Palladium(II) Pyrazolin-4-ylidenes: Substituent Effects on the Formation and Catalytic Activity of Pyrazole-Based Remote NHC Complexes

Yuan Han, Li Juan Lee, and Han Vinh Huynh*

Department of Chemistry, National University of Singapore, 3 Science Drive 3, Singapore 117543, Singapore

Received November 14, 2008

Three 4-iodopyrazolium salts with 3,5-dimethyl (**3a**), 3,5-diphenyl (**3b**), and 3,5-diisopropyl (**3c**) substituents, respectively, were synthesized using a modular approach. The oxidative addition of **3a**−**c** to $Pd_2(dba)_3/PPh_3$ afforded products (*trans*-**4a**, *cis*-/*trans*-**4b** and **4c**) of different geometries or connectivities, indicating a dramatic substituent effect on the formation of pyrazolin-4-ylidene complexes. In addition, the reactions of **3a**−**c** with $Pd_2(dba)_3$ in the presence of pyridine yielded new mixed pyrazolin-4-ylidene/pyridine complexes (**5a**−**c**). All complexes have been fully characterized by multinuclear NMR spectroscopies, ESI mass spectrometry, and X-ray diffraction analyses. Furthermore, an initial catalytic study on Suzuki−Miyaura and Mizoroki−Heck cross-coupling reactions also reveals a significant substituent effect on catalytic activities.

Introduction

Recent studies pioneered by Raubenheimer and co-workers have shown that complexes containing N-heterocyclic carbene ligands with remote heteroatoms (*r*NHC) exhibit better catalytic performance compared to their classical NHC analogues in certain C−C coupling reactions.[1] The superiority of the former may stem from the stronger σ-donor ability of *r*NHC ligands as supported by computational studies.[1a,2] Despite these promising properties, *r*NHCs have not yet attracted the same degree of attention as common NHCs. In contrast to the versatile structures known for normal NHCs,[3] the structure of *r*NHCs was limited to one-N-six-membered ring motifs[1,2,4] derived from pyridine (**A**), quinoline (**B**), and acridine (**C**) (Figure 1). Cyclopropenylidenes (**D**)[5] are not NHCs, but also contain a remote heteroatom with respect to the carbene center. Only recently, we introduced two-N-five-membered *r*NHCs derived from pyrazole (**E**)[6] as direct isomers to standard NHCs to this little explored field.

In our previous reports, we have established a facile synthetic pathway to Pd(II) pyrazolin-4-ylidene complexes supported by phosphines via oxidative addition of 4-iodopyrazolium salts to $Pd_2(dba)_3/PPh_3$.[6] As a continuation of our research and with the attempt to tune the sterics and electronics around the carbene carbon, we herein present results of our study on the influence of 3,5-substituents in pyrazolin-4-ylidenes on complexation. In addition, the synthesis of new mixed *r*NHC-pyridine complexes is also described, extending the scope of pyrazolin-4-ylidene ligands to phosphine-free systems. A preliminary study investigating the influence of 3,5-substituents on the catalytic activities of the resulting complexes in Suzuki−Miyaura and Mizoroki−Heck coupling reactions is included as well.

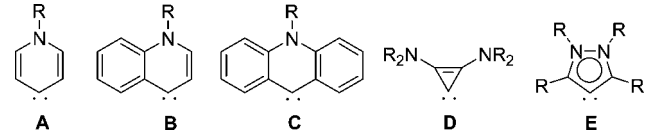


Figure 1. Different types of *r*NHCs: pyridin-4-ylidene (**A**); quinolin-4-ylidene (**B**); acridin-9-ylidene (**C**); cyclopropenylidene (**D**); pyrazolin-4-ylidene (**E**).

