Bench-Stable and Recoverable Palladium(I) Dimer as an Efficient Catalyst for Heck Cross-Coupling

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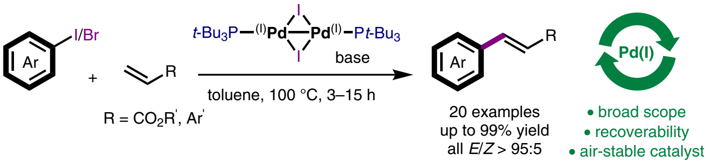

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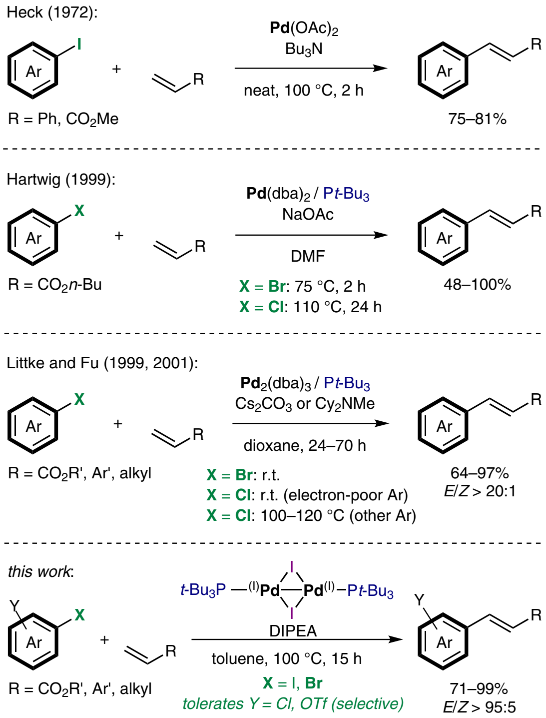
Abstract The application of air- and moisture-stable dinuclear palladium(I) complex $[Pd(\mu\text{-}I)(Pt\text{-}Bu_3)]_2$ as an efficient catalyst for the Heck cross-coupling reaction of aryl iodides and bromides with acrylates and styrenes is described. The developed protocol is robust and operationally simple and shows a high functional-group tolerance. The employed palladium(I) dimer catalyst is highly robust under these nucleophilic as well as elevated-temperature conditions, allowing its recovery after reaction completion and recycling.

Key words palladium(I) dimer, cross-coupling, Heck reaction, dinuclear catalysis, alkenes, catalyst recycling

Metal-catalyzed cross-coupling reactions have found widespread applications since the initial report in 1972 by Richard Heck on the palladium-catalyzed coupling of organic halides with olefins (Scheme 1).[1] Numerous advances in terms of substrate scope, cross-coupling partners, and catalysts have been made since then.[2] While Heck initially reported good conversion of iodobenzene at 100 °C, bromobenzene proved much less reactive.[1a] By using the bulky tri-*tert*-butylphosphine ligand ($Pt\text{-}Bu_3$), Hartwig as well as Littke and Fu were able to expand the scope to aryl bromides and chlorides.[3] The exchange of insoluble Cs_2CO_3 base for Cy_2NMe allowed for milder reaction conditions that transformed aryl bromides and activated aryl chlorides already at ambient temperature.[4]

From an industrial perspective, synthesis of agrochemical and medicinal compounds without the use of transition-metal-catalyzed cross-couplings is almost unthinkable and great efforts for a cost-effective use thereof have been undertaken.[5] This includes the search for means of recycling the catalyst and employing lower catalyst loading. Thus far, most advances in this area have been made by using heterogeneous catalysts,[6] including nanoparticles, while recoverable homogeneous Pd catalysts have remained scarce.[5]



Scheme 1 Seminal work on the Heck cross-coupling reaction, including the initial report by Heck and the use of $Pd/t\text{-}Bu_3P$ for the activation of aryl bromides and chlorides, and an outline of this work employing dinuclear Pd(I) catalysis

Despite the ubiquitousness of Pd(0) as a homogeneous catalyst for cross-coupling reactions, its utility is hampered by its instability under ambient conditions, i.e. air and moisture. In order to avoid handling air-sensitive Pd(0), a

