J = 2.7, 1.8$ Hz, 1 H, Cp), 4.24 (br s, 1 H, Cp), 4.14 (dd, $J = 2.4, 1.6$ Hz, 1 H, Cp), 3.97 (dd, $J = 13.6, 2.0$ Hz, 1 H, C_3H_5), 3.49 (br s, 2 H, CH_2SO_3), 2.68-2.58 (m, 1 H, Cy), 1.33 (s, 9 H, *t*Bu), 1.23 (s, 9 H, *t*Bu), 2.20-0.64 (m, 21 H, Cy) ppm. Two signals with integral intensities corresponding to two hydrogen atoms at C_3H_5 were not observed due to broadening. 1H NMR (400 MHz, $CDCl_3$, 50°C): $\delta = 6.74$ (br d, $J = 10.7$ Hz, 1 H, NH), 5.67 (qi, $J = 9.9$ Hz, 1 H, C_3H_5), 5.28 (dt, $J = 2.8, 1.5$ Hz, 1 H, Cp), 5.12 (dd, $J = 13.6, 10.6$ Hz, 1 H, C_3H_5), 4.80-4.04 (very br s, 1 H, C_3H_5), 4.75 (dd, $J = 2.7, 1.4$ Hz, 1 H, Cp), 4.72 (t, $J = 1.6$ Hz, 1 H, Cp), 4.30 (dd, $J = 2.7, 1.8$ Hz, 1 H, Cp), 4.23 (dt, $J = 2.5, 1.2$ Hz, 1 H, Cp), 4.14 (dd, $J = 2.5, 1.6$ Hz, 1 H, Cp), 4.04 - 3.31 (very br s, 1 H, C_3H_5), 3.94 (dd, $J = 13.5, 2.9$ Hz, 1 H, C_3H_5), 3.48 (br s, 2 H, CH_2SO_3), 2.66-2.57 (m, 1 H, Cy), 2.24-0.70 (m, 21 H, Cy), 1.34 (s, 9 H, *t*Bu), 1.24 (s, 9 H, *t*Bu) ppm. $^{31}P\{^1H\}$ NMR (161 MHz, $CDCl_3$, 25°C): $\delta = 27.2$ (br s) ppm. FTIR (DRIFTS, KBr): $\nu_{max} = 3599$ w, 3450 w, 3240 m, 3102 w, 3062 w, 2958 m, 2930 s, 2853 m, 1644 w, 1574 s, 1484 w, 1456 m, 1448 m, 1407 w, 1389 w, 1365 m, 1332 m, 1290 w, 1271 m, 1223 m, 1197 m, 1178 s, 1155 m, 1114 w, 1092 w, 1038 m, 1007 w, 966 w, 918 w, 907 w, 890 w, 855 w, 831 w, 813 w, 771 w, 746 m, 679 w, 616 m, 592 w, 539 w, 525 m, 508 m, 493 m, 478 w cm^{-1} . Anal. Calc. for $C_{35}H_{54}NFeO_4PPdS \cdot 0.3CH_2Cl_2$ (803.6): C 52.76, H 6.85, N 1.74%. Found: C 52.85, H 6.84, N 1.56%. The amount of residual solvent was confirmed by NMR analysis (δ_H 5.30). HR ESI-MS calc. for $C_{27}H_{26}NNaPO_4FeSPd$ ($[M + Na]^+$): 800.17876, found: 800.18026.

Catalytic Experiments. In air, the preformed catalyst 7^R or 6^R (1 mol.% based on indole) was placed into a Schlenk tube equipped with a stirring bar, followed by indole (58.6 mg, 0.50 mmol) and $KHCO_3$ as the base (150 mg, 1.50 mmol; 3 equiv.). Solid iodoarenes (0.60 mmol, 1.2 equiv) were added at this stage before deoxygenating the solid mixture through three vacuum/argon cycles. Liquid iodoarenes were added by syringe after deoxygenation. Next, 2 mL of degassed water (bubbled for 30 min with argon) were added and the Schlenk tube was transferred into a preheated oil bath (100±2°C) and stirred for 24 h. All reactions were clearly biphasic, potentially limiting the mass transfer, which was also the limitation for the conversion. The reaction was terminated by cooling to room temperature and adding dichloromethane (5 mL). The organic phase was separated, and the water phase was washed two times using 5 mL of dichloromethane. The combined organic phases were dried over $MgSO_4$ and evaporated after filtration. The resulting crude products were dissolved in DMSO- d_6 and analysed by NMR spectroscopy.

