# Studies on Alkyl–Nitrogen Bond Formation *via* Reductive Elimination from Monomeric Palladium Complexes in High Oxidation State

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Dedicated to Professor *Dieter Seebach* on the occasion of his 75th birthday

Oxidation of a series of defined palladium(II) complexes bearing a bidentate ligand, and a methyl and an amidato substituent was carried out with the aim to gain a better understanding of the inherent requirements for C–N bond-formation from Pd complexes in high oxidation state. This work clarified the role of the individual nitrogen sources and has important implication for alkyl–nitrogen bond-forming reactions catalyzed by Pd.

**Introduction.** – Reductive elimination from $Pd^{II}$ complexes represents a versatile reaction to induce single-bond formation [1]. Several important catalytic coupling reactions include this process as a key step [2]. In the area of C–heteroatom bond formation, the established *Buchwald–Hartwig* coupling consists of an aryl or alkenyl-nitrogen bond-formation [3][4]. As a consequence, extensive work has been devoted to the development of and the study on reductive elimination from amido-palladium(II) complexes containing aryl groups [3][1]). In sharp contrast to these accomplishments, the reductive formation of alkyl–N bonds from $Pd^{II}$ complexes represents an unsolved challenge in palladium chemistry, although there have been attempts to this end [6a][2]). As to a rare exception, *Stahl* and co-workers have reported an example of $C_{alkyl}$–N bond-formation from Pd under oxidative conditions[3]). Additional examples have become available, although no general reactivity has so far been uncovered [8][4]).

In the absence of general $Pd^{II}$-catalyzed alkyl–N coupling reactions, development of alternative approaches is warranted.

Over the past years, we have pioneered transition-metal catalysis for intramolecular diamination of alkenes [10][11]. In most of these reactions, alkyl–N bond-formation

[1]) For mechanistic studies on isolated palladium-amidate complexes, see [5].

[2]) For an attempt on reductive elimination of alkylamines from alkyl-amido-palladium complexes, see [6b].

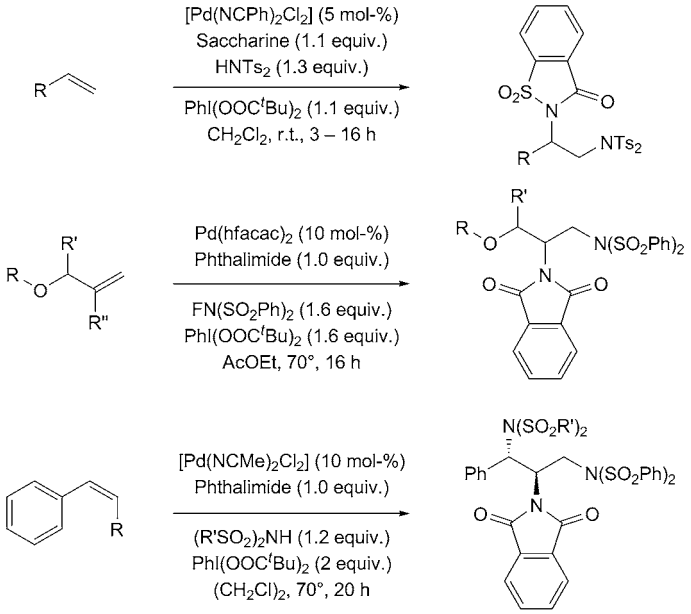
[3]) For a $C_{alkyl}$–N bond-formation from Pd under oxidative conditions, see [7].

[4]) For examples of Pd-catalyzed oxidative allylic C–H amidation, see [9].

from a $\sigma$-alkyl-Pd intermediate represents the second step of the overall process, and we have introduced Pd high-oxidation-state catalysis[5]) for its realization [13].

In addition, we have recently approached the problem of Pd-catalyzed alkyl–N bond-formation as the final step of a sequential intermolecular diamination of alkenes and have again developed suitable conditions in order to realize the final $Csp^3$–N bond formation from high-oxidation-state $Pd^{IV}$ intermediates (*Scheme 1*) [14–16]. These reactions require electron-deficient N-atoms in order to be stable under oxidative conditions and to be transferred from the coordination sphere of the $Pd^{IV}$ intermediate.

Scheme 1. *Palladium(II/IV)-Catalyzed Intermolecular Diamination of Alkenes*




Based on extensive work, we have provided conclusive evidence for this step of alkyl–N bond formation from a $Pd^{IV}$ intermediate to proceed through a transition state reminiscent of an $S_N2$ reaction [12][6]). This scenario was deduced from D-labeling studies in intramolecular diamination reactions [11b] as well as from a theoretical study on $Pd^{II/IV}$-catalyzed C–H amidation reactions [18]. It is now a generally accepted pathway for alkyl–X bond formation from high-oxidation-state Pd intermediates [19].

Our ongoing efforts to develop an intermolecular diamination of alkenes require precise knowledge on the nature of the individual nitrogen sources in alkyl–N bond-formation reactions. In particular, the involvement of two different N sources in the regioselective diamination reactions from *Scheme 1* poses the question on the role of the individual N sources throughout the process. Obviously, the more acidic bis(sulfonylimides) represent the preferred partners in the step of the $Pd^{IV}$-derived

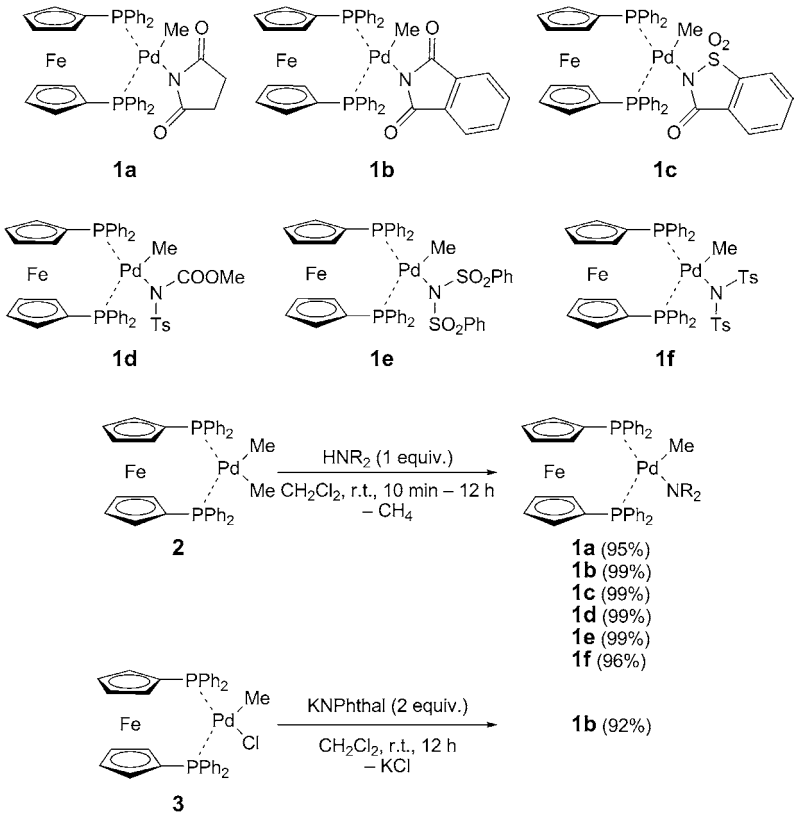
[5]) For recent reviews on $Pd^{IV}$ catalysis, see [12].

[6]) Such a scenario is reminiscent to related Pt intermediates in *Shilov* chemistry, see [17].

alkyl–N bond formation. To clarify this point, we embarked in a study on isolated (alkyl)(amidato)palladium complexes, and we present here a more detailed investigation in order to uncover the role of the N group in reductive C–N bond-formation from higher-oxidation-state Pd intermediates.

**Results and Discussion.** – In an attempt to study the context of $C_{sp3}$–N bond-forming processes from defined Pd complexes, we prepared the dppf-ligated (amidato)(methyl)palladium complexes **1a**–**1f**. Compounds **1a**–**1f** are most conveniently generated upon release of $CH_4$ *via* protonolysis of the corresponding dimethyl palladium precursor complex **2**. Alternatively, they can be obtained upon treatment of [PdCl(dppf)(Me)] (**3**) with a twofold excess of the amide salt. For example, complex **1b** can be synthesized in this way from **3** and potassium phthalimide in 98% isolated yield (*Scheme 2*).

Scheme 2. *Chemical Structures for (Amidato)(methyl)palladium Complexes* **1a**–**1f** *and Their Synthesis from Dimethyl Palladium Complex* **2** *and Chloro Methyl Palladium Complex* **3**




All six complexes, **1a**–**1f**, proved stable toward several attempts to induce direct reductive elimination under thermal conditions. This confirms that, for the present complexes, C–N bond formation from ($\sigma$-alkyl)(amidato)palladium(II) complexes is

not a feasible process, which is in agreement with the behavior of related aryl amidato–$Pd^{II}$ complexes [5a].

Two of the obtained products were characterized by X-ray analysis[7]). The resulting structures are shown in *Fig. 1*. The structures display the expected square-planar environment for the central $Pd^{II}$-atom, and very similar structural features regarding comparable individual Pd–N and Pd–$C_{methyl}$ bond lengths and angles.

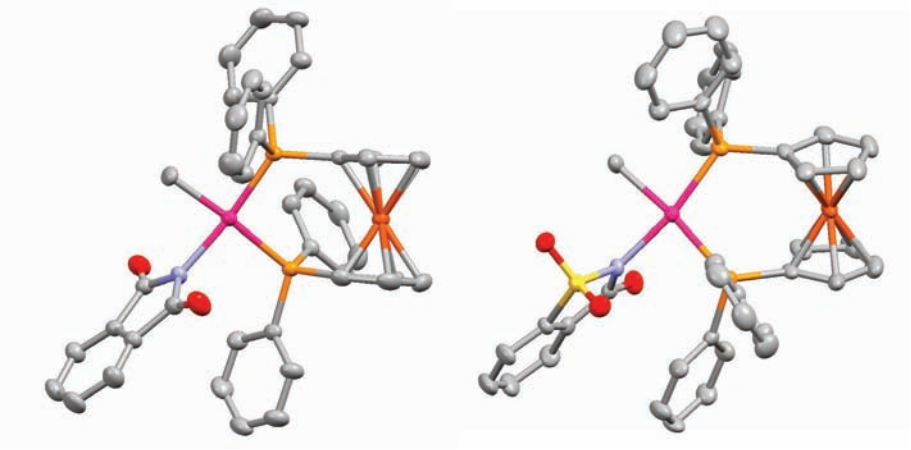


Fig. 1. *X-Ray crystal structures of [Pd(dppf)(Me)(phthalimide)]* (**1b**) *and [Pd(dppf)(Me)(saccharide)]* (**1c**). Selected bond lengths [Å] and angles [°]: **1b**: Pd1–N1, 2.072(2); Pd1–C9, 2.085(3); P1–Pd1, 2.3609(7); P2–Pd1, 2.2437(8); N1–Pd1–C9, 84.45(10). **1c**: Pd1–N1, 2.094(4); Pd1–C8, 2.122(5); P1–Pd1, 2.3854(14); P2–Pd1, 2.2387(14); N1–Pd1–C8, 84.90(18).