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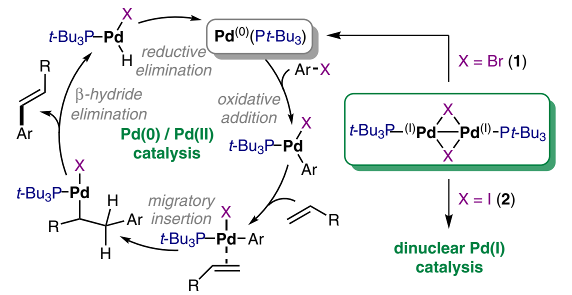
number of air-stable pre-catalysts have been developed and successfully applied in cross-coupling reactions.[7] Despite the bench-stable nature of these pre-catalysts, they form highly active monophosphine Pd(0)–L *in situ* and cannot be transformed back to their robust (precursor) form after the reaction is complete.

In this context, bromide-bridged Pd(I) dimer [Pd(μ-Br)(P*t*-Bu$_3$)]$_2$ (**1**) has been used as a highly active precursor for the *in situ* formation of Pd(0) in Suzuki–Miyaura coupling and Buchwald–Hartwig amination.[8] While the Pd(I)–bromo dimer has a limited stability in air,[9] we found that the iodo analogue [Pd(μ-I)(P*t*-Bu$_3$)]$_2$ (**2**) is more robust and completely bench-stable. We developed a novel cross-coupling concept based on dinuclear Pd(I) catalysis,[10] rather than mononuclear Pd(0) catalysis, and employed the bench-stable iodide-bridged Pd(I) dimer **2** as a catalyst in carbon–heteroatom bond formations, such as the trifluoromethylthiolation and -selenolation of aryl iodides and bromides.[11]

Encouraged by our successful use of the robust dinuclear Pd(I) catalyst, we wondered whether its high stability might even allow for its use as a catalyst under more nucleophilic and demanding conditions. As such, the Pd(I) dimer would represent an ideal candidate as a bench-stable and recoverable catalyst for economic cross-coupling reactions that require more forcing reaction conditions. With this in mind, we set out to investigate the use of the air- and moisture-stable Pd(I)–iodo dimer as a recoverable catalyst in Heck cross-coupling reactions.

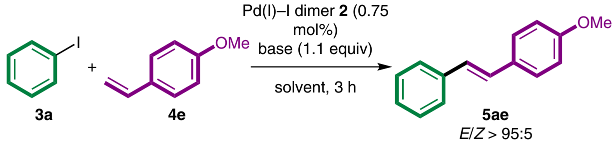
Our previous studies have shown that nucleophiles are able to convert halide-bridged Pd(I) dimers **1** and **2** into Pd(0) if they possess sufficient nucleophilicity, and we identified the minimum nucleophilicity necessary in each case.[12] On the basis of the relatively high nucleophilicity necessary to convert **2**, we envisioned that applications in Heck cross-coupling should be feasible, despite the need for a base and high temperatures. More specifically, we anticipated that by careful choice of the base, the dinuclear Pd(I) catalyst would stay intact. As such, Heck cross-coupling by dinuclear Pd(I) catalysis rather than by sensitive mononuclear Pd(0) catalysis might be possible, which would be advantageous, as the air-stable Pd(I) dimer could be recovered after the reaction (Scheme 2).



Scheme 2 Textbook mechanism of the Pd(0)-catalyzed Heck cross-coupling and anticipated dinuclear Pd(I) catalysis employing Pd(I)–iodo dimer **2** as a recoverable catalyst

We set our focus on N-based nucleophiles, since those frequently feature nucleophilicities <16.1,[12,13] which is required for the Pd(I) species to stay intact. An initial screening (see Table 1) showed that more sterically encumbered tertiary amines (entries 4 and 5) yielded the cross-coupling product in good yield. In contrast, more nucleophilic bases, such as 1,3,4,6,7,8-hexahydro-2*H*-pyrimido[1,2-*a*]pyrimidine (hppH, entry 3) or DABCO (entry 2) only afforded moderate amounts of product, and secondary amines, such as piperidine (entry 1) were inefficient, resulting in low yields. These observations are in line with our previous studies on the nucleophile-assisted activation of Pd(I) dimers, which showed that using additives with high nucleophilicities resulted in a rapid conversion of Pd(I)–Pd(I) to Pd(0).[12] This, in turn, had a detrimental effect on its catalytic efficiency, due to the high concentration of unstable monophosphine Pd(0) generated, which led to loss of Pd (most likely by the formation of Pd black).