X-ray Crystallography. Full-sphere diffraction data ($\pm h \pm k \pm l$, $\theta_{max} = 27.5^\circ$) were collected with a Bruker D8 VENTURE Kappa Duo diffractometer equipped with a Cryostream Cooler (Oxford Cryosystems) using $CuK\alpha$ ($\lambda = 1.54178$ Å; only for $2^{Cy} \cdot BH_3$) or $MoK\alpha$ ($\lambda = 0.71073$ Å; all other compounds) radiation. The structures were obtained using direct methods (SHELXT, recent version²³) and subsequently refined by full-matrix least-squares based on F^2 (SHELXL-2017²⁴). Nonhydrogen atoms were refined with anisotropic displacement parameters. Amide NH (except for $6^{Ph} \cdot C \cdot CH_2Cl_2 \cdot MeOH$) and BH_3 hydrogens were identified on the difference electron density maps and refined as riding atoms with $U_{iso}(H)$ set to $1.2U_{eq}$ of their bonding atom. Hydrogen atoms in the CH_n groups were placed in their theoretical positions and refined similarly. Particular details are as follows.

Compound $2^{Cy} \cdot BH_3$ crystallised as a three-component, non-merohedral twin. The refined contributions of the three domains were approximately 0.661:0.214:0.125. In the structure of 2^{Ph} , one ethyl substituent of the Et_3NH^+ cation had to be refined over two positions due to disorder. Similarly, the allyl moieties in all $Pd(\eta^3\text{-allyl})$ complexes reported here were disordered and had to be modelled over two positions, rotated approximately 180° along the Pd-allyl axis. The solvent molecules in the structure of $7^{Cy} \cdot 0.125CH_2Cl_2 \cdot 0.875 MeOH$ occupy the same space and were refined so that their occupancies sum up to 1. Lastly, the solvent molecules in the structures of $6^{Ph} \cdot C \cdot CH_2Cl_2 \cdot MeOH$ and $6^{Ph} \cdot S \cdot 1.5CHCl_3$ were disordered within structural voids and could not be satisfactorily incorporated in the structure model. Therefore, their contribution to the overall scattering was eliminated using PLATON SQUEEZE.²⁵ The removed electron density was in good agreement with the expected value (106 electrons for $6^{Ph} \cdot C \cdot CH_2Cl_2 \cdot MeOH$ with 120 expected, and 696 electrons for $6^{Ph} \cdot S \cdot 1.5CHCl_3$ with 696 electrons expected).

Selected crystallographic data and refinement parameters are available as Supporting Information, Table S1. All geometric data and structural diagrams were obtained using a recent version of the PLATON program.²⁶ The numerical values were rounded to one decimal place with respect to their estimated standard deviations (ESDs). Parameters pertaining to atoms in geometrically constrained positions (hydrogens) are given without ESDs.

Lorsqu'un écrit scientifique issu d'une activité de recherche financée au moins pour moitié par des dotations de l'État, des collectivités territoriales ou des établissements publics, par des subventions d'agences de financement nationales ou par des fonds de l'Union européenne est publié dans un périodique paraissant au moins une fois par an, son auteur dispose, même après avoir accordé des droits exclusifs à un éditeur, du droit de mettre à disposition gratuitement dans un format ouvert, par voie numérique, sous réserve de l'accord des éventuels coauteurs, la version finale de son manuscrit acceptée pour publication, dès lors que l'éditeur met lui-même celle-ci gratuitement à disposition par voie numérique ou, à défaut, à l'expiration d'un délai courant à compter de la date de la première publication. Ce délai est au maximum de six mois pour une publication dans le domaine des sciences, de la technique et de la médecine et de douze mois dans celui des sciences humaines et sociales.

