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Superstable Palladium(0) Complex as an Air- and Thermostable Catalyst for Suzuki Coupling Reactions

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An unprecedentedly thermo- and air-stable Pd^0 complex from readily available electron-poor trifluoromethylated phosphine was serendipitously discovered. As detailed and comparative DFT calculations indicate, the stability of the complex is associated with unusually strong ligand–ligand

Introduction

Attractive noncovalent interactions play a fundamental role in determining and maintaining the three-dimensional structure of large molecules, such as proteins and supramolecular architectures.^[1,2] They are also known to govern selective processes, such as molecular recognition and stereocontrol of organic reactions.^[3] The influence exerted by these ubiquitous interactions can vary greatly, as their overall contribution spans a wide energy range. With regard to molecules with low molecular weights, it was established that they are ancillary contributors that determine the overall molecular structure, shape, and behavior. As a result, the relevance of secondary interactions within molecules, especially intramolecular dispersion interactions, is often neglected. Nevertheless, there is growing recent evidence showing that extended attractive dispersion forces do play an important, even decisive, role in molecular chemistry by assisting or counteracting the effect of primary chemical bonds or steric repulsion.

It was recently pinpointed that aromatic π - π interactions contributed markedly to the formation of an 18-electron palladium-phosphine complex.^[4] Furthermore, CH- π and CF- π type interactions can drive the formation of structural isomers of carbene-palladium complexes,^[5] and dis-

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noncovalent interactions. The unique stability and the presence of hydrophobic structural elements of the complex offer several practical advantages, which were exploited in catalytic Suzuki–Miyaura coupling reactions.

persion interactions can induce counterintuitive steric effects in bulky carbene analogues.^[6] Additional examples reveal that secondary interactions can decisively affect chemical structure and reactivity. After introducing several *tert*-butyl groups, dispersion forces astonishingly overcome the lability of an elongated covalent bond in hexaphenyl ethane.^[7] Moreover, frustrated Lewis pairs, sterically overcrowded Lewis pairs unable to form a dative complex, still generate highly reactive bifunctional encounter complexes by attractive noncovalent interactions.^[8]

These examples stretch the boundaries of current paradigms and illuminate the need to locate and recognize additional structural elements exerting extended intramolecular attractions to advance the understanding of chemical bond and reactivity further.

Herein, we report our serendipitous finding of an unprecedentedly stable Pd^0 phosphine complex^[9] in which unusually strong noncovalent interactions between the electron-poor, CF₃-tagged phosphine ligands contribute substantially to the overall stability of the complex. This stability could be of a great practical advantage in palladium catalysis, which was demonstrated in Suzuki–Miyaura coupling reactions.

Results and Discussion

Recently, we developed a practical and cost-saving tagging approach for organocatalyst immobilization that takes advantage of the hydrophobicity of the shortest fluorous group, the trifluoromethyl group.^[10] As a continuation of this effort, we became interested in extending our recycling approach and in synthesizing the trifluoromethylated analogue of $Pd(P)_4$ ($P = PPh_3$). This latter complex is still considered as the workhorse of the palladium-catalyzed crosscoupling reactions,^[11] although myriad of more active cata-

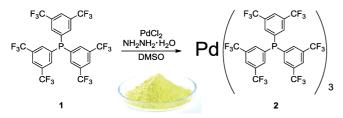
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SHORT COMMUNICATION

lyst have been developed over the last two decades.^[12] Especially, the fine-chemical industry relies on this catalyst owing to its favorable cost/reactivity relationship and easy accessibility.^[13] Nevertheless, there are several technical problems associated with the usage of $Pd(P)_4$; its air and thermosensitivity and its propensity to degrade easily upon storage. Additionally, often-observed catalyst degradation that occurs during cross-coupling reactions necessitates the employment of relatively high catalyst loadings and impairs the efficient separation of metal impurities from the product.