Table 1 Optimization of Reaction Conditions for the Synthesis of **5ae**[a]



Entry	Base	Solvent	Temp (°C)	Yield (%)[b]
1	piperidine	toluene	100	22
2	DABCO	toluene	100	36
3	hppH	toluene	100	52
4	*n*-Bu$_3$N	toluene	100	73
5	DIPEA	toluene	100	77
6	DIPEA	dioxane	100	10
7	DIPEA	MeCN	100	11
8	DIPEA	DMF	100	64
9	DIPEA	toluene	80	59

[a] Reaction conditions: **2** (0.75 mol%), **3a** (0.40 mmol), **4e** (0.48 mmol), base (0.64 mmol), solvent (4 mL), indicated temperature, 3 h.
[b] Yield determined by quantitative ^{1}H NMR analysis of the crude reaction mixture by using 1,4-dioxane as internal standard.

With DIPEA (Table 1, entry 5) as a suitable base in hand, we aimed to further optimize the reaction conditions, and established that conducting the reaction in toluene at 100 °C afforded the cross-coupling product in good yield. More polar solvents such as dioxane, acetonitrile, or DMF led to diminished yields (entries 6–8), as did lowering the reacting temperature to 80 °C (entry 9). Decreasing the amount of base (from 1.6 equiv to 1.1 equiv relative to aryl iodide) and alkene coupling partner (from 1.2 equiv to 1.01 equiv)

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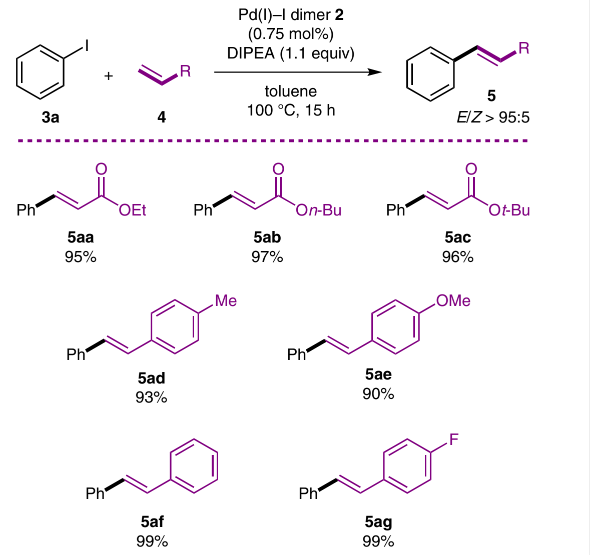
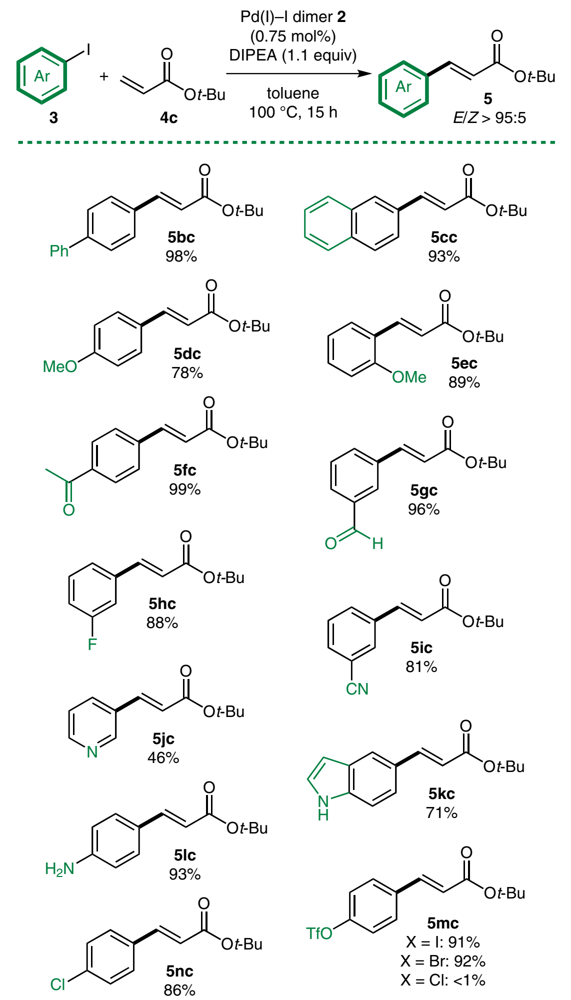
further increased the cross-coupling efficiency and afforded **5ae** in very good yield of 90%, even on larger scale (0.8 mmol, see Scheme 3). We then explored the scope of alkene cross-coupling partners **4** by using the optimized set of reaction conditions. A number of acrylates **4a–c** as well as electron-rich and electron-poor styrenes **4d–g** were coupled in excellent yields (Scheme 3).