DFT Calculations. Density functional theory calculations were performed using Gaussian 16, revision C.01.²⁷ The reported energies correspond to Gibbs free energies obtained after full geometry optimizations, starting from atomic coordinates determined by X-ray diffraction analysis where possible (the more populated orientation of the π -coordinated allyl group was used), using PBEo density functional²⁸ combined with the Stuttgart-Dresden core potential²⁹ for Fe and Pd and Jul-cc-pVDZ³⁰ basis set for the remaining atoms. The solvent effects were approximated using the polarised continuum model (PCM).¹⁸ Cartesian coordinates of the DFT optimized structures are available in the Supporting Information.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <http://pubs.acs.org/doi/10.1021/acs.organomet. XXXX>

FTIR spectra of **6^{Ph}-C** and **6^{Ph}-S**, additional structural data and structure diagrams, summary of relevant crystallographic parameters (Table S1), and copies of the NMR spectra (PDF)

Cartesian coordinates of the DFT optimized structures (XYZ)

Accession Codes

CCDC 2077801-2077807 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, 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.

AUTHOR INFORMATION

Corresponding Authors

Petr Štěpnička – Department of Inorganic Chemistry, Faculty of Science, Charles University, Hlavova 2030, 128 40 Prague, Czech Republic; orcid.org/0000-0002-5966-0578; E-mail address: petr.stepnicka@natur.cuni.cz

Jean-Cyrille Hierso – Institut de Chimie Moléculaire de l'Université de Bourgogne (ICMUB) UMR CNRS 6302, Université Bourgogne Franche-Comté (UBFC), 9 avenue Alain Savary, 21078 Dijon, France; orcid.org/0000-0002-2048-647X; E-mail address: jean-cyrille.hierso@u-bourgogne.fr

Authors

Petr Vosáhl – Department of Inorganic Chemistry, Faculty of Science, Charles University, Hlavova 2030, 128 40 Prague, Czech Republic; orcid.org/0000-0003-0981-3676

Léa Radal – Institut de Chimie Moléculaire de l'Université de Bourgogne (ICMUB) UMR CNRS 6302, Université Bourgogne Franche-Comté (UBFC), 9 avenue Alain Savary, 21078 Dijon, France

Marine Labonde – Institut de Chimie Moléculaire de l'Université de Bourgogne (ICMUB) UMR CNRS 6302, Université Bourgogne Franche-Comté (UBFC), 9 avenue Alain Savary, 21078 Dijon, France

Ivana Císařová – Department of Inorganic Chemistry, Faculty of Science, Charles University, Hlavova 2030, 128 40 Prague, Czech Republic; orcid.org/0000-0002-9612-9831

Julien Roger – Institut de Chimie Moléculaire de l'Université de Bourgogne (ICMUB) UMR CNRS 6302, Université Bourgogne Franche-Comté (UBFC), 9 avenue Alain Savary, 21078 Dijon, France; orcid.org/0000-0002-4964-366X

Nadine Pirio – Institut de Chimie Moléculaire de l'Université de Bourgogne (ICMUB) UMR CNRS 6302, Université Bourgogne Franche-Comté (UBFC), 9 avenue Alain Savary, 21078 Dijon, France; orcid.org/0000-0003-4921-2912

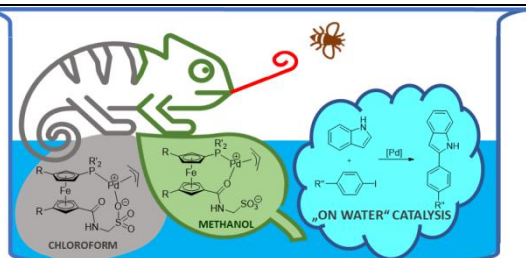
Notes

The authors declare no competing financial interests.

ACKNOWLEDGMENTS

This article is dedicated to Professor Pierre H. Dixneuf in recognition of his outstanding contributions to organometallic chemistry and catalysis. This work was supported by the Charles University Research Centre Programme (project UNCE/SCI/014). Computational resources were provided by the project "e-Infrastruktura CZ" (e-INFRA LM2018140) falling within the scheme Projects of Large Research, Development and Innovations Infrastructures. P. V. also thanks the Foundation of Faculty of Science, Charles University for supporting his stay in Dijon. In Dijon, this work was supported by the ANR-PRC 2016 programme (ALCATRAS, ANR-16-CE07-0001-01), the CNRS, Université de Bourgogne, Conseil Régional de Bourgogne through the plan d'actions régional pour l'innovation (PARI), and the fonds européen de développement régional (FEDER). The authors also thank Dr. R. Gyepes from the Department of Inorganic Chemistry, Faculty of Science, Charles University for valuable suggestions regarding DFT computations. Thanks are also due to Dr. H. Catey from Institut de Chimie Moléculaire de l'Université de Bourgogne, Université Bourgogne Franche-Comté for complementary crystallographic measurements.