For the sake of catalyst recycling and removal, we selected the P[3,5-(CF₃)₂C₆H₃]₃ (1) ligand (also denoted as $\mathbf{P}^{\mathbf{F}}$) to replace \mathbf{P} , in Pd⁰ complexes. Our "a priori" ligand choice could be underpinned only by its hydrophobic character, as the poor σ -donor nature of phosphine 1 is apparently the opposite of the current trend in ligand development for palladium-catalyzed cross-coupling applications. Nevertheless, recent reports^[14–17] have validated the efficiency of electron-deficient phosphine ligands in various palladium-catalyzed reactions. In those examples, the ligands made the metal center more electron-deficient and had an accelerating effect on the rate of reductive elimination^[14] or on the concerted metalation–deprotonation step.^[15]

For the synthesis of the envisioned trifluoromethylated variant of $Pd(P)_4$, the previously developed protocol was employed.^[18] Accordingly, the addition of **1** (5 equiv.) to $PdCl_2$ in DMSO was followed by reduction with hydrazine hydrate at 120 °C (Scheme 1).



Scheme 1. Synthesis of moisture- and air-stable fluorinated Pd⁰ catalyst **2**.

Resulting bright-yellow Pd^0 complex **2** was isolated and characterized by NMR spectroscopy. Subsequently, the combination of several analytical methods was used to determine the structure and stoichiometry of complex **2**. Although elemental analysis failed owing to the incomplete combustion of the highly fluorinated compound, an unexpected 1:3 molar ratio of palladium and phosphorus was indicated by microwave plasma–atomic emission spectroscopy (MP-AES). The same stoichiometry was reinforced by the MALDI-TOF MS measurements. Finally, the structure and stoichiometry of **2** were unequivocally determined by single-crystal X-ray diffraction (Figure 1) combined with phase identification and characterization of the isolated sample by powder diffraction.

Besides the stoichiometry, the most unusual and peculiar characteristic of complex **2** was its high air and thermostability.^[19] After prolonged exposure to air and moisture at

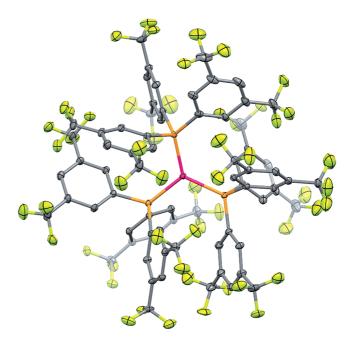
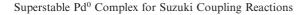


Figure 1. ORTEP style diagram of the measured X-ray structure of complex **2**. Displacement ellipsoids are drawn at the 30% probability level. Hydrogen atoms are omitted for clarity.

room temperature, the sample preserved its bright-yellow color, which was a good indicator of the quality and structural integrity of the Pd⁰ complex. An additional GLP-controlled stability test (40 °C and 75% humidity) demonstrated that complex **2** could be stored in an open vial for a longer period of time (for years) without any detectable degradation or decomposition (color; ¹H NMR, ¹⁹F NMR, and ³¹P NMR spectroscopy data; and catalytic efficiency).

We also experienced a similar trend in complex stability at higher temperature. Whereas nonfluorinated $Pd(P)_4$ decomposed in air at 98 °C in a differential scanning calorimetry analysis, fluorinated 2 had a significantly higher decomposition point (170 °C) and a rather high melting point (m.p. 225 °C) under an atmosphere of N₂. The stability of the complex, however, was not confined to the solid phase. Solution-phase NMR studies indicated the nondissociative nature of complex 2 in [D₈]THF at ambient temperature. The ³¹P NMR spectra of the complex consisted of a single signal and no formation of a tetrakis complex was observed if phosphine 1 was added to the solution of complex 2. It is also important to note that the presence of fluorine atoms influences the solubility profile of the Pd⁰ complex. Compound 2 is practically insoluble in most classical solvents (e.g., chloroform, hexanes, alcohols) at room temperature, but it is well soluble in THF.

The above data clearly indicate that the introduction of CF₃ groups into the *meta* positions of ligand **P** results in an unexpected and significant change in complex stability. To probe the origin of this enhanced stability, comparative DFT calculations were performed for the series of Pd(**P**)_n and Pd(**P**^F)_n complexes (n = 1–4). We used a dispersion-corrected density functional (B3LYP-D3) in these calculations to account reasonably for medium- and long-range



noncovalent interactions.^[20] The dissociation energies of the \mathbf{P} and \mathbf{P}^{F} phosphine ligand were computed for these series, and the results are presented in Figure 2.