Results and Discussion

Synthesis and Characterizations of 4-Iodopyrazolium Salts. Three 4-iodopyrazolium salts (**3a**−**c**) that differ only in their 3,5-substituents have been synthesized in three steps as depicted in Scheme 1. This modular approach is highly desirable, as ligands with a wide range of substitution patterns can be conveniently obtained through the condensation of readily available diketones with substituted hydrazines, which in turn allows facile fine-tuning of steric and electronic properties of the resulting *r*NHC ligands. The introduction of an iodo substituent at the 4-position in the second step deactivates the pyrazole for electrophilic attack, and thus relatively strong alkylating reagents such as alkyl iodides and Meerwein's salts are required. Alkyl bromides generally afforded only negligible yields even under harsh reaction conditions and prolonged reaction time. When alkyl iodides are employed, the 4-iodopyrazole has to be heated under reflux either with a large excess

* Corresponding author. E-mail: chmhhv@nus.edu.sg.

(1) (a) Schneider, S. K.; Roembke, P.; Julius, G. R.; Loschen, C.; Raubenheimer, H. G.; Frenking, G.; Herrmann, W. A. *Eur. J. Inorg. Chem.* **2005**, 2973. (b) Schneider, S. K.; Roembke, P.; Julius, G. R.; Raubenheimer, H. G.; Herrmann, W. A. *Adv. Synth. Catal.* **2006**, *348*, 1862. (c) Schneider, S. K.; Rentzsch, C. F.; Krüger, A.; Raubenheimer, H. G.; Herrmann, W. A. *J. Mol. Catal. A: Chem.* **2007**, *265*, 50.

(2) Schneider, S. K.; Julius, G. R.; Loschen, C.; Raubenheimer, H. G.; Frenking, G.; Herrmann, W. A. *Dalton Trans.* **2006**, 1226.

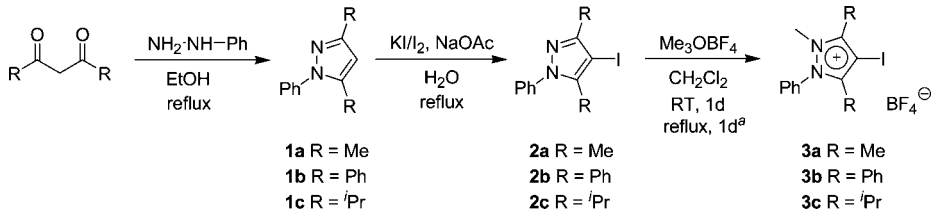
(3) For a recent review, see: Hahn, F. E.; Jahnke, M. C. *Angew. Chem., Int. Ed.* **2008**, *47*, 3122.

(4) Meyer, W. H.; Deetlefs, M.; Pohlmann, M.; Scholz, R.; Esterhuysen, M. W.; Julius, G. R.; Raubenheimer, H. G. *Dalton Trans.* **2004**, 413.

(5) (a) Tamm, M.; Grzegorzewski, A.; Hahn, F. E. *J. Organomet. Chem.* **1995**, *501*, 309. (b) Lavallo, V.; Canac, Y.; Donnadieu, B.; Schoeller, W. W.; Bertrand, G. *Science* **2006**, *312*, 722. (c) Lavallo, V.; Ishida, Y.; Donnadieu, B.; Bertrand, G. *Angew. Chem., Int. Ed.* **2006**, *45*, 6652. (d) Schoeller, W. W.; Frey, G. D.; Bertrand, G. *Chem.−Eur. J.* **2008**, *14*, 4711. (e) Kuchenbeiser, G.; Donnadieu, B.; Bertrand, G. *J. Organomet. Chem.* **2008**, *693*, 899. (f) Holschumacher, D.; Hrib, C. G.; Jones, P. G.; Tamm, M. *Chem. Commun.* **2007**, 3661.