*Iodosobenzene Diacetate as Oxidant*. Oxidation with $PhI(OAc)_2$ was initially investigated for the two isolated complexes **1b** and **1c**. As expected from our results on alkene-diamination reactions [11a–11c][14][16], adding 1 equiv. of this strong oxidant induced oxidation at Pd to generate $Pd^{IV}$ complexes from **1b** and **1c**. Especially, on the basis of the similarities for **1b** and **1c** as observed in their respective X-ray crystallographic structures, a similar reaction outcome was expected. However, the reactions followed entirely different pathways and resulted in the formation of completely different products. Complex **1b** did not provide any C–N bond formation, but rather led to exclusive formation of AcOMe. In contrast, complex **1c** gave a single product of C–N bond formation, which was identified as 2-methyl-2*H*-1$\lambda^6$,2-benzothiazol-1,1,3-trione (='methyl saccharide') (*Scheme 3*). Based on its $^{31}$P-NMR signal, the remaining $Pd^{II}$ product was identified as $[Pd(OAc)_2(dppf)]$ which was isolated in 94% yield. This result suggests that oxidation with $PhI(OAc)_2$ occurs chemoselectively at the Pd-center[8]). Both the Fe- and the P-atoms of the dppf ligand remain untouched.

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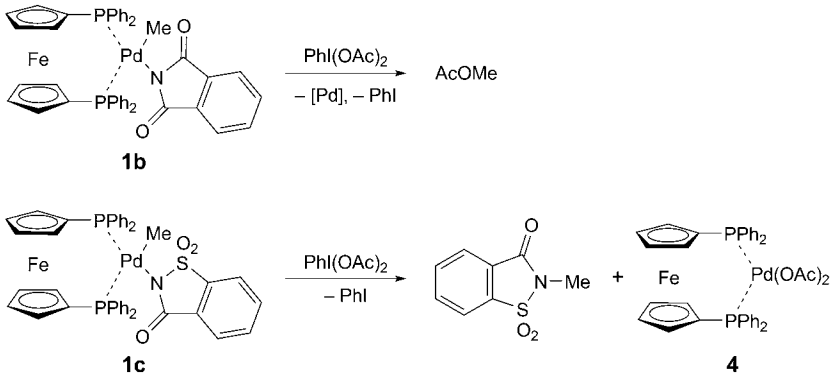
[7]) CCDC-693034 (for **1b**) and CCDC-693035 (for **1c**) contain the supplementary crystallographic data for this article. These data can be obtained free of charge *via* http://www.ccdc.cam.ac.uk/data_request/cif.

[8]) $PhI(OAc)_2$ as oxidant has recently been key in the development of $Pd^{IV}$ catalysis. See [12][19][20a–20k]. For $Pd^{III}$ complexes, see [20l–20n].

Scheme 3. *Oxidatively Induced Reductive Elimination of an Alkyl–N Bond*



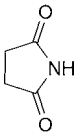
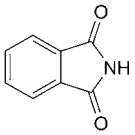
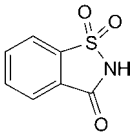
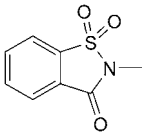
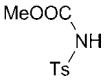
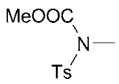
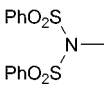

Next, oxidation reactions on the whole set of compounds **1a** – **1f** were carried out. In complete agreement with the earlier observation, a clear anion effect was observed, and only the anions, whose corresponding acids present a p$K_a$ values below that of AcOH provided the desired $C_{sp^3}$–N coupling. Hence, while $Pd^{II}$ complexes bearing methyl *N*-tosyl carbamate, saccharide, dibenzenesulfonimide or di-*p*-toluenesulfonamide as the amide moiety smoothly afforded C–N coupling under oxidation with $PhI(OAc)_2$, the same complexes bearing phthalimide or succinimide moieties did not promote this coupling. Instead, C–O formation was obtained owing to acetate transfer from the oxidant (*Table 1*, *Entries 1* and *2*). With dibenzenesulfonimide or di-*p*-toluenesulfonamide as amide, the reaction was complete after 10 min (*Entries 5* and *6*), indicating that the higher the leaving-group character of the N-containing group is, the faster the reaction proceeds. These results strongly underline the importance of the amide's leaving-group character for the successful realization of the C–N coupling.

Reactions compiled in *Table 1* are expected to proceed through a discrete octahedral $Pd^{IV}$ intermediate **A** [21], which is generated from the square-planar $Pd^{II}$ precursors **1** upon oxidation with $PhI(OAc)_2$ [12][19][20] (*Scheme 4*). In such a case, reductive elimination can arise *via* previous dissociation of an acetate group, which gives rise to the pentacoordinate $Pd^{IV}$ intermediate **B**. As a result, acetate acts as the nucleophile in the reductive functionalization of the Me group leading to formation of AcOMe.

In contrast, for those cases in which the amide dissociates preferentially, the resulting pentacoordinate $Pd^{IV}$ intermediate **C** undergoes C–N bond formation to the expected methylated amide as the coupling product. Since the alkyl amination proceeds *via* an $S_N2$-type transition state **D**, previous dissociation of the amide from the Pd-center in **A** is a prerequisite. A related proposal was made by *Goldberg* and coworkers for stoichiometric C–N bond formation *via* reductive elimination from a (Me)(tosylamido)-$Pt^{IV}$ complex [22].

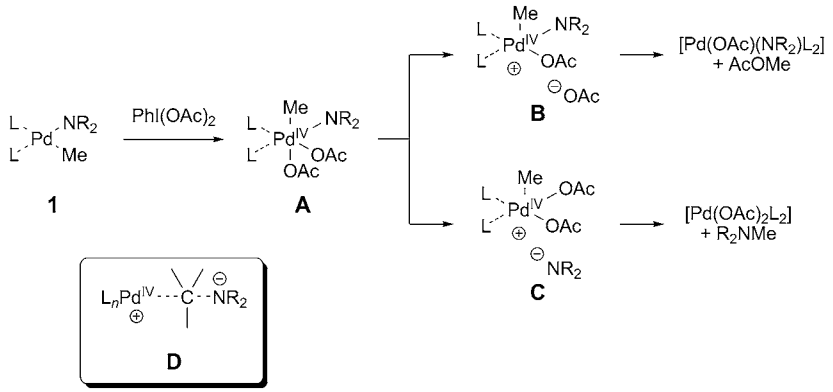
Overall, the chemoselectivity of the C–N over the C–O bond formation can be correlated to the dissociation tendency of the corresponding anion and, ultimately, to the p$K_a$ of the corresponding protonated acid/amide. This is in agreement with the observed selectivities in *Table 1* [23]

Table 1. *Oxidation of Amidato(dppf)(methyl)palladium(II) Complexes* **1a**–**1f** *with* $PhI(OAc)_2$[a])

| *Entry* | Pd Complex | Parent amide | Time [min] | Product |
|---|---|---|---|---|
| *1* | **1a** |  | 120 |  |
| *2* | **1b** |  | 120 |  |
| *3* | **1c** |  | 120 | **5c**  |
| *4* | **1d** |  | 120 | **5d**  |
| *5* | **1e** |  | 10 | **5e**  |
| *6* | **1f** |  | 10 | **5f**  |

[a]) Reaction conditions: [Pd(amidato)(dppf)(Me)] (0.5 mmol), $PhI(OAc)_2$ (0.55 mmol), $CH_2Cl_2$ (0.7 ml), 25°.

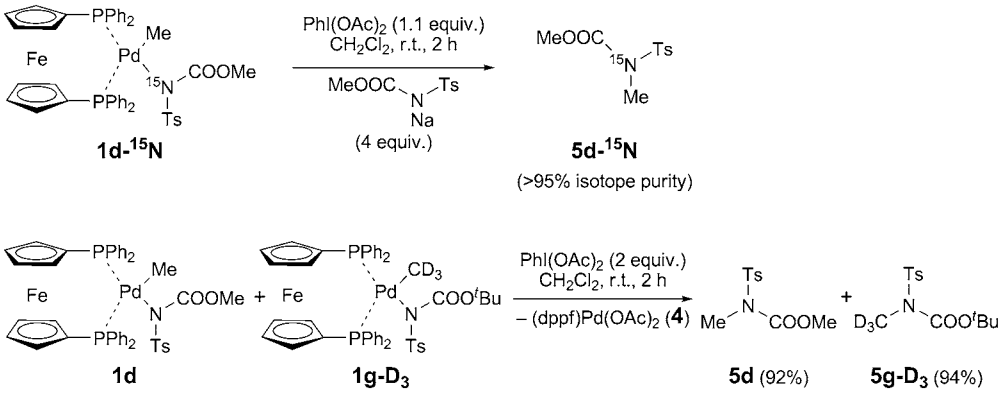
Scheme 4. *Mechanistic Proposal for the* $Pd^{IV}$*-Mediated C–N Coupling from Pd Complexes* **1**



However, detection of the relevant $\sigma$-alkyl–$Pd^{IV}$ intermediates such as **A** has so far remained elusive [18][9]). For the carbamate complex **1d**, $^{31}$P-NMR-spectroscopic monitoring of the oxidation process revealed the clean formation of two new Pd complexes, *i.e.*, **6a** (major) and **6b** (minor). We tentatively assign these compounds as $Pd^{IV}$-amidate intermediates **6a** and **6b** (*Fig. 2*), which proved too reactive for isolation. Until *ca.* 60% conversion, oxidation of **1d** to **6a** and **6b** was slower than reductive elimination from **6a** and **6b** to palladium diacetate **4**. During this period, however, the ratio **6a**/**6b** of the two isomers was not constant. It appears that isomer **6b** reacts at a faster rate than **6a**. At *ca.* 80% conversion, no starting material **1d** was left, and only intermediate **6a** remained, which subsequently formed additional product **4**. After a total reaction time of just 90 min, the signals of these intermediate completely vanished and gave rise to those of the well-known complex **4**. At this stage, the $^1$H-NMR only displayed signals corresponding to **4** and free methyl *N*-methyl-*N*-tosylcarbamate (**5d**), indicating that formation of the latter under oxidative conditions is indeed a feasible and again completely selective process. Oxidation of **1d** constitutes the first realization of a successful observation on $C_{sp^3}$–N bond formation from a discrete monomeric Pd complex.

A series of three control experiments (*Scheme 5*) was carried out in order to illustrate additional features of the stoichiometric coupling reactions. First, the reaction is not influenced by external anions as deduced from an experiment with $^{15}$N labeling. In this case, treatment of compound **1d-$^{15}$N** with iodosobenzene diacetate in the presence of 4 equiv. of the sodium salt of unlabeled methyl *N*-tosylcarbamate gave rise to the formation of the $^{15}$N-labeled coupling compound **5d-$^{15}$N** as the only a product. This result demonstrates that the N-containing group in the coordination sphere of Pd is transferred exclusively.