REFERENCES



1. *Catalysis: From Principles to Applications*, Beller, M.; Renken, A.; van Santen, R. A.; Eds., Wiley-VCH: Weinheim, 2012.
2. *Phosphorus(III) Ligands in Homogeneous Catalysis: Design and Synthesis*, Kamer, P. C. J.; van Leeuwen, P. W. N. M.; Eds., Wiley: Chichester, 2012.
3. (a) Bader, A.; Lindner, E. Coordination chemistry and catalysis with hemilabile oxygen-phosphorus ligands. *Coord. Chem. Rev.* **1991**, *108*, 27-110; (b) Slone, C. S.; Weinberger, D. A.; Mirkin, C. A. The Transition Metal Coordination Chemistry of Hemilabile Ligands. *Progr. Inorg. Chem.* **1999**, *48*, 233-350.
4. (a) *Aqueous-Phase Organometallic Chemistry*, Cornils, B.; Herrmann, W. A.; Eds., 2nd ed., Wiley-VCH: Weinheim, 2004; (b) Pinault, N.; Bruce, D. W. Homogeneous catalysts based on water-soluble phosphines. *Coord. Chem. Rev.* **2003**, *241*, 1-25; (c) Shaughnessy, K. H. Hydrophilic Ligands and Their Application in Aqueous-Phase Metal-Catalyzed Reactions. *Chem. Rev.* **2009**, *109*, 643-710; (d) Butler, R. N.; Coyne, A. G. Water: Nature's Reaction Enforcer—Comparative Effects for Organic Synthesis "In-Water" and "On-Water". *Chem. Rev.* **2010**, *110*, 6302-6337; (e) Kitanosono, T.; Masuda, K.; Xu, P.; Kobayashi, S. Catalytic Organic Reactions in Water toward Sustainable Society. *Chem. Rev.* **2018**, *118*, 679-746.
5. (a) Montalbetti, C. A. G. N.; Falque, V. Amide bond formation and peptide coupling. *Tetrahedron* **2005**, *61*, 10827-10852; (b) El-Faham, A.; Albericio, F. Peptide Coupling Reagents, More than a Letter Soup. *Chem. Rev.* **2011**, *111*, 6557-6602.
6. Schulz, J.; Císařová, I.; Štěpnička, P. Phosphinoferrocene Amidosulfonates: Synthesis, Palladium Complexes, and Catalytic Use in Pd-Catalyzed Cyanation of Aryl Bromides in an Aqueous Reaction Medium. *Organometallics* **2012**, *31*, 729-738.
7. For alternative approaches toward the synthesis of phosphino-amidosulfonates, see: (a) Nuzzo, R. G.; Feitler, D.; Whitesides, G. M. Water-soluble complexes of tertiary phosphines and rhodium(I) as homogeneous catalysts. *J. Am. Chem. Soc.* **1979**, *101*, 3683-3685; (b) Nuzzo, R.; Haynie, S. L.; Wilson, M. E.; Whitesides, G. M. Synthesis of functional chelating diphosphines containing the bis[2-(diphenylphosphino)ethyl]amino moiety and the use of these materials in the preparation of water-soluble diphosphine complexes of transition metals. *J. Org. Chem.* **1981**, *46*, 2861-2867; (c) Fremy, G.; Castanet, Y.; Grzybek, R.; Monflier, E.; Morteux, A.; Trzeciak, A. M.; Ziolkowski, J. J. A new, highly selective, water-soluble rhodium catalyst for methyl acrylate hydroformylation. *J. Organomet. Chem.* **1995**, *505*, 11-16; (d) Lavenot, L.; Bortoletto, M. H.; Roucoux, A.; Larpent, C.; Patin, H. Synthesis of new hydrophilic phosphines by addition of diphenylphosphine on activated alkenes: characterization of their rhodium complexes. *J. Organomet. Chem.* **1996**, *509*, 9-14.
8. (a) Štěpnička, P. Phosphino-carboxamides: the inconspicuous gems. *Chem. Soc. Rev.* **2012**, *41*, 4273-4305; (b) Štěpnička, P. Coordination and catalytic chemistry of phosphinoferrocene carboxamides. *Coord. Chem. Rev.* **2017**, *353*, 223-246.