Scheme 3 Scope of alkene coupling partner **4**. *Reagents and conditions:* **2** (0.0015 mmol, 0.75 mol%), **3a** (0.2 mmol), **4** (0.202 mmol), DIPEA (0.22 mmol), toluene (1.5 mL). The reaction giving product **5ae** was performed on larger scale (0.8 mmol of **3a**). Yields of isolated products are given.

Moreover, a wide range of aryl iodides possessing both electron-rich and electron-poor substituents in *ortho*, *meta*, or *para* positions was tolerated and afforded the corresponding Heck products **5** in good to excellent yields (Scheme 4). This includes functional groups such as aryls (**5bc**, **5cc**), ethers (**5dc**, **5ec**), fluorides (**5hc**), cyanides (**5ic**), ketones (**5fc**), aldehydes (**5gc**), and even unprotected amines (**5kc**, **5lc**). Notably, the presented Heck protocol is selective and transforms aryl iodides and bromides efficiently, but leaves other potentially reactive functionalities such as aryl chlorides and triflates untouched (**5mc**, **5nc**).

This observation is in contrast to the reports of Hartwig, Littke, and Fu, who used the Pd/P*t*-Bu$_3$ catalytic system to activate aryl bromides and chlorides.[3,4] Their use of different Pd-to-ligand ratios suggested that a monophosphine Pd(0)–P*t*-Bu$_3$ was the active catalyst.[4] Hence, if Pd(0) were to be formed from the Pd(I) dimer under our reaction conditions, we would expect aryl chlorides to be reactive. We performed a series of test reactions. The results are shown in Table 2.



Scheme 4 Scope of aryl halides **3** in Heck cross-coupling reactions with *tert*-butyl acrylate (**4c**). *Reagents and conditions:* **2** (0.0015 mmol, 0.75 mol%), **3** (0.2 mmol), **4c** (0.202 mmol), DIPEA (0.22 mmol), toluene (1.5 mL). The reaction giving product **5mc** was conducted by using different 4-halophenyl triflates (X = I, Br, Cl). Yields of isolated products are given.

While a range of Pd(0) catalysts (entries 3–5) were able to transform chlorobenzene to the Heck cross-coupling product **5ae**, employing the bench-stable Pd(I)–iodo dimer **2** as a catalyst did not result in any formation of product, even under prolonged heating (entry 1). The less stable Pd(I)–bromo dimer, however, led to minor amounts of product being formed (entry 2). This is very likely due to its conversion into Pd(0) under the nucleophilic conditions. These observations are in agreement with *in situ* ^{31}P NMR monitoring studies, which showed that while Pd(I)–iodo dimer **2** stays intact under the reaction conditions, Pd(I)–bromo dimer **1** decomposes.[14] Further stoichiometric studies on Pd(I)–iodo dimer **2** showed that the dimer stays intact in the presence of aryl iodide, styrene, and DIPEA, and the only other species observed was free phosphine ligand.