Scheme 5. *Competition Experiments with Pd Complex* **1d**




Second, under these conditions the N-atoms also do not undergo exchange between preformed Pd complexes. When compound **1d** and the corresponding derivative **1g** bearing a $CD_3$ substituent, and *tert*-butyl *N*-tosylcarbamate as N source were submitted

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[9]) For isolated $Pd^{IV}$ complexes with potential relevance to related catalytic aryl functionalization, see [24].

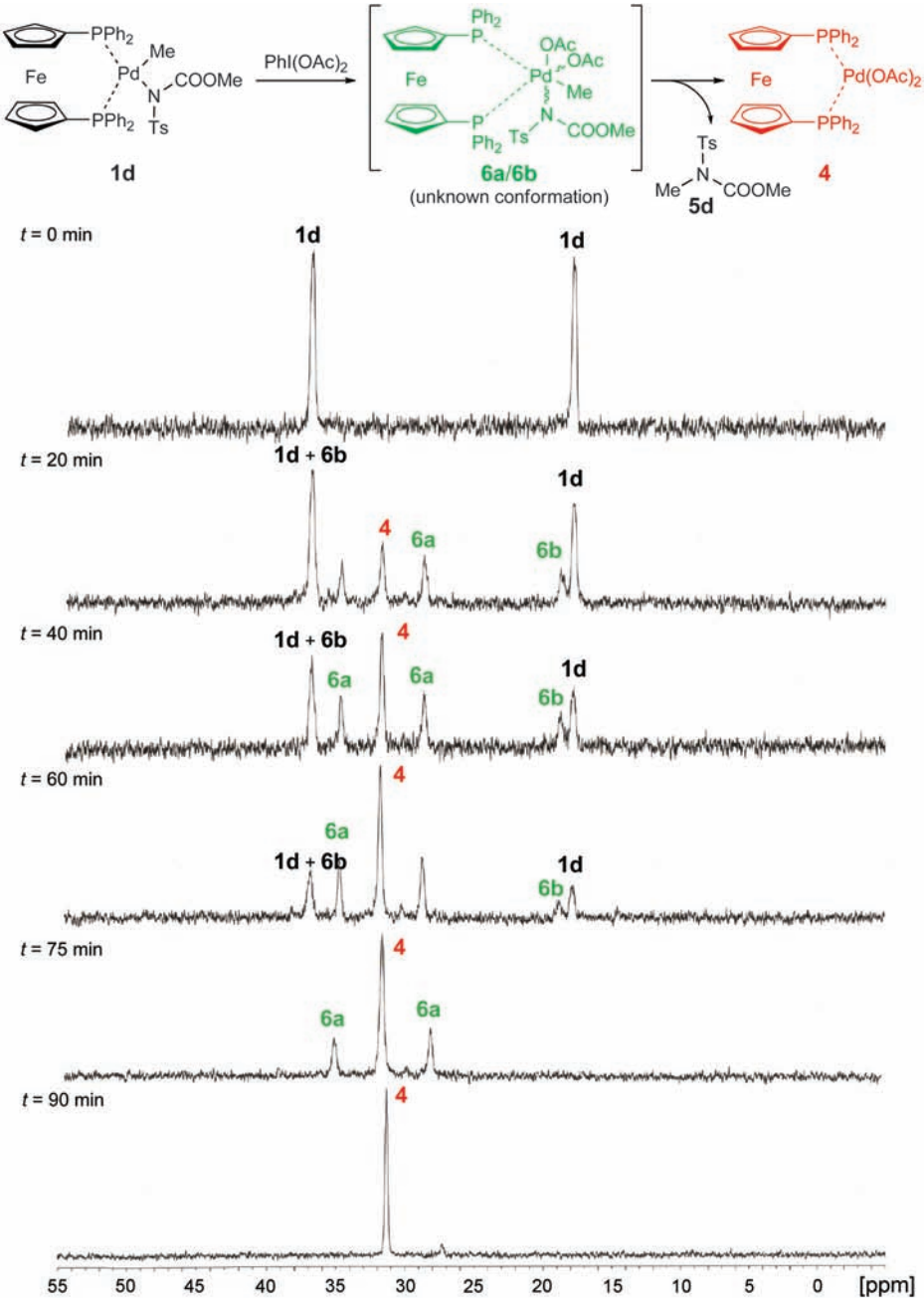
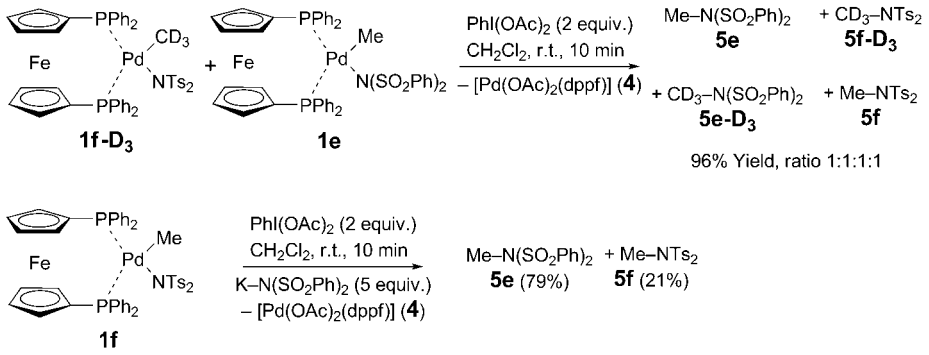



Fig. 2. *$^{31}$P-NMR Monitoring of the Oxidation of* **1d** *with Iodosobenzene Diacetate*

to oxidation, no cross-over products were formed, and only the three expected products **4**, **5d**, and **5g-D$_3$** were obtained. This outcome provides strong evidence that the involved Pd$^{IV}$ intermediates are monomeric in nature[10]).

The situation may undergo a change for the case of less coordinating anions such as bis(sulfonylimides). A second cross-over experiment between **1e** and **1f-D$_3$** led to an equimolar mixture of all four C–N coupling products (*Scheme 6*).

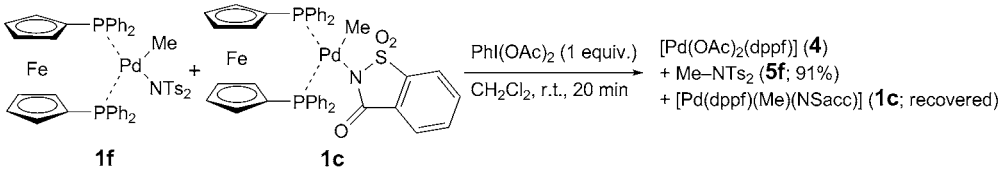
Scheme 6. *Labeling Experiments for Pd Complex* **1e**




Anion exchange in Pd complexes was then investigated by performing the oxidation of this type of Pd compounds in the presence of an excess of a similar amide salt. Thus, a $CH_2Cl_2$ solution of Pd complex **1f** was added to 5 equiv. of potassium dibenzenesulfonimidate, and the resulting mixture was treated with $PhI(OAc)_2$ (*Scheme 6*). The reaction was complete after 10 min, and interestingly two different coupling products, $(PhSO_2)_2NMe$ (**5e**) and $Ts_2NMe$ (**5f**), were obtained in 4 : 1 ratio. These results indicate an equilibrium between amides before oxidation, suggesting that the anion exchange would take place on Pd$^{II}$ complexes rather than at the stage of the high oxidation state Pd$^{IV}$ complexes.

To study the influence of the amidato ligand on the oxidation process, a competition experiment was carried out. Thus, complexes **1c** and **1f** were mixed in a 1 : 1 ratio and reacted with a limiting amount of 1 equiv. of $PhI(OAc)_2$ in $CH_2Cl_2$ at room temperature (*Scheme 7*).

Scheme 7. *Competitive Experiment Showing Oxidation Selectivity*

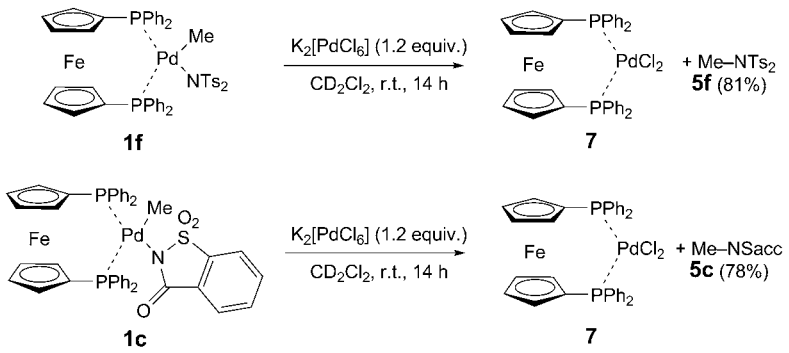



[10]) This observation leads us to exclude bimetallic Pd catalysis, which so far has only been invoked in non-related reductive $C_{sp^2}$–heteroatom bond-formation [25]. For the discussion on Pd$^{IV}$ intermediates *vs.* dimeric Pd$^{III}$ intermediates in aryl functionalization, see [26].

The maximum conversion of 50% was obtained, and the entire reaction proceeded to completion within 20 min. Selective oxidation of only one of the complexes took place, the other one remaining intact and leading to exclusive formation of $Ts_2NMe$. This indicates that complex **1f** reacts with the oxidant much faster than the complex **1c**. Since the only difference between both complexes rests in the amide group utilized, it can be concluded that the leaving-group character of the amide moiety plays again a crucial role in the transformation. The better leaving group promotes faster and selective alkyl-amide couplings, which is in agreement with the empirical rule that cationic $Pd^{IV}$ intermediates promote faster reductive elimination [12][21][27].

Since **1f** reacts significantly faster in the reductive C–N bond forming reaction than **1c** (*cf.*, *Table 1*), we cannot definitely exclude a scenario of parallel oxidation of both **1f** and **1c**, followed by subsequent oxidation of remaining **1f** through the $Pd^{IV}$ complex originating from **1c**. We consider such an event less likely due to the fact that **1c** does promote C–N bond formation under the given reaction conditions. However, it could be demonstrated that, in the presence of a hexachloropalladate reagent, both **1c** and **1f** undergo oxidation, followed by reductive C–N bond formation (*Scheme 8*). Due to the low solubility of the hexachloropalladate salt, this process is slow and requires significantly longer reaction times. Still, the reactions were found to be selective and gave rise to the corresponding *N*-methylated products **5f** and **5c**, respectively. In both cases, after the reaction [$PdCl_2$(dppf)] (**7**) was indicated as the only dppf-ligated product in the $^{31}$P-NMR spectrum of the crude reaction mixture[11]).

Scheme 8. *Reductive C–N Bond Formation Promoted by* $[PdCl_6]^{2-}$




Palladium(IV) catalyses are usually conducted without addition of a chelating ligand[12]). To test the ligand scope of the present C–N bond-forming reaction, several (dibenzene)(sulfinimidato)(methyl)palladium(II) complexes bearing bis(phosphine) or even diamine ligands were synthesized and reacted with $PhI(OAc)_2$. In all cases, C–N coupling was mostly obtained indicating that the process is not dependant of the

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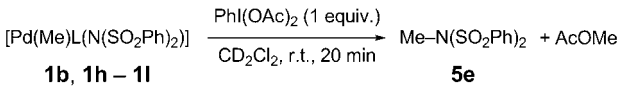
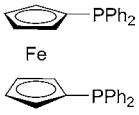
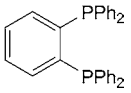
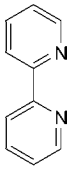
[11]) Due to the incomplete yield, we cannot rule out formation of MeCl as minor coupling product, which may arise from competing elimination or transmetallation processes, respectively.