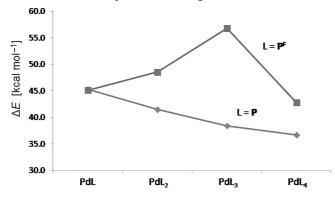


Figure 2. Variation of ligand dissociation energies computed for $Pd(P)_n$ and $Pd(P^F)_n$ complexes.

In line with previous calculations,^[4] the phosphine dissociation energies were predicted to decrease gradually in the Pd(**P**)_n series, which was born out by the trend obtained for the equilibrium Pd–P bond lengths as well (they became longer with increasing number of coordinated phosphine ligands).^[21] In contrast, the computed dissociation energies tended to increase along the Pd(**P**^F)_n series; they reached a maximum at n = 3, and the coordination of the fourth phosphine was found to be weaker again.

Calculations predicted practically identical metal-ligand bond strengths in the $Pd(\mathbf{P})$ and $Pd(\mathbf{P}^{\mathbf{F}})$ monophosphine species, and this indicates that the overall stabilization effect of the two components of the Pd-phosphine bond (ligandto-metal σ donation and metal-to-ligand π backdonation) is very similar in the two systems. The relative stabilities of the diphosphine complexes, however, differ notably [by 7 kcal mol⁻¹ in favor of Pd($\mathbf{P}^{\mathbf{F}}$)₂]. Interestingly, the Pd($\mathbf{P}^{\mathbf{F}}$)₂ complex has a bent equilibrium structure (PdP_2 was found to be linear);^[4,21] this points to significant attractive arylaryl interactions between the two PF phosphine ligands (Figure 3, a).^[22] Structural analysis revealed that in these aryl-aryl contacts, a CF₃ group interacts with the π system of a neighboring aryl unit.^[23] The interacting aryl groups display either parallel (stacking) or T-shape arrangements, as highlighted in Figure 3 (a). These structural motifs can be identified in the $Pd(\mathbf{P}^{\mathbf{F}})_3$ complex 2 as well (Figure 3, b):^[24] this implies a high degree of shape complementarity between the diphosphine complex and the P^F phosphine (1). This allows facile coordination of the third ligand and favorable ligand-ligand interactions to yield remarkable stabilization for the $Pd(\mathbf{P}^{\mathbf{F}})_3$ complex 2.^[25] The formation of the $Pd(\mathbf{P}^{\mathbf{F}})_4$ tetrakis complex was predicted to be thermodynamically feasible [the computed phosphine dissociation energy is clearly larger than that of $Pd(\mathbf{P})_4$; however, the coordination of the fourth trifluoromethylated phosphine is likely hindered kinetically, as it requires substantial structural reorganization of the coordination sphere of the extremely stable $Pd(\mathbf{P}^{\mathbf{F}})_3$ species. These results provide rationale for the experimental observation of triphosphine complex $Pd(\mathbf{P}^{\mathbf{F}})_3$ as opposed to $Pd(\mathbf{P})_4$.

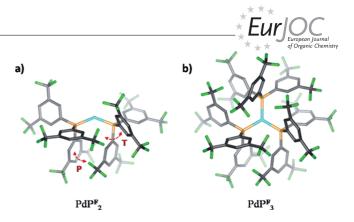


Figure 3. Optimized structures of the $Pd(\mathbf{P}^F)_2$ and $Pd(\mathbf{P}^F)_3$ complexes. Interligand aryl–aryl contacts are highlighted by red arrows (P and T refer to parallel and T-shape arrangement of the interaction aryl groups). All hydrogen atoms are omitted for clarity.