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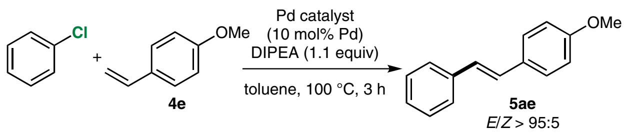
Table 2 Test Reactions To Elucidate the Catalytically Active Species: Heck Cross-Coupling of Chlorobenzene with 4-Methoxystyrene (**4e**) by Using Different Pd Catalysts[a]



Entry	Pd catalyst	Conversion (%)[b,c]
1	[Pd(μ-I)(P*t*-Bu$_3$)]$_2$ (**2**, 5 mol%)	0 (0)
2	[Pd(μ-Br)(P*t*-Bu$_3$)]$_2$ (**1**, 5 mol%)	15 (34)
3	Pd(P*t*-Bu$_3$)$_2$ (10 mol%)	55 (79)
4	Pd$_2$(dba)$_3$ (5 mol%), P*t*-Bu$_3$ (10 mol%)	33 (43)
5	Pd$_2$(dba)$_3$ (5 mol%), P*t*-Bu$_3$ (20 mol%)	32 (55)

[a] Reaction conditions: Pd catalyst (10 mol% Pd), chlorobenzene (0.2 mmol), **4e** (0.202 mmol), DIPEA (0.22 mmol), toluene (1.5 mL), 100 °C, 3 h.
[b] Conversion determined by GC-MS analysis of the crude reaction mixture after filtration over a plug of silica.
[c] Values in brackets refer to conversions after 24 h.

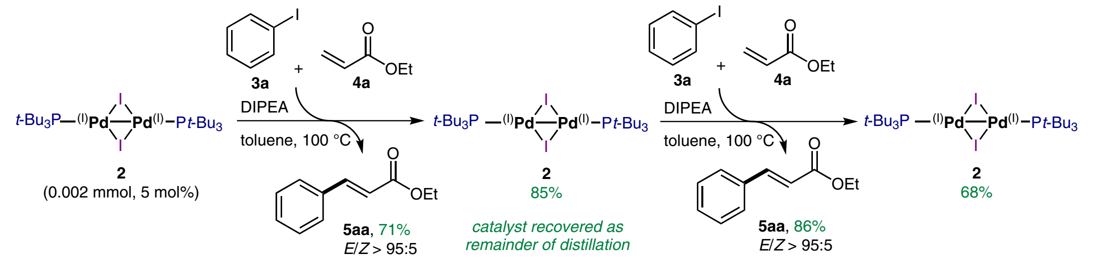
However, a control experiment confirmed that loss of ligand also occurs in the absence of any additives and reagents, and is most probably a result of prolonged heat exposure in solution.

Our experimental observations are therefore not in line with typical Pd(0) catalysis, and instead suggest a different mode of reactivity with Pd(I)–iodo dimer **2**. In contrast to previous reports using the tri-*tert*-butylphosphine ligand, aryl chlorides are not reactive under our reaction conditions. As such, the presented protocol allows for the selective transformation of aryl iodides and bromides in the presence of aryl chlorides and triflates.