[12]) For some exceptions, see [28]. For a recent report on $Pd^{IV}$ catalysis emplying bis(phosphine) ligands, see [29a]. However, this result was questioned by *Kang* and *Gade*, who suggested a metal-free acid-promoted reaction to be operative in this case; see [29b].

respective chelating bisphosphine ligand. When 1,2-bis(diphenylphosphino)benzene and 1,2-bis(diphenylphosphino)ethane were employed, traces of AcOMe were formed as side products (*Table 2*, *Entries 2* and *3*).

Table 2. *Oxidation of (Dibenezenesulfonimidato)(methyl)palladium(II) Complexes Bearing Different Ligands with PhI(OAc)$_2$*[a])




| *Entry* | Pd Complex | Ligand | Yield of Me–N($SO_2Ph$)$_2$ (**1e**) [%][b]) | Yield of AcOMe [%][b]) |
|---|---|---|---|---|
| *1* | **1b** |  | 100 | 0 |
| *2* | **1h** |  | 93 | 7 |
| *3* | **1i** |  | 93 | 7 |
| *4* | **1j** |  | 100 | 0 |

[a]) Reaction conditions: 1 equiv. of (dibenzenedisulfonimidato)(methyl)Pd$^{II}$ complex, 1 equiv. of PhI(OAc)$_2$, $CD_2Cl_2$ (0.6 ml), room temperature, 10–20 min. [b]) Yields based on $^1$H-NMR integration.

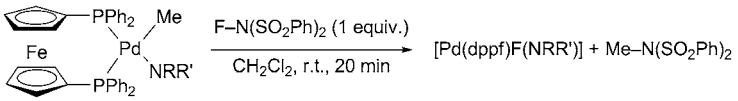
N-*Fluorodibenzenesulfonimide* ((PhSO$_2$)$_2$NF, NFSI) *as Oxidant.* This compound is usually employed as a source for electrophilic fluorination [30]. However, as was initially demonstrated by *Michael* and co-workers [31], it can also be used for oxidative fluorination of a Pd$^{II}$ center [32], upon which the remaining bis(sulfonimide) is engaged in C–N bond formation. This concept was employed by *Liu* in the realization of a Pd$^{II/IV}$-catalyzed aminofluorination of styrenes [33][13]).

We had used NFSI as oxidant and N source in one of the intermolecular diamination reactions [15]. To continue our study, oxidation reactions of several amidato(methyl)palladium(II) complexes were performed in the presence of NFSI. We observed selective formation of *N*-methyldibenzenesulfonimide (**5e**) as the only coupling product of the reductive elimination. Again, these results validate the concept of the leaving-group effect by which the anion transferred is the one presenting the lowest coordinating ability in the Pd$^{IV}$ transition state.

[13]) For the use of NFSI in a Pd-catalyzed fluorination of an arene, see [34].

All reactions were monitored by $^1$H- and $^{31}$P-NMR indicating the presence of selective C–N coupling products at the end of the reaction. Hence, employing this oxidant and using dppf as ligand and succinimide as the amide group, *N*-methylbis(phenylsulfonyl)imide (**5e**) was obtained in nearly quantitative yield (*Table 3*, *Entry 1*). Changing succinimide by phthalimide or saccharine resulted in formation of the same product in up to 90% isolated yield (*Entries 2* and *3*). Dibenzenesulfonimidato complex **1e** afforded the product in quantitative yield (*Entry 4*). For the bis(tosyl) derivative **1f**, a mixture of two products was obtained, which corresponds to the similar anion strengths of the two bis(sulfonylimides) (*Entry 5*). The favored formation of **5e** over **5f** may be the result of a kinetic preference after formation of the fluorinated Pd$^{IV}$ intermediate [18]. In these five cases, the Pd$^{II}$ species that results from the reductive elimination could not be identified. This compound exhibits a pronounced *singlet* in $^{31}$P-NMR and presents signals with similar shifts at *ca.* 26 ppm in all five cases. It is expected that the product should be the dppf-ligated monofluoride complex incorporating the initial (amidato)palladium ligand. Palladium fluoride complexes are usually of problematic stability[14]), and no efforts were made to further substantiate their nature in the present study. With bipy as ligand, selective and quantitative $C_{sp^3}$–N coupling was also achieved in both cases (*Entries 5* and *6*).

Table 3. *Oxidative $C_{sp^3}$–N Coupling Promoted by F–N(PhSO$_2$)$_2$*[a])




**1a – 1c, 1e – 1l** **8** **5e**

| *Entry* | Pd Complex | Ligand | Amide | Product |
|---|---|---|---|---|
| *1* | **1a** | dppf | succinimide | Me–N(SO$_2$Ph)$_2$ |
| *2* | **1b** | dppf | phthalimide | Me–N(SO$_2$Ph)$_2$ |
| *3* | **1c** | dppf | saccharine | Me–N(SO$_2$Ph)$_2$ |
| *4* | **1e** | dppf | dibenzenesulfonimide | Me–N(SO$_2$Ph)$_2$ |
| *5* | **1f** | dppf | bistosylimide | Me–N(SO$_2$Ph)$_2$[b]) |
| *6* | **1k** | bipy | phthalimide | Me–N(SO$_2$Ph)$_2$ |
| *7* | **1l** | bipy | saccharine | Me–N(SO$_2$Ph)$_2$ |

[a]) Reaction conditions: 1 equiv. of (amidato)(methyl)Pd$^{II}$ complex, 1 equiv. of NFSI, $CD_2Cl_2$ (0.6 ml), room temperature, 24 h. [b]) A mixture of Me–N(PhSO$_2$)$_2$ and Me–NTs$_2$ in ratio 1.5 : 1 was obtained.

In a final experiment, a 1 : 1 mixture of complex **1c** and its $CD_3$ derivative **1c-D$_3$** were oxidized with NFSI to give the expected product *N*-methylbis(phenylsulfonyl)-imide (**5e**) in 94% yield (*Scheme 9*). The product shows a 50% deuteration level indicating that both Pd complexes reacted at comparable rate. The absence of any detectable secondary isotope effect in the reductive C–N bond formation confirms that this final step is not the rate-limiting event. This is in agreement with the outcome of our earlier calculations on a related C–N bond formation from a $\sigma$-benzyl-Pd$^{IV}$ intermediate.

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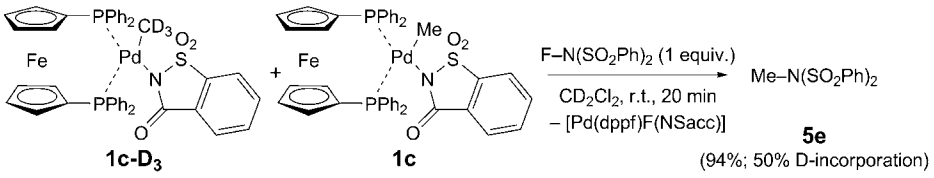
[14]) The stability of palladium fluoride complexes is often problematic. For a discussion, see [35].

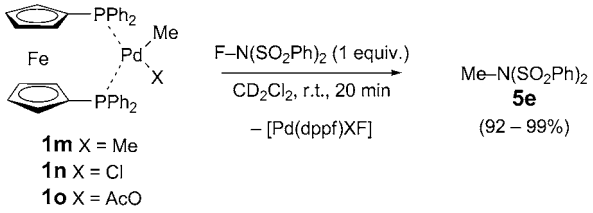
Scheme 9. *Absence of a Secondary Isotope Effect in Reductive C–N Bond Formation*




For reactions with NFSI, the selectivity in favor of the bis(phenylsulfonyl)imide anion as nucleophile in the C–N bond formation should also apply to reaction of Pd complexes with incorporated anions other than amidato groups.

In a final set of reactions, three $Pd^{II}$ complexes without coordinated amidato group were investigated. For dppf-ligated methyl-palladium complexes **1m**–**1o** bearing additional Me, Cl, and AcO groups, respectively, oxidation with NFSI again only furnished the C–N bond-formation product **5e** (*Scheme 10*). The example of complex **1m** is particularly interesting, as dimethyl complexes of $Pd^{IV}$ are usually known to undergo reductive C–C bond formation to release ethane [21]. However, in the present case, the C–N bond formation represents the preferred pathway.

Scheme 10. *C–N Bond Formation from Palladium Complexes* **1m**–**1o**




These results unambiguously indicate that no prior incorporation of the N nucleophile into the coordination sphere of Pd is required for the C–N bond-forming event.

**Conclusions.** – We have investigated a series of defined $Pd^{II}$ complexes containing different amidato ligands in the oxidative C–N bond formation upon oxidation with $PhI(OAc)_2$ and NFSI. Upon formation of $Pd^{IV}$ intermediates, different behavior in reductive elimination was observed, depending on the nature of the N-containing ligand. For oxidation with $PhI(OAc)_2$, the chemoselectivity of the C–N bond formation over the C–O bond formation can be correlated to the dissociation tendency of the corresponding anion and, ultimately, to the $pK_a$ of the corresponding conjugated acid/amide.

For NFSI as oxidant, the bis(sulfonylimide) anion usually outperforms all other N-containing groups in the C–N bond formation, ensuring complete selectivity.

These results are of high importance to rationalize our reagent combination for intermolecular regioselective diamination of alkenes. They demonstrate that, regardless of the nature of the $\sigma$-alkyl-palladium intermediate that originates from amino-palladation, the second step of C–N bond formation will always occur selectively. This selectivity arises from the preferential role of a bis(sulfonimide) as nucleophile in the

C–N bond formation from a $Pd^{IV}$ catalyst state. The presence of alternative N-containing groups as potentially competing nucleophiles does not interfere at this stage.

The authors thank the *Fonds der Chemischen Industrie*, *ICIQ Foundation*, *ICREA*, and the *Spanish Ministry for Economy* (CTQ2011-25027) for financial support. Dr. *Lydia Brelot* (Strasbourg University) is acknowledged for the X-ray structure analyses. Part of this work is taken from the Ph.D. Thesis of *A. I.* [36].

## Experimental Part

*General.* Abbreviations: bipy: 2,2′-bipyridine, dppf: 1,1′-bis(diphenylphosphino)ferrocene, hfacac: hexafluoroacetylacetonate, HNPhthal: phthalimide, HNSacc: saccharin, NFSI: *N*-fluorobenzenesulfonimide.