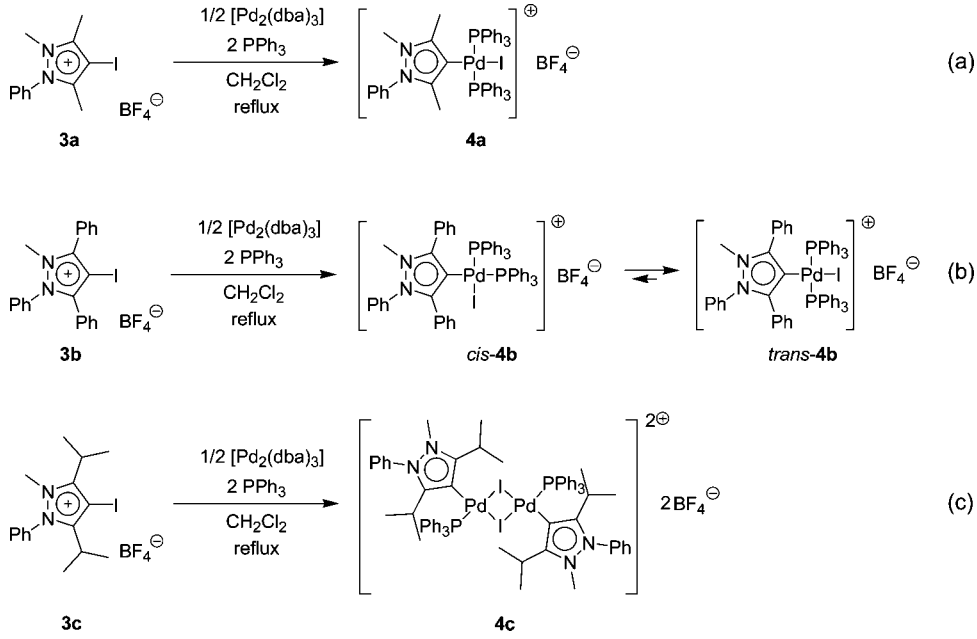
10.1021/om8010849 CCC: $40.75
Publication on Web 04/08/2009

Scheme 1. Synthetic Pathway to 4-Iodopyrazolium Salts 3a−c[a]



[a] Only for the synthesis of **3b** and **3c**.

Scheme 2. Synthesis of Pyrazolin-4-ylidene−Phosphine Complexes 4a−c



or in neat alkylating agent in order to obtain a reasonable yield.[6a] However, when Meerwein's stronger trimethyloxonium salt is used, the alkylation can proceed smoothly with a stoichiometric amount of the reagent and under milder reaction conditions. Furthermore, it was found that the rate of alkylation is also affected by the 3,5-substituents. Correspondingly, the reaction of **2b** and **2c**, bearing bulkier 3,5-diphenyl and 3,5-diisopropyl substituents, respectively, required heating under reflux for an additional day in order to obtain **3b** and **3c** in good yields.

The formation of all three 4-iodopyrazolium salts was confirmed by a base peak in the positive ESI-MS spectra at m/z = 313 (**3a**), 437 (**3b**), and 369 (**3c**), respectively, corresponding to the $[M - BF_4]^+$ fragment. In addition, the ^{13}C NMR spectra revealed C−I carbon resonances at 67.4 ppm (**3a**), 68.5 ppm (**3b**), and 60.7 ppm (**3c**), respectively, which are shifted downfield upon N-methylation with respect to the analogous carbon resonances for their neutral precursors (**2a−c**). Interestingly, these chemical shifts decrease in the order **3b** > **3a** > **3c**, in accordance with the electron-donating ability of the 3,5-substituents Ph (**3b**) < Me (**3a**) < ^{i}Pr (**3c**). Two singlets with an intensity ratio of ∼1:4 are observed in the ^{19}F NMR spectrum for the BF_4^- counteranion in each salt, due to the presence of two NMR-active isotopes ^{10}B and ^{11}B.

Synthesis and Characterizations of Pd(II) Pyrazolin-4-ylidene-Phosphine Complexes. In an attempt to obtain cationic Pd(II) *r*NHC-phosphine complexes, $Pd_2(dba)_3$ was treated with 2 equiv of **3a/b/c** and 4 equiv of PPh_3 in dichloromethane under reflux for 6 h according to our previously reported procedure (Scheme 2).[6b] Interestingly, these three reactions gave rise to products different in geometry or connectivity from each other, indicating a dramatic influence of the 3,5-substituents in *r*NHC ligands on complexation.