Having confirmed that Pd(I) dimer **2** stays intact in the course of the reaction, we wondered whether it would also be possible to recover the dimer after completion of the reaction. With this in mind, we aimed to establish reaction conditions that allow for maximum amounts of catalyst to be recovered. Reaction monitoring by ^{1}H and ^{31}P NMR spectroscopy as well as gas chromatography coupled with mass spectrometry (GC-MS) showed that essentially full conversion to product is reached after three hours and that prolonged heating under the nucleophilic conditions slowly decomposes the Pd(I) dimer. For a successful recovery of the Pd(I) dimer catalyst **2**, we thus chose a reaction time of three hours. Two methods for recovery of the catalyst were then tested: (a) extraction of the crude reaction mixture and (b) distillation (Scheme 5). Since Pd(I)–iodo dimer **2** is barely soluble in polar solvents such as acetonitrile, we anticipated that a simple extraction of the obtained crude product after workup should be able to extract the formed product from the insoluble Pd(I) dimer. Using this procedure, we were able to recover 82% of the employed catalyst and obtained an acceptable 80% of cross-coupling product **5aa** after further purification of the MeCN extract by column chromatography. Pleasingly, similar results were also obtained by subjecting the crude reaction mixture to Kugelrohr distillation at 125 °C, which afforded **5aa** as the distillate in 71% yield and 85% of the employed catalyst **2** as the remainder. Notably, both ^{1}H and ^{31}P NMR analysis of the Pd(I) catalyst after recovery only showed traces of decomposition (see Supporting Information for details). In addition, the obtained residue was fully dissolved in benzene, indicating that no insoluble Pd black was formed in the process, and that Pd(I)–iodo dimer **2** remains stable even under high temperatures of 125 °C. Furthermore, the recyclability of the recovered catalyst was also viable and afforded **5aa** in 86%.

In summary, we have developed a robust and operationally simple protocol for the Heck cross-coupling of aryl iodides and bromides with acrylates or styrenes. This transformation is made possible by the use of the bench-stable Pd(I)–iodo dimer [Pd(μ-I)(P*t*-Bu$_3$)]$_2$ (**2**). A wide substrate scope and high functional-group tolerance, including toward unprotected amines, was observed. Selective coupling of aryl iodides and bromides occurred, tolerating other commonly reactive acceptors such as C–Cl or C–OTf bonds. The dinuclear Pd(I) catalyst also shows potential as an economic catalyst for large-scale applications, by combining attractive features such as its (a) stability towards air and moisture, (b) effectiveness at low catalyst loadings, (c) recoverability, and (d) recyclability.

The starting materials were all commercially available and used without further purification. Toluene was degassed and dried by using an Innovative Technology PS-MD-5 solvent purification system. Solvents



Scheme 5 Recovery and recyclability of Pd(I)–iodo dimer catalyst **2** by Kugelrohr distillation. *Reagents and conditions:* **2** (0.002 mmol, 5 mol%), **3a** (0.4 mmol), **4a** (0.404 mmol), DIPEA (0.44 mmol), toluene (3 mL), 100 °C, 3 h; yields of isolated products are given.

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used in workup and purification were distilled prior to use. Pd(I)–iodo dimer **2** was prepared from $Pd_2(dba)_3$, $Pt\text{-}Bu_3$, and PdI_2 according to a literature procedure.[11b] All ^1H, ^{13}C, and ^{31}P NMR spectra were recorded on Varian VNMRS 600, Varian VNMRS 400, or Varian Mercury 300 spectrometers at ambient temperature. Chemical shifts (δ) are reported in ppm referenced either to the residual solvent peak ($CDCl_3$ for ^1H and ^{13}C spectra) or $PO(OMe)_3$ (δ = 3.05) added as an internal standard for ^{31}P NMR. GC-MS was performed on an Agilent Technologies 5975 series MSD mass spectrometer coupled with an Agilent Technologies 7820A gas chromatograph. HRMS was performed by using a Thermo Scientific LTQ Orbitrap XL spectrometer. IR spectra were recorded on a Spectrum 100 spectrometer with an UATR Diamond/KRS-5 crystal with attenuated total reflectance (ATR). Kugelrohr distillation was performed by using a Büchi Glass Oven B-585 Kugelrohr apparatus.

Heck Cross-Coupling Reactions; General Procedure

Aryl iodide **3** (0.2 mmol, 1.0 equiv), acrylate/styrene **4** (0.202 mmol, 1.01 equiv), DIPEA (28.4 mg, 0.22 mmol, 1.1 equiv), and Pd(I)–iodo dimer **2** (1.3 mg, 0.0015 mmol, 0.75 mol%) were weighed into a 4 mL screw cap vial, purged with argon, and dissolved in anhydrous toluene (1.5 mL). The vial was capped with a PTFE-lined screw cap and sealed with PTFE tape prior to heating to 100 °C under stirring by using an aluminum heating block outside the glovebox. After 15 h, the reaction mixture was allowed to cool to r.t. and diluted with EtOAc (to 20 mL); excess base was quenched by the addition of sat. aq NH_4Cl (20 mL). The organic phase was separated and the aqueous layer was extracted with EtOAc (2 × 20 mL). The combined organic layer was dried over $MgSO_4$ and the solvent was removed under reduced pressure. The obtained crude product was purified by flash column chromatography.