All org. reagents, if not noted otherwise, were purchased from *Acros*. Palladium salts were purchased from *Strem*. $CH_2Cl_2$ was dried over $CaCl_2$ and distilled from $CaH_2$. Column chromatography (CC): silica gel ($SiO_2$; *Merck*, type *60*, 0.063–0.2 mm). Reactions were monitored by TLC carried out on 0.25 mm *E. Merck* silica gel plates (*60F-254*) using UV light as visualizing agent and 10% ethanolic phosphomolybdic acid or ninhydrin soln. and heat as developing agents. IR Spectra: *Thermo Scientific Nicolet 6700* FT-IR spectrometer (smart orbit *Diamond*). NMR Spectra: *Bruker Avance 400* MHz, *Bruker DPX 300* MHz, and *Bruker DRX 500* MHz spectrometers; chemical shifts in ppm downfield from TMS; the following calibrations were used: $CDCl_3$ $\delta$(H) 7.26 and $\delta$(C) 77.00 ppm, and $CD_2Cl_2$ $\delta$(H) 5.32 and $\delta$(C) 53.80 ppm, the $^{15}$N-NMR spectrum of **1d** was recorded with $Me^{15}NO_2$ as external standard. LC/ESI-MS: *Agilent 1100* HPLC with a *Bruker micro-TOF* instrument; unless otherwise stated, a *Supelco C8* (5 cm × 4.6 mm, 5 μm particules) column was used with an linear elution gradient from 100% $H_2O$ (0.5% $HCO_2H$) to 100% MeCN in 13 min at a flow rate of 0.5 ml/min. EI- and HR-EI-MS: *Kratos MS 50* at the service centers of the Kekulé-Department, Bonn University, and *Bruker Daltonik Autoflex II TOF/TOF* spectrometer.

*Synthesis of (Amidato)(methyl)palladium Complexes* **1**. Complexes **1a**–**1f** were synthesized by reaction of equimolar amounts free amides and the known complex [Pd(dppf)$Me_2$] [37]. In a typical experiment, [Pd(dppf)$Me_2$] (1.0 mmol) was dissolved in 4 ml of freshly dist. $CH_2Cl_2$ under $N_2$. Subsequently, the respective amide (1.0 mmol, 1 equiv.) was added slowly over a period of several min under stirring. The reaction required 1 h for complexes **1c** and **1d**, 14 h for **1a** and **1b**, and proceeded within minutes for **1e** and **1f**. After that period, the volume of the soln. was reduced, and the product was precipitated by addition of 3 ml of freshly dist. $Et_2O$. The resulting complexes were dried under reduced pressure and recrystallized from $CH_2Cl_2$/$Et_2O$ mixture where required.

cis-*Methyl(succinimidato)[1,1′-bis(diphenylphosphino)ferrocene]palladium(II)* (**1a**). Light orange solid. Yield: 95%. IR: 3412, 3052, 2975, 1712, 1618, 1481, 1435, 1353, 1281, 1265, 1243, 1166, 1097, 734, 697. $^1$H-NMR (400 MHz, $CD_2Cl_2$): 0.45 (*dd*, *J* = 7.0, 5.2, 3 H); 1.59 (*dd*, *J* = 12.0, 4.6, 2 H); 2.12 (*dd*, *J* = 12.0, 4.6, 2 H); 3.59 (*s*, 2 H); 4.12 (*s*, 2 H); 4.51 (*s*, 2 H); 4.85 (*s*, 2 H); 7.25 (*t*, *J* = 7.0, 4 H); 7.36 (*t*, *J* = 7.0, 2 H); 7.51–7.56 (*m*, 10 H); 7.84–7.89 (*m*, 4 H). $^{13}$C-NMR (100 MHz, $CD_2Cl_2$): 9.5 (*d*, *J* = 100.4); 31.9; 71.9 (*d*, *J* = 6.1); 73.1 (*d*, *J* = 77.3); 74.0 (*d*, *J* = 6.9); 75.0 (*d*, *J* = 9.2); 77.0 (*d*, *J* = 13.0); 128.1 (*d*, *J* = 9.2); 128.8 (*d*, *J* = 11.5); 130.3; 131.0; 132.8 (*d*, *J* = 49.0); 134.4 (*d*, *J* = 13.8); 134.9 (*d*, *J* = 12.2); 135.4 (*d*, *J* = 36.0); 188.5. $^{31}$P-NMR (121 MHz, $CD_2Cl_2$): 21.31 (*d*, *J* = 28.3); 34.33 (*d*, *J* = 28.2). HR-ESI-MS: 796.0441 ($[M+Na]^+$, $C_{39}H_{35}FeNNaO_2P_2Pd^+$; calc. 796.0425).

*cis-Methyl(phthalimidato)[1,1′-bis(diphenylphosphino)ferrocene]palladium(II)* (**1b**). Yellow solid. Yield: 99%. IR: 3054, 2363, 2346, 1648, 1436, 1371, 1304, 1130, 720, 695. $^1$H-NMR (400 MHz, $CD_2Cl_2$): 0.54 (*s*, 3 H); 3.67 (*s*, 2 H); 4.14 (*s*, 2 H); 4.51 (*s*, 2 H); 4.84 (*s*, 2 H); 7.03–7.09 (*m*, 6 H); 7.25–7.29 (*m*, 4 H); 7.47–7.54 (*m*, 10 H); 7.93 (br. *s*, 4 H). $^{13}$C-NMR (100 MHz, $CD_2Cl_2$): 9.5 (*d*, *J* = 95.2); 72.0 (*d*, *J* = 6.0), 74.0 (*d*, *J* = 6.8), 75.0 (*d*, *J* = 9.1), 76.9 (*d*, *J* = 12.1), 120.3, 128.0 (*d*, *J* = 9.9); 128.8 (*d*, *J* = 10.6); 130.0; 130.7; 131.0; 132.5; 133.0; 134.3 (*d*, *J* = 12.9); 134.7; 135.0 (*d*, *J* = 12.9); 135.1; 138.1 (*d*, *J* = 3.8); 178.8. $^{31}$P-NMR (121 MHz, $CD_2Cl_2$): 19.28; 33.35. HR-ESI-MS: 844.0419 ($[M+Na]^+$, $C_{43}H_{35}FeNNaO_2P_2Pd^+$; calc. 844.0425).

Complex **1b** was recrystallized from $CH_2Cl_2$ to give suitable crystals for X-ray single crystal diffraction. Data were collected with a *Nonius KappaCCD* diffractometer. $C_{43}H_{35}FeNO_2P_2Pd \cdot 2\,CH_2Cl_2$,

$M_r$ 991.76, triclinic, $P\bar{1}$, $a = 9.5996(3)$, $b = 13.9609(6)$, $c = 17.1652(7)$ Å, $\alpha = 89.668(2)^\circ$, $\beta = 77.079(2)^\circ$, $\gamma = 71.674(2)^\circ$, $V = 2123.32(14)$ Å$^3$, $Z = 2$, $T = 123$ K, $\mu(\mathrm{MoK}_\alpha) = 0.71073$, 22625 reflections, 9073 unique reflections ($2\theta_{max} = 50^\circ$), $R1 = 0.0503$ [$I > 2\sigma(I)$], $wR2 = 0.0866$ (all data), 506 parameters and 0 restraints. Empirical absorption correction was applied[7]).

cis-*Methyl(saccharinato)[1,1′-bis(diphenylphosphino)ferrocene]palladium(II)* (**1c**). Orange solid. Yield: 99%. IR: 2966, 1665, 1431, 1434, 1282, 1253, 1167, 1153, 1148, 1120, 1092, 1026, 975, 744, 695, 676. $^1$H-NMR (400 MHz, $CD_2Cl_2$): 0.78 (*dd*, $J = 4.4$, 7.3, 3 H); 3.54 (br. *s*, 32 H); 4.06 (br. *s*, 32 H); 4.43 (br. *s*, 32 H); 4.71 (br. *s*, 32 H); 6.90–6.96 (*m*, 4 H); 7.00–7.05 (*m*, 2 H); 7.21–7.38 (*m*, 4 H); 7.43–7.52 (*m*, 10 H); 7.79–7.85 (*m*, 4 H). $^{13}$C-NMR (100 MHz, $CD_2Cl_2$): 11.9 (*d*, $J = 90.5$); 72.3 (*d*, $J = 6.1$); 74.1 (*d*, $J = 6.9$); 75.0 (*d*, $J = 9.2$); 76.9 (*d*, $J = 12.2$); 116.8; 119.3; 123.3 (*d*, $J = 8.4$); 127.7 (*d*, $J = 9.9$); 128.7; 128.9 (*d*, $J = 11.5$); 130.1 (*d*, $J = 1.5$); 131.2 (*d*, $J = 2.3$); 132.4 (*d*, $J = 52.9$); 134.5; 134.9 (*d*, $J = 13.0$); 135.07 (*d*, $J = 13.8$); 166.0. $^{31}$P-NMR ($CD_2Cl_2$, 121 MHz): 19.0 (*d*, $J = 17.8$, 1 P); 35.8 (*d*, $J = 17.8$, 1 P). HR-ESI-MS: 675.0138 ([$M - C_6H_4NO_3S$]$^+$, $C_{35}H_{31}FeP_2Pd^+$; calc. 675.0285).

Complex **1c** was recrystallized from $CH_2Cl_2$ to give suitable crystals for X-ray single-crystal diffraction. Data were collected with a *Nonius KappaCCD* diffractometer. $C_{42}H_{35}FeNO_3P_2PdS \cdot CH_2Cl_2$, $M_r$ 942.89, monoclinic, *P*21/c, $a = 17.5980(6)$, $b = 12.1880(5)$, $c = 18.7924(5)$ Å, $\beta = 95.567(2)^\circ$, $V = 4011.7(2)$ Å$^3$, $Z = 4$, $T = 123$ K, $\mu(\mathrm{MoK}_\alpha) = 0.71073$, 29856 reflections, 9180 unique reflections ($2\theta_{max} = 50^\circ$), $R1 = 0.0587$ [$I > 2\sigma(I)$], $wR2 = 0.1371$ (all data), 488 parameters and 0 restraints. Empirical absorption correction was applied[7]).

cis-*[1,1′-Bis(diphenylphosphino)ferrocene](Methoxycarbonyl)(tosyl)amino](methyl)palladium(II)* (**1d**). Orange solid. Yield: 99%. IR: 3051, 1685, 1481, 1434, 1300, 1284, 1256, 1182, 1165, 1145, 1097, 1079, 1027, 881, 815, 747, 695, 662. $^1$H-NMR ($CD_2Cl_2$, 500 MHz): 0.66 (*dd*, $J = 4.4$, 7.0, 3 H); 2.31 (*s*, 3 H); 3.30 (*s*, 3 H); 3.70 (br. *s*, 2 H); 4.19 (br. *s*, 2 H); 4.55 (br. *s*, 2 H); 4.74 (br. *s*, 2 H); 7.09 (*d*, $J = 7.9$, 2 H); 7.15–7.34 (*m*, 2 H); 7.36–7.45 (*m*, 4 H), 7. 55–7.68 (10 H); 7.67 (*d*, $J = 7.9$, 2 H); 7.95–8.05 (*m*, 4 H). $^{13}$C-NMR ($CD_2Cl_2$, 100 MHz): 12.7 (*dd*, $J = 3.1$, 94.3); 21.1; 51.5; 72.0 (br. *s*); 73.2 (*d*, $J = 5.4$); 74.6 (*d*, $J = 9.2$); 76.3 (*d*, $J = 8.5$); 79.4 (*dd*, $J = 9.2$, 54.0); 127.9 (*d*, $J = 9.2$); 128.2 (*d*, $J = 2.3$); 128.4, 128.50, 130.0 (br. *m*); 130.8; 134.6 (*d*, $J = 12.3$); 141.2 (*d*, $J = 15.3$); 157.2. $^{31}$P-NMR ($CD_2Cl_2$, 121 MHz): 18.0 (*d*, $J = 19.8$, 1 P); 37.1 (*d*, $J = 19.8$, 1 P). HR-ESI-MS: 926.0524 ([$M + Na$]$^+$, $C_{44}H_{41}FeNNaO_4P_2PdS^+$; calc. 926.0514).