The nature and strength of intermolecular aryl-aryl contacts were further analyzed by considering arene dimer models, as depicted in Figure 4. In these models, the interacting CF₃-substituted benzene molecules are in the same arrangements as they appear in the $Pd(\mathbf{P}^{F})_{3}$ complex.^[21] The computed interaction energies in these arene dimers are -7.9 and -3.5 kcal mol⁻¹ (for model-1 and model-2, respectively), which suggests that the P-type aryl-aryl interactions represent considerably stronger stabilizing effects, but the contribution of T-type interactions is appreciable as well.^[26,27] These contacts are illustrated by noncovalent interaction plots in Figure 4.^[28] We find that the attractive feature of these contacts is predominantly due to dispersion interactions.^[21,29] Intermolecular attractive forces are also present in the $Pd(\mathbf{P})_3$ and $Pd(\mathbf{P})_4$ complexes through Ph···Ph contacts, but they are much weaker, as revealed by the interaction energies of relevant benzene dimer models $(-2.7 \text{ and } -2.5 \text{ kcal mol}^{-1} \text{ for P- and T-type dimers})$. These results suggest that the enhanced stability of the $Pd(\mathbf{P}^F)_3$ complex 2 is thus related to stabilizing interligand noncovalent interactions, which are found to be particularly strong between CF₃-substituted aryl groups.

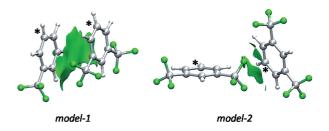


Figure 4. Truncated models of P- and T-type aryl--aryl interactions in $Pd(\mathbf{P}^{\mathbf{F}})_3$. Carbon atoms bound to phosphorus in $Pd(\mathbf{P}^{\mathbf{F}})_3$ are marked by asterisks. Green regions between the arene molecules represent stabilizing noncovalent interactions.

The structural data provided by X-ray for complex $2^{[21]}$ are in good agreement with the computed geometries. Both P- and T-type intramolecular aryl–aryl contacts can be readily identified in the X-ray structure. Furthermore, the neighboring molecules in the crystal interact predominantly through intermolecular CF··· π interactions; however, F···F

SHORT COMMUNICATION

contacts are also present. These interactions are responsible for the stability of the crystal lattice of 2.

Owing to the unique physicochemical properties of complex 2, promising catalytic performance was expected and synthetic efforts were then directed to this end. We were particularly interested in catalyst robustness in terms of decomposition under the catalytic conditions, which is still a challenge in palladium catalysis, and it is an important design criteria that impacts the overall utility of a given palladium complex in industry. As a model reaction, the Suzuki-Miyaura cross-coupling^[30] of 2-bromopyridine (3a) with an easily available boronic acid coupling partner, electron-rich dioxaborolane 4a, was chosen. Although poor catalytic performance was obtained at lower temperature, excellent results were realized under more forcing conditions (Table 1, entry 5). The requirement for elevated temperatures stems from the increased stability of the catalyst toward ligand dissociation; however, the low reactivity was also related to the poor solubility of complex 2 in the applied aqueous methanol solvent system (it starts to dissolve only at 70 °C). However, the catalyst loading could be reduced to 0.02 mol-% or even lower, and the reaction still had reasonable conversions within 1 h and reached an appreciable turnover frequency (TOF) of 4450 h^{-1} .

Table 1. Suzuki reactions of 2-bromopyridine with dioxaborolane ${\bf 4a}^{\rm [a]}$

| $ \begin{array}{c} & & OEt \\ & & & & \\ & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ & & & & $ | | | | | |
|---|------------------|---------------|----------------------|--------------------------|--|
| Entry | Catalyst [mol-%] | <i>T</i> [°C] | Conv. ^[b] | Yield ^[c] [%] | |
| 1 | 0.33 | 25 | 0 | _ | |
| 2 | 0.33 | 50 | 5 | _ | |
| 3 | 0.33 | 70 | 24 | 16 | |
| 4 | 0.33 | 90 | 60 | 47 | |
| 5 | 0.33 | 110 | >99 | 88 | |
| 6 | 0.66 | 110 | >99 | 87 | |
| 7 | 1.3 | 110 | >99 | 89 | |
| 8 | 0.02 | 110 | 91 | 89 | |
| 9 | 0.007 | 110 | 50 | 39 | |

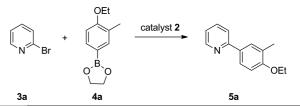
[a] Reaction conditions: A mixture of 2-bromopyridine (1 mmol), dioxaborolane **4a** (1.5 equiv.), **2** (0.33 mol-%), and K_2CO_3 (2 equiv.) in MeOH/H₂O (10:1) was stirred and heated in a test vial for 1 h. [b] Conversion was determined by GC analysis of the crude mixture by using octadecane as an internal standard. [c] Yield of isolated product.