tert-Butyl (*E*)-3-(4-{[(Trifluoromethyl)sulfonyl]oxy}phenyl)acrylate (5mc)

The title compound was obtained according to the general procedure from either 4-iodophenyl triflate or 4-bromophenyl triflate. The crude mixture was purified by column chromatography (hexane–EtOAc, 20:1); R_f = 0.41 (hexane–EtOAc, 10:1); this afforded the product as a colorless oil.

Yield: 64.8 mg (0.184 mmol, 91%; from aryl iodide) or 65.2 mg (0.185 mmol, 92%; from aryl bromide).

IR (neat): 2969, 2325, 2095, 1711, 1409, 1165, 993, 866, 720 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.58–7.49 (m, 3 H, Ar*H*, C*H*), 7.29–7.22 (m, 2 H, Ar*H*), 6.34 (d, *J* = 16.0 Hz, 1 H, C*H*), 1.51 (s, 9 H, CH_3).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 165.8 (C), 150.2 (C), 141.2 (CH), 135.2 (C), 129.7 (CH), 122.5 (CH), 122.0 (CH), 118.85 (q, *J* = 320.9 Hz, CF_3), 81.1 (C), 28.3 (CH_3).

^{19}F NMR ($CDCl_3$, 376 MHz): δ = –72.87 (s, 3 F, SO_2CF_3).

MS (EI): *m*/*z* (%) = 352.1 (100) $[M]^+$, 353.1 (16), 354.0 (6), 354.9 (1).

HRMS: *m*/*z* $[M]^+$ calcd for $C_{14}H_{15}F_3O_5S$: 352.0587; found: 352.0588.

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Supporting Information

Supporting information for this article is available online at http://dx.doi.org/10.1055/s-0036-1588318.

References

(1) (a) Heck, R. F.; Nolley, J. P. *J. Org. Chem.* **1972**, *37*, 2320. (b) de Meijere, A.; Diederich, F. *Metal-Catalyzed Cross-Coupling Reactions*; Wiley-VCH: Weinheim, **2008**, 2nd ed..

(2) (a) Johansson Seechurn, C. C. C.; Kitching, M. O.; Colacot, T. J.; Snieckus, V. *Angew. Chem. Int. Ed.* **2012**, *51*, 5062. (b) Colacot, T. *New Trends in Cross-Coupling: Theory and Applications*; Royal Society of Chemistry: Cambridge, **2015**. (c) Whitcombe, N. J.; Hii, K. K.; Gibson, S. E. *Tetrahedron* **2001**, *57*, 7449. (d) Cabri, W.; Candiani, I. *Acc. Chem. Res.* **1995**, *28*, 2. (e) Felpin, F.-X.; Nassar-Hardy, L.; Le Callonnec, F.; Fouquet, E. *Tetrahedron* **2011**, *67*, 2815. (f) Beletskaya, I. P.; Cheprakov, A. V. *Chem. Rev.* **2000**, *100*, 3009.

(3) (a) Shaughnessy, K. H.; Kim, P.; Hartwig, J. F. *J. Am. Chem. Soc.* **1999**, *121*, 2123. (b) Littke, A. F.; Fu, G. C. *J. Org. Chem.* **1999**, *64*, 10.

(4) Littke, A. F.; Fu, G. C. *J. Am. Chem. Soc.* **2001**, *123*, 6989.

(5) Barnard, C. *Platin. Met. Rev.* **2008**, *52*, 38.

(6) Yin, L.; Liebscher, J. *Chem. Rev.* **2007**, *107*, 133.