Synthesis of $^{15}$N-labeled methyl *N*-tosyl carbamate was carried out starting from $^{15}NH_4NO_3$ (*Eurisotope*; 98% isotopic purity) as described in [9c][38]. Reaction with [Pd(dppf)$Me_2$] as described above gave **1d-$^{15}$N** in 99% yield. $^{15}$N-NMR ($CD_2Cl_2$, 75 MHz): −254 (*s*, 1 N). HR-ESI-MS: 904.0594 ($C_{44}H_{41}Fe^{15}NO_4P_2{}^{106}PdS^+$; calc. 904.0586).

cis-*[1,1′-Bis(diphenylphosphino)ferrocene][(methoxycarbonyl)(tosyl)amino][(D$_2$)methyl]palladium(II)* (**1d-D$_3$**). IR: 3406, 3054, 2979, 1732, 1374, 1265, 1131, 1045, 736, 704. $^1$H-NMR (400 MHz, $CD_2Cl_2$): 2.31 (*s*, 3 H); 3.24 (*s*, 3 H); 3.65 (br. *s*, 2 H); 4.14 (*s*, 2 H); 4.50 (*s*, 2 H); 4.68 (*s*, 2 H); 7.04 (*s*, 2 H); 7.22 (br. *s*, 2 H); 7.35 (*s*, 2 H); 7.54–7.60 (*m*, 12 H); 7.93 (br. *s*, 4 H). $^{31}$P-NMR (121 MHz, $CD_2Cl_2$): 17.85 (*d*, $J = 20.8$); 37.28 (*d*, $J = 20.8$).

cis-*[1,1′-Bis(diphenylphosphino)ferrocene](di-*p*-toluenedisulfinimidato)(methyl)palladium(II)* (**1f**). Orange-red solid. Yield: 99%. IR: 3853, 3055, 1494, 1481, 1436, 1317, 1278, 1152, 1133, 1082, 1055, 998, 955, 812, 748, 696, 667. $^1$H-NMR (400 MHz, $CD_2Cl_2$): 0.63 (br. *s*, 3 H); 2.31 (*s*, 6 H); 3.48 (br. *s*, 2 H); 4.14 (*s*, 2 H); 4.50 (*s*, 2 H); 4.72 (br. *s*, 2 H); 6.99 (br. *s*, 4 H); 7.22 (br. *s*, 4 H); 7.35 (*s*, 4 H); 7.38–7.42 (*m*, 4 H); 7.53 (br. *s*, 5 H); 7.66 (*t*, $J = 8.7$, 4 H); 7.84 (br. *s*, 3 H). $^{31}$P-NMR (121 MHz, $CD_2Cl_2$): 17.41(*d*, $J = 23.7$); 37.44 (*d*, $J = 23.7$). HR-ESI-MS: 886.0595 ([$M + Na$]$^+$, $C_{43}H_{37}NNaO_2P_2PdS_2^+$; calc. 886.0572).

cis-*[1,1′-Bis(diphenylphosphino)ferrocene][[(*tert*-butoxy)carbonyl](tosyl)amino][(D$_3$)methyl]palladium(II)* (**1g-D$_3$**). Yellow solid. Yield: 99%. IR: 3395, 3054, 2979, 1734, 1674, 1436, 1265, 1165, 1142, 1096, 1070, 736, 702. $^1$H-NMR (400 MHz, $CD_2Cl_2$): 1.34 (*s*, 9 H); 2.30 (*s*, 3 H); 3.39 (br. *s*, 1 H); 3.59 (br. *s*, 1 H); 4.10 (*s*, 2 H); 4.50 (br. *s*, 1 H); 4.57 (br. *s*, 1 H); 7.02 (*d*, $J = 7.3$, 2 H); 7.09 (br. *s*, 2 H); 7.27–7.35 (*m*, 4 H); 7.54 (*s*, 10 H); 7.65 (br. *s*, 2 H); 7.83–7.92 (*m*, 4 H). $^{13}$C-NMR ($CD_2Cl_2$, 100 MHz): 12.8 (*m*); 21.3; 28.4; 51.5; 72.0 (br. *s*); 73.2 (*d*, $J = 5.5$); 74.7 (*d*, $J = 9.1$); 76.3 (*d*, $J = 8.5$); 79.2; 79.5 (*dd*, $J = 9.1$, 54.0); 128.0 (*d*, $J = 9.1$); 128.5 (*d*, $J = 2.4$); 128.5; 128.6; 129.9 (br. *m*); 130.4; 134.7 (*d*, $J = 12.2$); 141.1 (*d*, $J = 15.2$); 157.4. $^{31}$P-NMR (121 MHz, $CD_2Cl_2$): 17.95 (*d*, $J = 17.8$); 38.02 (*d*, $J = 17.8$).

cis-*[1,2-Bis(diphenylphosphino)benzene](dibenzenesulfinimidato)palladium(II)* (**1h**). White solid. Yield: 99%. IR: 3056, 2923, 1733, 1481, 1445, 1436, 1318, 1306, 1265, 1157, 1139, 1097, 1080, 1025, 1001,

964, 871, 733, 690, 669. $^1$H-NMR (400 MHz, $CD_2Cl_2$): 0.58 (*dd*, *J* = 7.9, 2.3, 3 H); 7.12 (*t*, *J* = 7.6, 4 H); 7.31 (*t*, *J* = 7.6, 3 H); 7.34–7.37 (*m*, 3 H); 7.41–7.45 (*m*, 8 H); 7.49 (*d*, *J* = 7.3, 6 H); 7.52–7.63 (*m*, 10 H). $^{13}$C-NMR (100 MHz, $CD_2Cl_2$): 12.4 (*d*, *J* = 94.3); 128.1; 128.9 (*d*, *J* = 9.9); 129.2 (*d*, *J* = 11.5); 130.2 (*d*, *J* = 55.9); 130.8; 131.3; 131.5; 131.6; 131.8; 133.2 (*d*, *J* = 111.9); 134.0 (*d*, *J* = 12.2); 134.5 (*d*, *J* = 13.0); 143.9. $^{31}$P-NMR (121 MHz, $CD_2Cl_2$): 38.25 (*d*, *J* = 13.8); 55.86 (*d*, *J* = 13.8). HR-ESI-MS: 567.0639 ($[M - C_{12}H_{10}NO_4S_2]^+$, $C_{31}H_{27}P_2Pd^+$; calc. 567.0623).

cis-*[1,2-Bis(diphenylphosphino)ethane](dibenzenesulfinimidato)(methyl)palladium(II)* (**1i**). White solid. Yield: 99%. IR: 3055, 2360, 1436, 1264, 1139, 1080, 966, 871, 735, 703. $^1$H-NMR (400 MHz, $CD_2Cl_2$): 0.51 (*dd*, *J* = 7.6, 2.3, 3 H); 2.07–2.13 (*m*, 1 H); 2.14–2.24 (*m*, 2 H); 2.25–2.32 (*m*, 1 H); 7.12 (*t*, *J* = 7.6, 4 H); 7.30 (*t*, *J* = 7.6, 2 H); 7.44 (*td*, *J* = 7.6, 1.7, 4 H); 7.48–7.57 (*m*, 12 H); 7.71–7.78 (*m*, 8 H). $^{13}$C-NMR (100 MHz, $CD_2Cl_2$): 10.7 (*d*, *J* = 94); 26.0 (*dd*, *J* = 26.0, 9.9); 29.3 (*dd*, *J* = 32.9, 21.4); 128.1 (*d*, *J* = 6.9), 129.1 (*d*, *J* = 9.9); 129.3 (*d*, *J* = 11.5); 129.8 (*d*, *J* = 54.4); 131.1 (*d*, *J* = 1.5); 131.3; 131.8 (*d*, *J* = 2.3); 132.3 (*d*, *J* = 27.6); 133.9 (*d*, *J* = 11.5); 134.2 (*d*, *J* = 12.2); 143.7. $^{31}$P-NMR (121 MHz, $CD_2Cl_2$): 34.25 (*d*, *J* = 11.8); 57.62 (*d*, *J* = 11.8). HR-ESI-MS: 519.0627 ($[M - C_{12}H_{10}NO_4S_2]^+$, $C_{27}H_{27}P_2Pd^+$; calc. 519.0623).

cis-*(2,2′-Bipyridine)(dibenzenesulfinimidato)(methyl)palladium(II)* (**1j**). White-off solid. Yield: 99%. IR: 3061, 2985, 2883, 1599, 1472, 1445, 1323, 1306, 1161, 1143, 1081, 1025, 950, 834, 761, 731, 688. $^1$H-NMR (400 MHz, $CD_2Cl_2$): 0.68 (*s*, 3 H); 7.32 (*t*, *J* = 6.4, 1 H); 7.38 (*t*, *J* = 7.6, 4 H); 7.49 (*t*, *J* = 7.6, 2 H); 7.53 (*dd*, *J* = 5.8, 1.1, 1 H); 7.94 (*d*, *J* = 7.6, 4 H); 8.07–8.09 (*m*, 2 H); 8.15 (*d*, *J* = 7.8, 2 H); 8.48 (*d*, *J* = 5.0, 1 H); 8.54 (*d*, *J* = 5.0, 1 H). $^{13}$C-NMR (100 MHz, $CD_2Cl_2$): 1.9; 121.8; 123.2; 126.7; 126.8; 128.4; 128.5; 132.0; 139.1; 139.6; 143.9; 149.5; 150.3; 157.9. HR-ESI-MS: 276.9963 ($[M - C_{12}H_{10}NO_4S_2]^+$, $C_{11}H_{11}N_2Pd^+$; calc. 276.9957).