9. (a) Schulz, J.; Císařová, I.; Štěpnička, P. Synthesis of an amidosulfonate-tagged biphenyl phosphine and its application in the Suzuki-Miyaura reaction affording biphenyl-substituted amino acids in water. *J. Organomet. Chem.* **2015**, *796*, 65-72; (b) Schulz, J.; Horký, F.; Štěpnička, P. Different Performance of Two Isomeric Phosphinobiphenyl Amidosulfonates in Pd-Catalyzed Cyanation of Aryl Bromides. *Catalysts* **2016**, *6*, 182; (c) Schulz, J.; Horký, F.; Císařová, I.; Štěpnička, P. Synthesis, Structural Characterization and Catalytic Evaluation of Anionic Phosphinoferrocene Amidosulfonate Ligands. *Catalysts* **2017**, *7*, 167.
10. (a) *Ferrocenes: Homogeneous Catalysis, Organic Synthesis, Materials Science*, Togni, A.; Hayashi, T.; Eds., VCH: Weinheim, 1995; (b) *Ferrocenes: Ligands, Materials and Biomolecules*, Štěpnička, P.; Ed.; Wiley: Chichester, 2008; (c) Atkinson, R. C. J.; Gibson, V. C.; Long, N. J. The syntheses and catalytic applications of unsymmetrical ferrocene ligands. *Chem. Soc. Rev.* **2004**, *33*, 313-328; (d) Gómez Arrayás, R.; Adrio, J.; Carretero, J. C. Recent applications of chiral ferrocene ligands in asymmetric catalysis. *Angew. Chem. Int. Ed.* **2006**, *45*, 7674-7715.
11. (a) Mom, S.; Beaupérin, M.; Roy, D.; Royer, S.; Amardeil, R.; Cattey, H.; Doucet, H.; Hierso, J.-C. Congested ferrocenyl polyphosphines bearing electron-donating or electron-withdrawing phosphanyl groups: assessment of metallocene conformation from NMR spin couplings and use in palladium-catalyzed chloroarenes activation. *Inorg. Chem.* **2011**, *50*, 11592-11603; (b) Thomas, D. A.; Ivanov, V. V.; Butler, I. R.; Horton, P. N.; Meunier, P.; Hierso, J.-C. Coordination Chemistry of Tetra- and Tridentate Ferrocenyl Polyphosphines: An Unprecedented [1,1'-Heteroannular and 2,3-Homoannular]-Phosphorus-Bonding Framework in a Metallocene Dinuclear Coordination Complex. *Inorg. Chem.* **2008**, *47*, 1607-1615; (c) Beaupérin, M.; Smaliy, R.; Cattey, H.; Meunier, P.; Ou, J.; Toy, P. H.; Hierso, J.-C. Modular functionalized polyphosphines for supported materials: previously unobserved ³¹P-NMR ABCD spin systems and heterogeneous palladium-catalyzed C-C and C-H arylation. *Chem. Commun.* **2014**, *50*, 9505-9508.
12. (a) Platon, M.; Roger, J.; Royer, S.; Hierso, J.-C. Palladium C-N bond formation catalyzed by air-stable robust polydentate ferrocenylphosphines: a comparative study for the efficient and selective coupling of aniline derivatives to dichloroarene. *Catal. Sci. Tech.* **2014**, *4*, 2072-2080; (b) Roger, J.; Mom, S.; Beaupérin, M.; Royer, S.; Meunier, P.; Ivanov, V. V.; Doucet, H.; Hierso, J.-C. Direct arylation of heterocycles: the performances of ferrocene-based polyphosphane ligands in palladium-catalyzed C-H bond activation. *Chem-CatChem* **2010**, *2*, 296-305; (c) Platon, M.; Wijaya, N.; Rampazzi, V.; Cui, L.; Rousselin, Y.; Saeys, M.; Hierso, J.-C. Thioetherification of Chloroheteroarenes: A Binuclear Catalyst Promotes Wide Scope and High Functional-Group Tolerance. *Chem. Eur. J.* **2014**, *20*, 12584-12594.