As shown in Scheme 2a, the reaction of **3a**, bearing the least bulky 3,5-dimethyl substituents, afforded the cationic complex *trans*-**4a** in quantitative yield. The trans configuration of **4a** is indicated by its ^{31}P NMR spectrum, which shows only one signal at 22.9 ppm, suggesting two equivalent phosphine ligands. This chemical shift is similar to those previously reported for other *trans*-$[PdI(rNHC)(PPh_3)_2]^+$ complexes based on the pyrazolin-4-ylidene system.[6b] Furthermore, the ^{13}C NMR signals for the carbenoid carbon and the two adjacent carbon atoms C3/C5 in complex **4a** are observed at 128.3, 145.1, and 145.6 ppm, respectively. All these signals appear as triplets due to heteronuclear coupling with constants of $^2J(C,P)$ = 7.3 Hz and $^3J(C,P)$ = 3.2 Hz, respectively, again corroborating the trans arrangement of the two phosphine ligands. Although the carbenoid resonance of 128.3 ppm is more upfield than the values commonly observed for analogous Pd(II) complexes of other

(6) (a) Han, Y.; Huynh, H. V. *Chem. Commun.* **2007**, 1089. (b) Han, Y.; Huynh, H. V.; Tan, G. K. *Organometallics* **2007**, *26*, 6581. Of close resemblance to our pyrazolin-4-ylidene ligands are five-membered-ring bent allenes and their complexes reported by Bertrand and co-workers very recently. Lavallo, V.; Dyker, C. A.; Donnadieu, B.; Bertrand, G. *Angew. Chem., Int. Ed.* **2008**, *47*, 5411. These allenes differ from our pyrazolin-4-ylidenes only in their N- and 3,5-substituents. However, we are in favor of considering them as *r*NHCs due to the bond parameters obtained from the molecular structures, which suggest an aromatic five-membered ring.

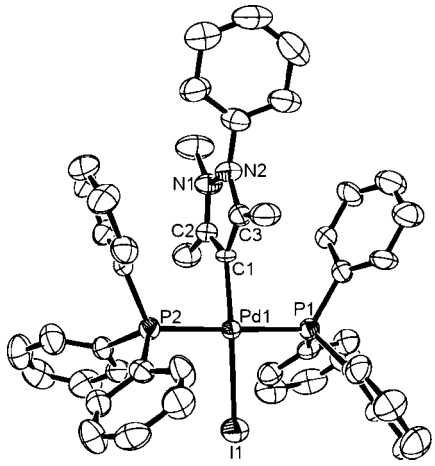


Figure 2. Molecular structure of the complex cation of *trans*-**4a**·Me_2CO showing 50% probability ellipsoids. BF_4^- counterion, solvent molecule, and hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (deg): Pd1−C1 2.006(8), Pd1−I1 2.6717(13), Pd1−P1 2.326(3), Pd1−P2 2.332(3), C1−C2 1.415(13), C1−C3 1.392(12), N1−C2 1.318(12), N2−C3 1.355(12), N1−N2 1.360(11); C1−Pd1−P1 90.2(3), C1−Pd1−P2 89.0(3), P1−Pd1−I1 90.75(7), P2−Pd1−I1 90.13(7), C2−C1−C3 103.8(8).

*r*NHCs[4] or standard NHCs,[1a,7] it is still significantly downfield-shifted by $\Delta\delta = 60.9$ ppm compared to the C4 carbon resonances in its ligand precursor.

Single crystals of complex **4a** were obtained by slow evaporation of a concentrated acetone/hexane solution and analyzed by X-ray diffraction. The molecular structure is depicted in Figure 2, and selected crystallographic data are summarized in the Supporting Information. As found in solution, complex **4a** adopts the expected *trans* configuration of the phosphine ligands in an essentially square-planar coordination geometry. The Pd−P bonds of 2.326(3) and 2.332(3) Å and Pd−$C_{carbene}$ bond of 2.006(8) Å fall in the range reported for other Pd(II) pyrazolin-4-ylidene complexes.[6] Furthermore, the carbene ring plane is oriented almost perpendicular to the $PdICP_2$ coordination plane with a dihedral angle of 89.63° to relieve steric congestion.