*cis-(2,2′-Bipyridine)(Methyl)(phthalimidato)palladium(II)* (**1k**). Yellow solid. Yield: 90%. IR: 2845, 1650, 1624, 1598, 1468, 1442, 1359, 1302, 1118, 753, 730. $^1$H-NMR (400 MHz, $CD_2Cl_2$): 0.68 (*s*, 3 H); 7.28 (*dd*, *J* = 7.6, 0.8, 1 H); 7.45–7.49 (*m*, 1 H); 7.55–7.57 (*m*, 2 H); 7.66–7.68 (*m*, 2 H); 7.89 (*td*, *J* = 7.8, 1.4, 1 H); 8.07 (*td*, *J* = 7.8, 1.4, 1 H); 8.13–8.15 (*m*, 1 H); 8.25 (*d*, *J* = 8.2, 1 H); 8.36 (*d*, *J* = 8.2, 1 H); 8.50 (*d*, *J* = 4.6, 1 H). $^{13}$C-NMR (100 MHz, $CD_2Cl_2$): −1.7; 121.1; 122.5; 123.5; 126.5; 126.7; 131.9; 137.7; 139.1; 139.5; 149.1; 153.4; 157.1; 180.0. HR-ESI-MS: 446.0091 ($C_{19}H_{15}N_3NaO_2Pd^+$; calc. 446.0096).

cis-*(2,2′-Bipyridine)(Methyl)(saccharinato)palladium(II)* (**1l**). White solid. Yield: 99%. IR: 3054, 1667, 1598, 1446, 1297, 1264, 1170, 1148, 1128, 966, 766, 735, 704, 678. $^1$H-NMR (400 MHz, $CD_2Cl_2$): 0.91 (*s*, 3 H); 7.39 (*pseudo-t*, *J* = 6.5, 1 H); 7.55 (*td*, *J* = 7.0, 1.1, 1 H); 7.70 (*dd*, *J* = 5.2, 3.5, 2 H); 7.83–7.85 (*m*, 1 H); 7.87–7.89 (*m*, 1 H); 7.95 (*td*, *J* = 7.0, 1.4, 1 H); 8.12–8.17 (*m*, 2 H); 8.29 (*d*, *J* = 8.1, 1 H); 8.52 (*dd*, *J* = 5.2, 0.8, 1 H); 8.59 (*d*, *J* = 5.2, 1 H). $^{13}$C-NMR (100 MHz, $CD_2Cl_2$): −0.9, 122.6, 122.7, 123.8, 125.9, 126.3, 126.4, 127.5, 128.5, 137.7, 137.8, 138.9, 139.1, 139.5, 149.2, 156.4, 157.4, 172.5. HR-ESI-MS: 276.9971 ($[M - C_7H_4NO_2S]^+$, $C_{11}H_{11}N_2Pd^+$; calc. 276.9957).

*Representative Oxidation Reaction with PhI(OAc)$_2$.* The respective $Pd^{II}$ complex **1** (0.5 mmol) was dissolved in $CH_2Cl_2$ (1.5 ml) and stirred under $N_2$. Solid $PhI(OAc)_2$ (161 mg, 0.5 mmol, 1 equiv.) was added in one portion, and the reaction was followed by TLC or $^{31}$P-NMR (for determination of reaction times, *cf. Table 1*). After full conversion of all starting material **1**, the volume of the reaction was reduced. Addition of $Et_2O$ led to precipitation of the $Pd^{II}$ residues and allowed extraction of the methylated amide product. Purification by chromatography ($SiO_2$, hexane/AcOEt, 3:1, *v*/*v*) gave the products **5** in anal. pure form. Compounds **5a**–**5g** are known [39]. The Pd product $[Pd(OAc)_2(dppf)]$ was identified by its $^1$H- and $^{31}$P-NMR spectrum [40].

Treatment of the complex **1c-$^{15}$N** with 2 equiv. of $PhI(OAc)_2$ in $CH_2Cl_2$ in the presence of 4 equiv. of sodium methyl *N*-tosyl carbamate gave rise to a dark red soln. within 2 h ($^{31}$P-NMR control). AcOEt and an aq. thiosulfate soln. were added, and the resulting mixture was stirred for 5 min. The org. phase was separated, and the aq. one was extracted with AcOEt. The combined org. phases were washed with brine and $H_2O$, dried, and evaporated to dryness. CC ($SiOl_2$; AcOEt/hexanes, 1:2 (*v*/*v*)) gave the coupling product in analytically pure form matching the NMR data for the unlabelled compound. Isomeric purity was confirmed by a MALDI experiment. HR-MALDI-MS: 244.0540 ($C_{10}H_{13}{}^{15}NO_4S^+$; calc. 244.0536).

*Representative Oxidation Reaction with NFSI.* The respective $Pd^{II}$ complex **1** (0.5 mmol) was dissolved in $CH_2Cl_2$, and the mixture was stirred under $N_2$. Solid NFSI (158 mg, 0.5 mmol, 1 equiv.) was added in one portion, and the reaction was usually terminated after 10 min. After full conversion of all

starting material **1**, the volume of the reaction was reduced. Addition of $Et_2O$ led to precipitation of the $Pd^{II}$ residues and allowed extraction of the methylated amide product **5e**.

## REFERENCES


[1] J. M. Brown, N. A. Cooley, *Chem. Rev.* **1988**, *88*, 1031.

[2] 'Metal-Catalyzed Cross-Coupling Reactions', Eds. A. de Meijere, F. Diederich, Wiley-VCH, Weinheim, 2nd edn., 2004; J. Tsuji, 'Palladium Reagents and Catalysts', Wiley, New York 2004; P. Espinet, A. Echavarren, *Angew. Chem.* **2004**, *116*, 4809; E. Negishi, *Bull. Chem. Soc. Jpn*. **2007**, *80*, 233; A. Suzuki, *Angew. Chem.* **2011**, *123*, 6854; A. Suzuki, *Angew. Chem., Int. Ed.* **2011**, *50*, 6722; E. Negishi, *Angew. Chem.* **2011**, *123*, 6870; E. Negishi, *Angew. Chem., Int. Ed.* **2011**, *50*, 6738.

[3] A. R. Muci, S. L. Buchwald, *Top. Curr. Chem*. **2002**, *219*, 131; J. F. Hartwig, *Angew. Chem., Int. Ed*. **1998**, *37*, 2046; J. F. Hartwig, *Inorg. Chem.* **2007**, *46*, 1936; J. F. Hartwig, *Acc. Chem. Res.* **1998**, *31*, 852; B. Schlummer, U. Scholz, *Adv. Synth. Catal.* **2004**, *346*, 1599; J. F. Hartwig, *Synlett* **2006**, 1283; S. L. Buchwald, C. Mauger, G. Mignani, U. Scholz, *Adv. Synth. Catal.* **2006**, *348*, 23; J. P. Wolfe, S. Wagaw, J.-F. Marcoux, S. L. Buchwald, *Acc. Chem. Res.* **1998**, *31*, 805; S. Shekhar, P. Ryberg, J. F. Hartwig, J. S. Mathew, D. G. Blackmond, E. R. Strieter, S. L. Buchwald, *J. Am. Chem. Soc.* **2006**, *128*, 3584.

[4] J. Barluenga, C. Valdés, *Chem. Commun.* **2005**, 4891.

[5] a) A. G. Sergeev, G. A. Artamkina, V. N. Khrustalev, M. Y. Antipin, I. P. Beletskaya, *Mendeleev Commun.* **2007**, *17*, 142; b) K. Fujita, M. Yamashita, F. Puschmann, M. Martinez Alvarez-Falcon, C. D. Incarvito, J. F. Hartwig, *J. Am. Chem. Soc.* **2006**, *128*, 9044; c) Q. Shen, J. F. Hartwig, *J. Am. Chem. Soc.* **2007**, *129*, 7734.

[6] a) O. Esposito, A. K. de K. Lewis, P. B. Hitchcock, S. Caddick, F. G. N. Cloke, *Chem. Commun.* **2007**, 1157; b) J. E. Ney, J. P. Wolfe, *J. Am. Chem. Soc.* **2006**, *128*, 15415.

[7] J. L. Brice, J. E. Harang, V. I. Timokhim, N. A. Anastasi, S. S. Stahl, *J. Am. Chem. Soc*. **2005**, *127*, 2868.

[8] H.-Y. Thu, W.-Y. Yu, C.-M. Che, *J. Am. Chem. Soc.* **2006**, *128*, 9048; J. J. Neumann, S. Rakshit, T. Dröge, F. Glorius, *Angew. Chem.* **2009**, *121*, 7024; J. J. Neumann, S. Rakshit, T. Dröge, F. Glorius, *Angew. Chem., Int. Ed.* **2009**, *48*, 6892; T.-S. Mei, X. Wang, J.-Q. Yu, *J. Am. Chem. Soc.* **2009**, *131*, 10806; C. J. Vickers, T.-S. Mei, J.-Q. Yu, *Org. Lett.* **2010**, *12*, 2511; S. L. Marquard, D. C. Rosenfeld, J. F. Hartwig, *Angew. Chem.* **2010**, *122*, 805; S. L. Marquard, D. C. Rosenfeld, J. F. Hartwig, *Angew. Chem., Int. Ed.* **2010**, *49*, 793; J. Pan, M. Su, S. L. Buchwald, *Angew. Chem.* **2011**, *123*, 8806; J. Pan, M. Su, S. L. Buchwald, *Angew. Chem., Int. Ed.* **2011**, *50*, 8647; U. Nettekoven, J. F. Hartwig, *J. Am. Chem.Soc.* **2002**, *124*, 1166; M. Kawatsura, J. F. Hartwig, *J. Am. Chem. Soc*. **2000**, *122*, 9546.

[9] a) T. A. Ramirez, B. Zhao, Y. Shi, *Chem. Soc. Rev.* **2012**, *41*, 931; b) K. J. Fraunhoffer, M. C. White, *J. Am. Chem. Soc.* **2007**, *129*, 7274; c) S. A. Reed, M. C. White, *J. Am. Chem. Soc.* **2008**, *130*, 3316; d) G. Liu, G. Yin, L. Wu, *Angew. Chem.* **2008**, *120*, 4811; G. Liu, G. Yin, L. Wu, *Angew. Chem., Int. Ed.* **2008**, *47*, 4733; e) S. A. Reed, A. R. Mazzotti, M. C. White, *J. Am. Chem. Soc.* **2009**, *131*, 11701; f) G. T. Rice, M. C. White, *J. Am. Chem. Soc.* **2009**, *131*, 11707; g) L. Wu, S. Qiu, G. Liu, *Org. Lett.* **2009**, *11*, 2707; h) M. R. Luzung, C. A. Lewis, P. S. Baran, *Angew. Chem.* **2009**, *121*, 7159; i) M. R. Luzung, C. A. Lewis, P. S. Baran, *Angew. Chem., Int. Ed.* **2009**, *48*, 7025; j) G. Yin, Y. Wu, G. Liu, *J. Am. Chem. Soc.* **2010**, *132*, 11978.

[10] F. Cardona, A. Goti, *Nature Chem.* **2009**, *1*, 269; R. M. de Figueiredo, *Angew. Chem*. **2009**, *121*, 1212; R. M. de Figueiredo, *Angew. Chem., Int. Ed.* **2009**, *48*, 1190; S. De Jong, D. G. Nosal, D. J. Wardrop, *Tetrahedron* **2012**, *68*, 4067; K. Muñiz, *Chem. Soc. Rev.* **2004**, *33*, 160; K. Muñiz, in 'Science of Synthesis, Stereoselective Synthese', Thieme, Stuttgart, 2011, Vol. I, pp. 5–67.