13. (a) Evrard, D.; Lucas, D.; Mugnier, Y.; Meunier, P.; Hierso, J.-C. On the Mechanistic Behavior of Highly Efficient Palladium-Tetrakisphosphine Catalytic Systems for Cross-Coupling Reactions: First Spectroscopic and Electrochemical Studies of Oxidative Addition on Pd(0)/Multidentate Ferrocenylpolyphosphine Complexes. *Organometallics* **2008**, *27*, 2643-2653; (b) Zinovyeva, V. A.; Mom, S.; Fournier, S.; Devillers, C. H.; Catey, H.; Doucet, H.; Hierso, J.-C.; Lucas, D. Kinetic and Electrochemical Studies of the Oxidative Addition of Demanding Organic Halides to Pd(0): the Efficiency of Polyphosphane Ligands in Low Palladium Loading Cross-Couplings Decrypted. *Inorg. Chem.* **2013**, *52*, 11923-11933.
14. (a) Chanda, A.; Fokin, V. V. Organic Synthesis "On Water". *Chem. Rev.* **2009**, *109*, 725-748; (b) Kitanosono, T.; Kobayashi, S. Reactions in Water Involving the "On-Water" Mechanism. *Chem. Eur. J.* **2020**, *26*, 9408-9429.
15. Lerayer, E.; Renaut, P.; Roger, J.; Pirio, N.; Catey, H.; Devillers, C.-H.; Lucas, D.; Hierso, J.-C. A general diastereoselective synthesis of highly functionalized ferrocenyl amphiphiles enabled on a large scale by electrochemical purification. *Chem. Commun.* **2017**, *53*, 6017-6020.
16. Radal, L.; Vosáňho, P.; Roger, J.; Catey, H.; Amardeil, H.; Čisáňová, I.; Štěpnička, P.; Pirio, P.; Hierso, J.-C. Highly functionalized Brønsted acidic/Lewis basic hybrid ferrocene ligands: synthesis and coordination chemistry. *Eur. J. Inorg. Chem.* **2019**, 865-874.
17. Imamoto, T.; Oshiki, T.; Onozawa, T.; Kusumoto, T.; Sato, K. Synthesis and Reaction of phosphine-Boranes. Synthesis of New Bidentate Ligands with Homochiral Phosphine Centers via Optically Pure Phosphine-Boranes. *J. Am. Chem. Soc.* **1990**, *112*, 5244-5252 and ref. 9c.
18. Tomasi, J.; Mennucci, B.; Cammi, R. Quantum Mechanical Continuum Solvation Models. *Chem. Rev.* **2005**, *150*, 2999-3093.
19. (a) Aullón, G.; Alvarez, S. Axial Bonding Capabilities of Square Planar d⁸-ML₄ Complexes. Theoretical Study and Structural Correlations. *Inorg. Chem.* **1996**, *35*, 3137-3144.
20. (a) Platon, M.; Amardeil, R.; Djakovitch, L.; Hierso, J.-C. Progress in palladium-based catalytic systems for the sustainable synthesis of annulated heterocycles: a focus on indole backbones. *Chem. Soc. Rev.* **2012**, *41*, 3929-3968; (b) Humphrey, G. R.; Kuethe, J. T. Practical Methodologies for the Synthesis of Indoles. *Chem. Rev.* **2006**, *106*, 2875-2911; (c) Krüger, K.; Tillack, A.; Beller, M. Catalytic Synthesis of Indoles from Alkynes. *Adv. Synth. Catal.* **2008**, *350*, 2153-2167; (d) R. Vicente. Recent advances in indole syntheses: New routes for a classic target. *Org. Biomol. Chem.* **2011**, *9*, 6469-6480.
21. Cacchi, S.; Fabrizi, G. Synthesis and Functionalization of Indoles Through Palladium-catalyzed Reactions. *Chem. Rev.* **2005**, *105*, 2873-2920.