In contrast to the formation of *trans*-**4a**, the reaction involving **3b**, bearing the bulkier 3,5-diphenyl substituents, afforded a *cis*-configured complex *cis*-**4b** as the kinetically favored product, which slowly converts to the thermodynamically more stable *trans*-isomer upon standing in solution (Scheme 2b). Complex *cis*-**4b** was isolated in 40% yield after recrystallization from a concentrated CH_2Cl_2/hexane solution. In the literature, most complexes of the type $[PdXL(PR_3)_2]^+$ (X = halide; L = NHC, *r*NHC, or Fisher-carbene; R = aryl or alkyl) adopt a *trans* configuration with only two exceptions.[1b,8] For example, Raubenheimer and co-workers reported that the complex *cis*-$[PdCl(NHC)(PPh_3)_2]^+BF_4^-$ derived from a quinolinium salt was observed only at low temperatures of −20 °C or below, whereas at room temperature its *trans*-isomer was observed exclusively. In our case, the isomerization of *cis*-**4b** to *trans*-**4b** in dichloromethane at ambient temperature is slow enough to allow for the isolation of the former. The ^{31}P NMR spectrum of *cis*-**4b** shows two doublets at 28.7 and 16.3 ppm with a coupling constant of $^2J(P,P) = 24.8$ Hz, pointing to two inequivalent phosphine ligands and thus a *cis* geometry. In the ^{13}C NMR spectrum, two downfield doublets of doublets are observed at 150.5 and 148.5 ppm, corresponding to the C3/C5 carbon atoms in the *r*NHC ring. In addition, the carbenoid carbon also appears as a doublet of doublets centered at 125.0 ppm with $^2J(P_{trans},C) = 143.9$ Hz and $^2J(P_{cis},C) = 5.5$ Hz, due to the coupling to two inequivalent phosphorus atoms.

Upon standing in CD_2Cl_2, *cis*-**4b** slowly isomerizes to *trans*-**4b**, as monitored by ^{31}P NMR spectroscopy, which shows a gradual decrease of the two doublets for *cis*-**4b** accompanied by a slow increase of one singlet at 20.3 ppm for *trans*-**4b**. A comparison of their integrals reveals a conversion of ∼9% after 28 days. However, this isomerization process is much faster in more polar solvents such as CH_3CN and DMSO. For example, after standing in CD_3CN for 2 days, *cis*-**4b** has completely converted to *trans*-**4b**. Such a solvent dependence of the *cis*−*trans* isomerization was also reported for a Pt(II) complex of the type $[PtCl(rNHC)(PPh_3)_2]^+BF_4^-$, where the *r*NHC is a quinoline-4-ylidene ligand.[4] The thermodynamic preference of *trans*-**4b** over *cis*-**4b** can be explained by the transphobia effect, a term proposed by Vicente and co-workers[9] for the difficulty of placing a phosphine ligand *trans* to carbon donors such as aryl or aroyl in Pd complexes. Apparently, the isomerization of *cis*-**4b** to *trans*-**4b** suggests that this transphobia effect is also valid for the carbene−phosphine pair.

As expected, the ^1H NMR spectrum of *trans*-**4b** shows a better resolved pattern in the aromatic region compared to that of *cis*-**4b**, which is dominated by broad signals. More importantly and different from the two doublets of doublets observed for the C3/C5 carbon atoms in *cis*-**4b**, the analogous carbon resonances in *trans*-**4b** arise at 149.8 and 148.6 ppm as two triplets due to coupling with two equivalent phosphine ligands with a constant of $^3J(P,C) = 3.7$ Hz. However, the carbene signal for *trans*-**4b** could not be clearly indentified due to the interference of many aromatic signals in the same range of 127−133 ppm.