(7) (a) Organ, M. G.; Chass, G. A.; Fang, D.-C.; Hopkinson, A. C.; Valente, C. *Synthesis* **2008**, 2776. (b) Valente, C.; Çalimsiz, S.; Hoi, K. H.; Mallik, D.; Sayah, M.; Organ, M. G. *Angew. Chem. Int. Ed.* **2012**, *51*, 3314. (c) Kinzel, T.; Zhang, Y.; Buchwald, S. L. *J. Am. Chem. Soc.* **2010**, *132*, 14073. (d) Marion, N.; Nolan, S. P. *Acc. Chem. Res.* **2008**, *41*, 1440.

(8) (a) Stambuli, J. P.; Kuwano, R.; Hartwig, J. F. *Angew. Chem. Int. Ed.* **2002**, *41*, 4746. (b) Prashad, M.; Mak, X. Y.; Liu, Y.; Repic, O. *J. Org. Chem.* **2003**, *68*, 1163. (c) Hooper, M. W.; Utsunomiya, M.; Hartwig, J. F. *J. Org. Chem.* **2003**, *68*, 2861. (d) Christmann, U.; Vilar, R. *Angew. Chem. Int. Ed.* **2005**, *44*, 366. (e) Hama, T.; Culkin, D. A.; Hartwig, J. F. *J. Am. Chem. Soc.* **2006**, *128*, 4976. (f) Hill, L. L.; Crowell, J. L.; Tutwiler, S. L.; Massie, N. L.; Hines, C.; Griffin, S. T.; Rogers, R. D.; Shaughnessy, K. H.; Grasa, G. A.; Johansson Seechurn, C. C. C.; Li, H.; Colacot, T. J.; Chou, J.; Woltermann, C. J. *J. Org. Chem.* **2010**, *75*, 6477. (g) Proutière, F.; Aufiero, M.; Schoenebeck, F. *J. Am. Chem. Soc.* **2012**, *134*, 606. (h) Mamone, P.; Grunberg, M. F.; Fromm, A.; Khan, B. A.; Goošen, L. J. *Org. Lett.* **2012**, *14*, 3716.

(9) (a) Colacot, T. *Platin. Met. Rev.* **2009**, *53*, 183. (b) Pd(I)–iodo dimer **2** was first synthesized by: Vilar, R.; Mingos, D. M. P.; Cardin, C. J. *J. Chem. Soc., Dalton Trans.* **1996**, 4313. (c) An improved synthesis of the corresponding Pd(I)–bromo dimer 1 for commercial applications was developed by Colacot and coworkers (Patent): Colacot, T. J.; Hooper, M. W.; Grasa, G. A. (Johnson Matthey) WO2011/12889A1, **2011**.

(10) (a) Bonney, K. J.; Proutière, F.; Schoenebeck, F. *Chem. Sci.* **2013**, *4*, 4434. (b) Kalvet, I.; Bonney, K. J.; Schoenebeck, F. *J. Org. Chem.* **2014**, *79*, 12041.

(11) (a) Yin, G.; Kalvet, I.; Schoenebeck, F. *Angew. Chem. Int. Ed.* **2015**, *54*, 6809. (b) Aufiero, M.; Sperger, T.; Tsang, A. S.; Schoenebeck, F. *Angew. Chem. Int. Ed.* **2015**, *54*, 10322.

(12) Aufiero, M.; Scattolin, T.; Proutière, F.; Schoenebeck, F. *Organometallics* **2015**, *34*, 5191.

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(13) Mayr's scale is based on the addition of nucleophiles to carbocations and Michael acceptors; see: (a) Maji, B.; Stephenson, D. S.; Mayr, H. *ChemCatChem* **2012**, *4*, 993. (b) Richter, D.; Mayr, H. *Angew. Chem. Int. Ed.* **2009**, *48*, 1958. (c) Kempf, B.; Hampel, N.; Ofial, A. R.; Mayr, H. *Chem. Eur. J.* **2003**, *9*, 2209.

(14) ^{31}P NMR only shows the presence of the free phosphine ligand *t*-Bu_3P. This is most likely a result of fast conversion of the Pd(I)–bromo dimer to the monophosphine Pd(0)–P*t*-Bu_3, an accumulation of which leads to decomposition to Pd black and free phosphine ligand. Please see ref. 12 for further information.

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