22. (a) Yamaguchi, A. D.; Itami, K. C-H Bond Functionalization: Emerging Synthetic Tools for Natural Products and Pharmaceuticals. *Angew. Chem. Int. Ed.* **2012**, *51*, 8960-9009; (b) Moncea, O.; Poincot, D.; Fokin, A. A.; Schreiner, P. R.; Hierso, J.-C. Palladium-Catalyzed C₂-H Arylation of Unprotected (N-H)-Indoles "On Water" Using Primary Diamantyl Phosphine Oxides as a Class of Primary Phosphine Oxide Ligands. *ChemCatChem* **2018**, *10*, 2915-2922. For examples exploiting substituted indoles and different arylating agents, see: (c) Y. Zhu, M. Bauer, L. Ackermann. Late-Stage Peptide Diversification by Bioorthogonal Catalytic C-H Arylation at 23 °C in H₂O. *Chem. Eur. J.* **2015**, *21*, 9980-9983; (d) A. J. Reay, L. A. Hammarback, J. T. W. Bray, T. Sheridan, D. Turnbull, A. C. Whitwood, I. J. S. Fairlamb. Mild and Regioselective Pd(OAc)₂-Catalyzed C-H Arylation of Tryptophans by [ArN₂]⁺X⁻, Promoted by Tosic Acid. *ACS Catal.* **2017**, *7*, 5174-5179; (e) N. Vasudevan, E. Wimmer, E. Barré, D. Cortés-Borda, M. Rodríguez-Zubiri, F.-X. Felpin. Direct C-H Arylation of Indole-3-Acetic Acid Derivatives Enabled by an Autonomous Self-Optimizing Flow Reactor. *Adv. Synth. Catal.* **2021**, *363*, 791-799.
23. Sheldrick, G. M. *SHELXT* - Integrated space-group and crystal-structure determination. *Acta Crystallogr., Sect. A: Found. Adv.* **2015**, *71*, 3-8.
24. Sheldrick, G. M. Crystal structure refinement with *SHELXL*. *Acta Crystallogr., Sect. C: Struct. Chem.* **2015**, *71*, 3-8.
25. Spek, A. L. *PLATON SQUEEZE*: a tool for the calculation of the disordered solvent contribution to the calculated structure factors. *Acta Crystallogr., Sect. C: Struct. Chem.* **2015**, *71*, 9-18.
26. (a) Spek, A. L. Single-crystal structure validation with the program *PLATON*. *J. Appl. Crystallogr.* **2003**, *36*, 7-13; (b) Spek, A. L. Structure validation in chemical crystallography. *Acta Crystallogr. D, Biol. Crystallogr.* **2009**, *65*, 148-155.
27. Gaussian 16, Revision C.01, M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, G. A. Petersson, H. Nakatsuji, X. Li, M. Caricato, A. V. Marenich, J. Bloino, B. G. Janesko, R. Gomperts, B. Mennucci, H. P. Hratchian, J. V. Ortiz, A. F. Izmaylov, J. L. Sonnenberg, D. Williams-Young, F. Ding, F. Lipparini, F. Egidi, J. Goings, B. Peng, A. Petrone, T. Henderson, D. Ranasinghe, V. G. Zakrzewski, J. Gao, N. Rega, G. Zheng, W. Liang, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, K. Throssell, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. J. Bearpark, J. J. Heyd, E. N. Brothers, K. N. Kudin, V. N. Staroverov, T. A. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. P. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, J. M. Millam, M. Klene, C. Adamo, R. Cammi, J. W. Ochterski, R. L. Martin, K. Morokuma, O. Farkas, J. B. Foresman, and D. J. Fox, Gaussian, Inc., Wallingford CT, 2016.
28. Adamo, C.; Barone, V. Toward reliable density functional methods without adjustable parameters: The PBE0 model. *J. Chem. Phys.* **1999**, *110*, 6158-6170.
29. (a) Dolg, M.; Wedig, U.; Stoll, H.; Preuss, H. Energy-adjusted *ab initio* pseudopotentials for the first row transition elements. *J. Chem. Phys.* **1987**, *86*, 866-872; (b) Andrae, D.; Häussermann, U.; Dolg, M.; Stoll, H.; Preuss, H. Energy-adjusted *ab initio* pseudopotentials for the second and third row transition elements. *Theor. Chim. Acta* **1990**, *77*, 123-141.
30. Papajak, E.; Zheng, J.; Xu, X.; Leverentz, H. R.; Truhlar, D. G. Perspective on Basis Sets Beautiful: Seasonal Plantings of Diffuse Basis Functions. *J. Chem. Theory Comput.* **2011**, *7*, 3027-3034.