Single crystals were grown by slow evaporation of a concentrated CH_2Cl_2/hexane solution (*cis*-**4b**) or by diffusion of diethyl ether into a CH_3CN solution (*trans*-**4b**) and subjected to X-ray diffraction analysis. Their molecular structures are shown in Figure 3. The Pd−$C_{carbene}$ [2.038(4) Å] and Pd−I [2.6539(4) Å] bond lengths in *cis*-**4b** are very similar to the corresponding parameters [Pd−$C_{carbene}$ = 2.033(7) Å; Pd−I = 2.6501(8) Å] in *trans*-**4b**. However, a comparison of the Pd−$C_{carbene}$ bonds in *trans*-**4b** and *trans*-**4a** [2.006(8) Å] revealed a pronounced elongation in the former. This may be attributed to the bulkier but less electron-donating Ph substituents in *trans*-**4b** compared to the Me groups in *trans*-**4a**. Finally, comparison of the Pd−P bonds in complex *cis*-**4b** revealed that the one *trans* to the *r*NHC ligand is significantly longer than that *trans* to the iodo ligand, which is consistent with a stronger *trans* influence of the *r*NHC ligand.

The oxidative addition of the bulkiest and electron-richest salt **3c** proved to be very difficult and again dramatically different from **3a** and **3b**, affording a dinuclear, dicationic complex **4c** in a low yield of 8% (Scheme 2c). Attempts to

(7) Mathews, C. J.; Smith, P. J.; Welton, T.; White, A. J. P.; Williams, D. J. *Organometallics* **2001**, *20*, 3848.

(8) Kremzow, D.; Seidel, G.; Lehmann, C. W.; Fürstner, A. *Chem.−Eur. J.* **2005**, *11*, 1833.

(9) (a) Vicente, J.; Abad, J. A.; Frankland, A. D.; Ramírez de Arellano, M. C. *Chem.−Eur. J.* **1999**, *5*, 3066. (b) Vicente, J.; Arcas, A.; Bautista, D.; Jones, P. G. *Organometallics* **1997**, *16*, 2127. (c) Vicente, J.; Arcas, A.; Blasco, M. A.; Lozano, J.; Ramírez de Arellano, M. C. *Organometallics* **1998**, *17*, 5374. (d) Vicente, J.; Chicote, M. T.; Rubio, C.; Ramírez de Arellano, M. C.; Jones, P. G. *Organometallics* **1999**, *18*, 2750. (e) Vicente, J.; Arcas, A.; Fernández-Hernández, J.; Bautista, D. *Organometallics* **2001**, *20*, 2767.