Surprisingly, even at higher temperatures (e.g., 110 °C), no decomposition of catalyst **2** could be detected visually. Thus, the formation and occurrence of any palladium nanoparticles during the reaction was negligible (if any). Furthermore, no palladium black formation occurred, and the reaction mixture remained bright-yellow after the coupling reaction. These intriguing results highlight the thermal robustness of the complex under forcing catalytic conditions and indicate that the catalytically active form of the palladium complex [presumably the $Pd(\mathbf{P}^{\mathbf{F}})_2$ species] is stable under the applied conditions^[31] Finally, the orange

stable under the applied conditions.^[31] Finally, the orange color, the common earmark of the workup procedure of the Suzuki reactions, was not present during chromatography of the reaction mixture, and the original catalyst could be isolated.

Subsequently, extensive solvent screening was performed for the above model reaction, which revealed the general applicability of catalyst **2** in safer solvents, classified as class II and class III in industry^[32] (Table 2.). We also showed that alternative solvents,^[33] such as methylal and ethylal, could be used efficiently at lower temperatures (40– 85 °C), an observation that reinforced the importance of catalyst solubility in the applied solvents. Ultimately, the base screening indicated that both K₂CO₃ and K₃PO₄ could be employed with almost the same efficiency in the coupling reactions.

Table 2. Solvent screening in the Suzuki reactions of 2-bromopyridine with dioxaborolane ${\bf 4a}$.^[a]



| Entry | Solvent ^[b] | Base | <i>T</i> [°C] | Conv. ^[c] [%] |
|-------|------------------------|--------------------------------|---------------|--------------------------|
| 1 | EtOH ^[d] | K ₂ CO ₃ | 110 | >99 |
| 2 | DMF | K ₃ PO ₄ | 110 | >99 (88) |
| 3 | NMP | K ₃ PO ₄ | 130 | 97 (76) |
| 4 | DMSO ^[d] | K_2CO_3 | 110 | >99 (95) |
| 5 | MEK ^[d] | K_2CO_3 | 90 | 89 |
| 6 | MIBK ^[d] | K_2CO_3 | 90 | 85 |
| 7 | THF ^[d] | K_2CO_3 | 110 | 85 |
| 8 | 2-MeTHF ^[d] | K ₂ CO ₃ | 90 | 90 |
| 9 | 1,3-dioxalane | K ₃ PO ₄ | 75 | 85 |
| 10 | glycerol-formal | K ₂ CO ₃ | 110 | 97 |
| 11 | methylal | K ₃ PO ₄ | 40 | 93 |
| 12 | ethylal | K ₃ PO ₄ | 85 | 99 |

[a] Reaction conditions: A mixture of 2-bromopyridine (3a, 1 mmol), dioxaborolane 4a (1.5 equiv.), 2 (0.33 mol-%), and base (2 equiv.) in solvent (5 mL) was stirred and heated in a test vial for 1 h. [b] NMP = N-methylpyrrolidone, MEK = methyl ethyl ketone, MIBK = methyl isobutyl ketone. [c] Conversion after 24 h was determined by GC analysis of the crude mixture by using octadecane as an internal standard; conversion after 3 h is given in parenthesis. [d] Organic solvent/water (10:1) mixture was used.

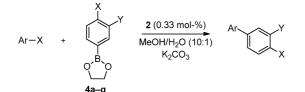
To gauge the generality of catalyst **2** in Suzuki–Miyaura reactions, a broad range of coupling reactions toward unsymmetrical biphenyls and N-containing heterocyclic biaryls were investigated (Table 3).