[11] a) J. Streuff, C. H. Hövelmann, M. Nieger, K. Muñiz, *J. Am. Chem. Soc.* **2005**, *127*, 14586; b) K. Muñiz, C. H. Hövelmann, J. Streuff, *J. Am. Chem. Soc.* **2008**, *130*, 763; c) K. Muñiz, *J. Am. Chem. Soc.* **2007**, *129*, 14542; d) C. H. Hövelmann, J. Streuff, L. Brelot, K. Muñiz, *Chem. Commun.* **2008**, 2334; e) K. Muñiz, C. H. Hövelmann, E. Campos-Gómez, J. Barluenga, J. M. González, J. Streuff, M. Nieger, *Chem. – Asian J.* **2008**, *3*, 776; f) K. Muñiz, J. Streuff, P. Chávez, C. H. Hövelmann, *Chem. – Asian J.* **2008**, *3*, 1248; g) P. Chavez, J. Kirsch, J. Streuff, K. Muñiz, *J. Org. Chem.* **2012**, *77*, 1922.

[12] A. J. Hickmann, M. S. Sanford, *Nature* **2012**, *484*, 177; K. Muñiz, *Angew. Chem.* **2009**, *121*, 9576; K. Muñiz, *Angew. Chem., Int. Ed.* **2009**, *48*, 9412.
[13] J.-E. Bäckvall, *Tetrahedron Lett.* **1978**, *19*, 163; J.-E. Bäckvall, *Acc. Chem. Res.* **1983**, *16*, 335.
[14] Á. Iglesias, E. G. Pérez, K. Muñiz, *Angew. Chem.* **2010**, *122*, 8286; Á. Iglesias, E. G. Pérez, K. Muñiz, *Angew. Chem., Int. Ed.* **2010**, *49*, 8109.
[15] K. Muñiz, J. Kirsch, P. Chávez, *Adv. Synth. Catal*. **2011**, *353*, 689.
[16] C. Martínez, K. Muñiz, *Angew. Chem.* **2012**, *124*, 7138; C. Martínez, K. Muñiz, *Angew. Chem., Int. Ed.* **2012**, *51*, 7031.
[17] R. A. Periana, D. J. Taube, S. Gamble, H. Taube, T. Satoh, H. Fujii, *Science* **1998**, *280*, 560; S. S. Stahl, J. A. Labinger, J. E. Bercaw, *Angew. Chem.* **1998**, *110*, 2298; S. S. Stahl, J. A. Labinger, J. E. Bercaw, *Angew. Chem., Int. Ed.* **1998**, *37*, 2180.
[18] Á. Iglesias, R. Álvarez, Á. R. de Lera, K. Muñiz, *Angew. Chem.* **2012**, *124*, 2268; Á. Iglesias, R. Álvarez, Á. R. de Lera, K. Muñiz, *Angew. Chem., Int. Ed.* **2012**, *51*, 2225.
[19] G. Liu, S. S. Stahl, *J. Am. Chem. Soc.* **2006**, *128*, 7179; G. Yin, T. Wu, G. Liu, *Chem. – Eur. J.* **2012**, *18*, 451; J. E. Bäckvall, E. E. Björkmann, *J. Org. Chem.* **1980**, *45*, 2893; X. Tong, M. Beller, M. K. Tse, *J. Am. Chem. Soc.* **2007**, *129*, 4906; H. Liu, J. Yu, L. Wang, X. Tong, *Tetrahedron Lett.* **2008**, *49*, 6924; T. W. Lyons, M. S. Sanford, *Tetrahedron* **2009**, *65*, 3211; L. V. Desai, M. S. Sanford, *Angew. Chem*. **2007**, *119*, 5839; L. V. Desai, M. S. Sanford, *Angew. Chem., Int. Ed*. **2007**, *46*, 5737.
[20] a) N. R. Deprez, M. S. Sanford, *Inorg. Chem.* **2007**, *46*, 1924; b) T. Yoneyama, R. H. Crabtree, *J. Mol. Catal. A* **1996**, *108*, 35; c) A. R. Dick, K. L. Hull, M. S. Sanford, *J. Am. Chem. Soc.* **2004**, *126*, 2300; d) L. V. Desai, K. L. Hull, M. S. Sanford, *J. Am. Chem. Soc.* **2004**, *126*, 9542; e) D. Kalyani, M. S. Sanford, *Org. Lett*. **2005**, *7*, 4149; f) E. J. Alexanian, C. Lee, E. J. Sorensen, *J. Am. Chem. Soc*. **2005**, *127*, 7690; g) L. V. Desai, K. J. Stowers, M. S. Sanford, *J. Am. Chem. Soc.* **2008**, *130*, 13285; h) K. J. Stowers, M. S. Sanford, *Org. Lett.* **2009**, *11*, 4584; i) S. R. Neufeldt, M. S. Sanford, *Org. Lett.* **2010**, *12*, 532; j) A. D. Satterfield, A. Kubota, M. S. Sanford, *Org. Lett.* **2011**, *13*, 1076; k) M. H. Emmert, A. K. Cook, Y. J. Xie, M. S. Sanford, *Angew. Chem.* **2011**, *123*, 9581; M. H. Emmert, A. K. Cook, Y. J. Xie, M. S. Sanford, *Angew. Chem., Int. Ed.* **2011**, *50*, 9409; l) D. C. Powers, T. Ritter, *Nature Chem*. **2009**, *1*, 302; m) D. C. Powers, M. A. L. Geibel, J. E. M. N. Klein, T. Ritter, *J. Am. Chem. Soc*. **2009**, *131*, 17050; n) D. C. Powers, D. Y. Xiao, M. A. L. Geibel, T. Ritter, *J. Am. Chem. Soc*. **2010**, *132*, 14530.
[21] A. J. Canty, *Acc. Chem. Res.* **1992**, *25*, 83.
[22] A. V. Pawlikowski, A. D. Getty, K. I. Goldberg, *J. Am. Chem. Soc.* **2007**, *129*, 10382.
[23] M. Breugst, T. Tokuyasu, H. Mayr, *J. Org. Chem.* **2010**, *75*, 5250.
[24] A. R. Dick, J. W. Kampf, M. S. Sanford, *J. Am. Chem. Soc.* **2005**, *127*, 12790; S. R. Whitfield, M. S. Sanford, *J. Am. Chem. Soc.* **2007**, *129*, 15143; J. M. Racowski, A. R. Dick, M. S. Sanford, *J. Am. Chem. Soc.* **2009**, *131*, 10974; N. R. Deprez, M. S. Sanford, *J. Am. Chem. Soc.* **2009**, *131*, 11234; Y. Ye, N. D. Ball, J. W. Kampf, M. S. Sanford, *J. Am. Chem. Soc*. **2010**, *132*, 14682.
[25] D. C. Powers, T. Ritter, *Acc. Chem. Res.* **2012**, *45*, 840; D. C. Powers, T. Ritter, *Top. Organomet. Chem*. **2011**, *503*, 129.
[26] D. C. Powers, E. Lee, A. Ariafard, M. S. Sanford, B. F. Yates, A. J. Canty, T. Ritter, *J. Am. Chem. Soc.* **2012**, *134*, 12002; N. D. Ball, J. B. Gary, Y. Ye, M. S. Sanford, *J. Am. Chem. Soc*. **2011**, *133*, 7577; A. Ariafard, C. J. T. Hyland, A. J. Canty, M. Sharma, B. F. Yates, *Inorg. Chem.* **2011**, *50*, 6449; T. Furuya, D. Benitez, E. Tkatchouk, A. E. Strom, P. Tang, W. A. Goddard III, T. Ritter, *J. Am. Chem. Soc.* **2010**, *132*, 3793; D. C. Powers, D. Benitez, E. Tkatchouk, W. A. Goddard III, T. Ritter, *J. Am. Chem. Soc*. **2010**, *132*, 14092.
[27] M. P. Lanci, M. S. Remy, W. Kaminsky, J. M. Mayer, M. S. Sanford, *J. Am. Chem. Soc*. **2009**, *131*, 15618.
[28] P. L. Arnold, M. S. Sanford, S. M. Pearson, *J. Am. Chem. Soc.* **2009**, *131*, 13912; T. Tsujihara, K. Takenaka, K. Onitsuka, M. Hatanaka, H. Sasai, *J. Am. Chem. Soc.* **2009**, *131*, 3452; K. Takenaka, S. Hashimoto, S. Takizawa, H. Sasai, *Adv. Synth. Catal.* **2011**, *353*, 1067.
[29] a) Y. Li, D. Song, V. M. Dong, *J. Am. Chem. Soc.* **2008**, *130*, 2962; b) Y.-B. Kang, L. H. Gade, *J. Am. Chem. Soc.* **2011**, *133*, 3658.
[30] J. Baudoux, D. Cahard, *Org. React.* **2008**, *69*, 1.

[31] P. A. Sibbald, F. E. Michael, *Org. Lett*. **2009**, *11*, 1147; P. A. Sibbald, C. F. Rosewall, R. D. Swartz, F. E. Michael, *J. Am. Chem. Soc*. **2009**, *131*, 15945.
[32] K. M. Engle, T.-S. Mei, X. Wang, J.-Q. Yu, *Angew. Chem.* **2011**, *123*, 1514; K. M. Engle, T.-S. Mei, X. Wang, J.-Q. Yu, *Angew. Chem., Int. Ed*. **2011**, *50*, 1478.
[33] S. Qiu, T. Xu, J. Zhou, Y. Guo, G. Liu, *J. Am. Chem. Soc.* 2010, *132*, 2856.
[34] K. L. Hull, W. Q. Anani, M. S. Sanford, *J. Am. Chem. Soc*. **2006**, *128*, 7134.
[35] A. Yahav, I. Goldberg, A.Vigalok, *J. Am. Chem. Soc.* **2003**, *125*, 13634; A. Yahav, I. Goldberg, A.Vigalok, *Inorg. Chem.* **2005**, *44*, 1547.
[36] Á. Iglesias, Ph.D. Thesis, Université de Strasbourg, 2009.
[37] M. Lautens, S. Hiebert, J.-L. Renaud, *J. Am. Chem. Soc.* **2001**, *123*, 6834; R. E. Rulke, J. M. Ernsting, A. L. Spek, C. J. Elsevier, P. W. N. M. van Leeuwen, K. Vrieze, *Inorg. Chem.* **1993**, *32*, 5769; W. de Graaf, J. Boersma, W. J. J. Smeets, A. L. Spek, G. van Koten, *Organometallics* **1989**, *8*, 2907.
[38] P. Rademacher, W. Wiegräbe, W. Lüttke, *Chem. Ber.* **1967**, *100*, 1213.
[39] S. van der Werf, J. B. F. N. Engberts, *Recl. Trav. Chim. Pays-Bas* **1970**, *89*, 423; S. Dandapani, D. P. Curran, *Tetrahedron* **2002**, *58*, 3855; M. Katohgi, H. Togo, K. Yamaguchi, M. Yokoyama, *Tetrahedron* **1999**, *55*, 14885; Y. Tanaka, Y. Tanaka, *Chem. Pharm. Bull.* **1974**, *22*, 2546; J. A. Bjorklund, T. Frenzel, M. Rueffer, M. Kobayashi, U. Mocek, C. Fox, J. M. Beale, S. Groeger, M. H. Zenk, H. G. Floss, *J. Am. Chem. Soc.* **1995**, *117*, 1533.
[40] T. Yanagi, T. Oh-e, N. Miyaura, A. Suzuki, *Bull. Chem. Soc. Jpn.* **1989**, *62*, 3892.

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