Gratifyingly, all these transformations proceeded smoothly within 1 h under the previously developed reaction conditions. Borolanes bearing electron-donating substituents gave slightly improved yields in the coupling reactions, but electron-withdrawing substituents did not impair the yields significantly. By using nonactivated aryl bromide **10**, bromoisoquinoline **8**, and indole derivative **6**, near quantitative yields were achieved, which confirmed the ap-



Superstable Pd⁰ Complex for Suzuki Coupling Reactions

Table 3. Suzuki reactions of aryl bromides with dioxaborolanes. $^{[\mathrm{al}],\,[\mathrm{34}]}$



| Entry | Aryl bromide | Dioxaborolane | t [min] | Product | Yield ^[b] [%] |
|-------------------|--------------|---|------------|-------------|-----------------------------|
| 1 | | $\mathbf{4b} (\mathbf{X} = \mathbf{OMe}, \mathbf{Y} = \mathbf{Me})$ | 60 | 5b | 73 |
| 2 | LBr | 4c (X = OMe, Y = OMe) | 60 | 5c | 75 |
| 3 | 3a | 4d (X = OMe, Y = H) | 60 | 5d | 58 |
| 4 | | 4e (X = Me, Y = H) | 60 | 5e | 62 |
| 5 | | $\mathbf{4f} \left(\mathbf{X} = \mathbf{F}, \ \mathbf{Y} = \mathbf{H} \right)$ | 180 | 5f | 90 |
| 6 | Br | 4a (X = OEt, Y = Me) | 60 | 7a | 93 |
| 7 | | 4b (X = OMe, Y = Me) | 60 | 7b | 90 |
| 8 | V IN H | 4c (X = OMe, Y = OMe) | 60 | 7c | 94 |
| 9 | 6 | 4d (X = OMe, Y = H) | 60 | 7d | 87 |
| 10 | | 4e (X = Me, Y = H) | 60 | 7e | 92 |
| 11 | | $\mathbf{4f} (\mathbf{X} = \mathbf{F}, \mathbf{Y} = \mathbf{H})$ | 60 | 7f | 77 |
| 12 | | 4g(X = H, Y = H) | 60 | 7g | 84 |
| 13 | Br | 4a (X = OEt, Y = Me) | 60 | 9a | 89 |
| 14 | | 4b (X = OMe, Y = Me | 60 | 9b | 85 |
| 15 | N N | 4c (X = OMe, Y = OMe) | 60 | 9c | 89 |
| 16 | 8 | 4d (X = OMe, Y = H) | 180 | 9d | 90 |
| 17 | | 4e (X = Me, Y = H) | 180 | 9e | 91 |
| 18 | | $\mathbf{4f} \left(\mathbf{X} = \mathbf{F}, \ \mathbf{Y} = \mathbf{H} \right)$ | 60 | 9f | 56 |
| 19 | Br | 4a (X = OEt, Y = Me) | 60 | 11 a | 96 |
| 20 | | $\mathbf{4b} (\mathbf{X} = \mathbf{OMe}, \mathbf{Y} = \mathbf{Me})$ | 60 | 11b | 97 |
| | 10 | | | | |
| 21 ^[c] | | $\mathbf{4b} (\mathbf{X} = \mathbf{OEt}, \mathbf{Y} = \mathbf{Me})$ | 5 | 5a | 91 |
| | 3b | | | | |

[a] Reaction conditions: A mixture of aryl halide (1 mmol), dioxaborolane (1.5 equiv.), **2** (0.33 mol-%), and K₂CO₃ (2 equiv.) in MeOH/H₂O (10:1) was stirred and heated in a test vial for 1–3 h at 110 °C. [b] Yield of isolated product. [c] Reaction was performed in a single-mode microwave reactor (Monowave 300) by using **2** (1 mol-%) and dppb (2 mol-%) as additives at 160 °C.

plicability and robustness of the catalyst. These examples indicate the viability of the catalyst in typical industrial applications.^[35]

Further exploration showed that the catalyst was not compatible with an activated Cl substituent, as in 2-chloropyridine owing to the electron-poor nature of the metal center in complex **2**. This limitation^[35] triggered us to enhance the reactivity and thermostability of the catalytic system further. We found that the catalytic activity and stability of complex **2** could be improved by using it in combination with other phosphine ligands, but especially with 1,4-bis(diphenylphosphanyl)butane (dppb). After optimizing the re-

actions conditions, the coupling of 4a with more challenging 2-chloropyridine (3b) was realized, and the product was obtained in excellent yield within only 5 min in a microwave reactor (Table 3, entry 21). Under the same microwave conditions, other dioxaborolanes were treated with 3b to provide the products in good to excellent yields (Table S4, Supporting Information).

Exploiting further the potential arising from the stability of complex 2, an advantageous formula was prepared by mixing 2 with potassium carbonate and the additive dppb and pressing the mixture into disk-shaped tablets (Figure 5). These catalyst tablets with a well-defined catalyst loading enabled the coupling reactions to be performed in a more user friendly manner, not only in terms of dosage, but also in terms of the visual indication of the reaction progress.^[36]



Figure 5. Reaction conditions for the Suzuki reaction by using preformed (0.05–3 mol-%) catalyst tablets: "1 ps. Suzuki tablet (1 mol-%)" was added to a stirred solution of **3a** (1 mmol) and **4b** (1.1 equiv.) in MeOH/H₂O (10:1), and the mixture was heated at 110 °C for 1 h.

Ultimately, an additional feature of catalyst **2** was utilized for synthetic applications. Owing to its enhanced hydrophobic nature, catalyst **2** could be adsorptively supported onto corundum.^[10] Although this immobilization is of a physical type, the catalyst could not be washed off from the solid support with aqueous methanol rinsing at 110 °C. This immobilized system was then applied as a catalyst bed in continuous flow Suzuki reactions (Figure 6.). In the presence of cesium carbonate, a simple protocol allowed the generation of biaryls **5d** and **5e** in good yields without washing the catalyst from the column.^[21] These preliminary results demonstrate another particularly attractive attribute of complex **2**.

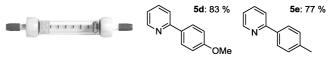


Figure 6. Flow reactions were performed by using a Syrris flow chemistry instrument equipped with a back pressure regulator. The catalyst bed was prepared from Al_2O_3 (5.7 g, 100–200 mesh, Aldrich) and catalyst **2** (64 mg, 1 mol-%), which were mixed and filled into a thermoglass column. The reactions were conducted on a 1 mmol scale at 110 °C.

Conclusions

In summary, we recognized that attractive noncovalent ligand–ligand interactions in a trifluoromethylated Pd⁰ phosphine complex can dramatically enhance the stability

SHORT COMMUNICATION

of the complex toward ligand dissociation. This "superstable" Pd⁰ system is a thermally, air, and moisture stable tricoordinate complex, and it was shown to be an efficient and robust promoter for Suzuki coupling reactions. Application of additive ligands (e.g., dppb), a user-friendly formulation, and simple immobilization techniques underline the practicality of this catalyst. Our present results may encourage further investigations to gain more insight into the role of stabilizing ligand–ligand interactions^[37] in homogeneous transition-metal catalysis, which can advance the field of catalyst developments further. Additional applications of this Pd catalyst in various cross-coupling reactions and C– H activations will be reported in due course.

Supporting Information (see footnote on the first page of this article): Experimental procedures, characterization data, spectroscopic data, theoretical calculation details, and crystallographic data.

CCDC-995867 (for Lt1 of **2**) and -995868 (for Lt2 of **2**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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Superstable Pd⁰ Complex for Suzuki Coupling Reactions

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SHORT COMMUNICATION

Superstable Palladium(0) Complex

| | / | F ₃ C | CF ₃ | | | T |
|----|------------------|-----------------------------|---------------------------------|-----------------|----------------------------|------|
| Pd | F ₃ C | F | | CF ₃ | | |
| | | Γ CF ₃ | \downarrow CF ₃ | 3 | SUPERSTABLE PRECATALYST | Pd(P |

An unprecedentedly thermo- and air-stable Pd⁰ complex from readily available electron-poor trifluoromethylated phosphine is reported. The stability of the complex is associated with unusually strong ligand–



ligand noncovalent interactions. The unique stability of the complex and the presence of hydrophobic structural elements are exploited in catalytic Suzuki–Miyaura coupling reactions.

| A. | Jakab, | Z. Dalicsek,* T. Holczbauer, | , |
|----|--------|--------------------------------|------|
| A. | Hamza | a, I. Pápai,* Z. Finta, G. Tim | ári, |
| T. | Soós* | •••••• | 1–8 |

Superstable Palladium(0) Complex as an Air- and Thermostable Catalyst for Suzuki Coupling Reactions

Keywords: Noncovalent interactions / Cross-coupling / Fluorinated ligands / Electron-deficient compounds / Palladium