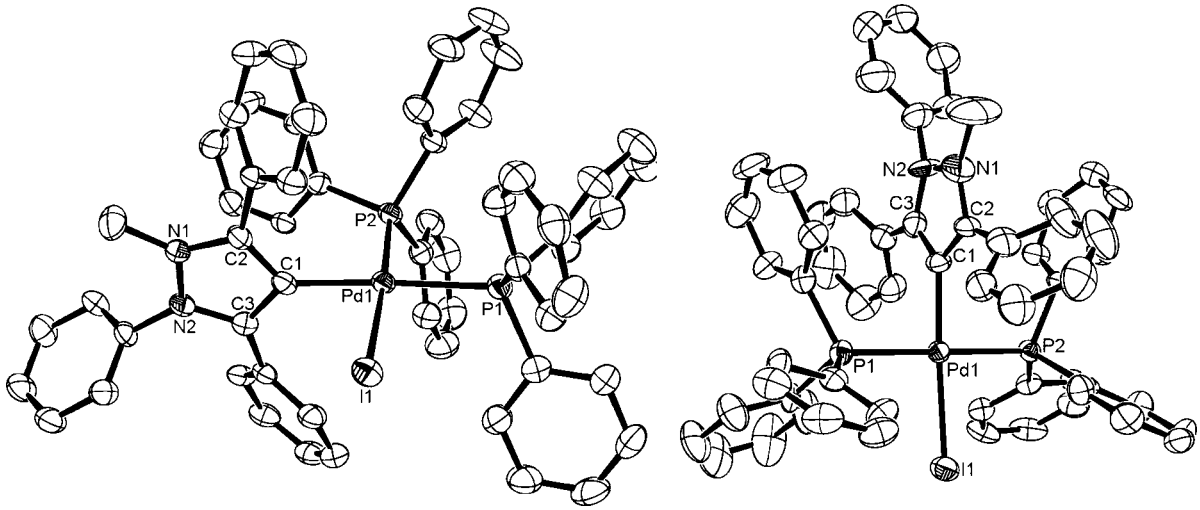


Figure 3. Molecular structures of the complex cations of *cis*-**4b**·CH_2Cl_2 (left) and *trans*-**4b**·0.5CH_3CN (right) showing 50% probability ellipsoids. BF_4^- counterion, solvent molecules, and hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (deg): *cis*-**4b**·CH_2Cl_2: Pd1−C1 2.038(4), Pd1−I1 2.6539(4), Pd1−P1 2.3861(12), Pd1−P2 2.2882(11), C1−C2 1.402(6), C1−C3 1.397(6), N1−C2 1.350(5), N2−C3 1.361(5), N1−N2 1.370(5); C1−Pd1−P2 89.81(12), P1−Pd1−I1 86.12(3), C1−Pd1−I1 86.95(11), P1−Pd1−P2 97.16(4), C2−C1−C3 104.4(4). *trans*-**4b**·0.5CH_3CN: Pd1−C1 2.033(7), Pd1−I1 2.6501(8), Pd1−P1 2.356(2), Pd1−P2 2.351(2), C1−C2 1.411(11), C1−C3 1.374(11), N1−C2 1.354(11), N2−C3 1.370(10), N1−N2 1.352(11); C1−Pd1−P1 89.5(2), C1−Pd1−P2 90.6(2), P1−Pd1−I1 92.17(5), P2−Pd1−I1 87.92(5), C2−C1−C3 106.1(7).

improve the yield of **4c** by varying stoichiometry and reaction conditions were met with limited success. In all cases, the majority of **3c** remained unreacted. Despite sufficient amount of phosphine, no mononuclear Pd(II) complex of the type $[PdI(r\text{NHC})(PPh_3)_2]^+BF_4^-$ was isolated from these attempts. A CH_2Cl_2 solution subjected to ESI mass spectrometry confirmed the identity of **4c** by a base peak at $m/z = 738$, corresponding to the $[M - 2BF_4]^{2+}$ fragment. However, the ^1H, ^{13}C, and ^{31}P NMR spectra of **4c** in CD_2Cl_2 are unexpectedly complicated. In the ^1H NMR spectrum, numerous doublets of different intensities arise in the range 0.46−1.48 ppm, which are assignable to the isopropyl-Me groups of 3,5-substituents. In addition, a few sets of overlapping septets and singlets are observed in the range 3.27−3.72 ppm arising from the isopropyl-CH protons and the N-Me groups, respectively. Correspondingly, the ^{13}C and ^{31}P NMR spectra are also rather complicated, indicating the presence of an isomeric mixture in solution. In principle, four geometric isomers of **4c**, namely *trans-anti*, *trans-syn*, *cis-anti*, and *cis-syn* (*trans*/*cis* refers to the arrangement of the PPh_3 ligands; *anti*/*syn* refers to the orientation of the unsymmetrical *r*NHC ligands) are feasible, which would lead to complicated spectra.

On the other hand, the respective NMR spectra of **4c** measured in CD_3CN are much simpler. In the ^1H NMR spectrum, four well-resolved doublets of equal intensity are observed at 1.39, 1.11, 0.88, and 0.35 ppm, each integrating to three protons and thus assigned to the isopropyl-Me groups. The isopropyl-CH protons resonate at 3.54 and 3.22 ppm as two septets. Correspondingly, the ^{13}C NMR spectra show four singlets in the range 19.6−21.0 ppm and another two singlets at 30.8 and 31.2 ppm for the isopropyl substituents. The carbene carbon resonates as a singlet at 106.3 ppm. Finally, the ^{31}P NMR spectrum shows only one singlet at 19.8 ppm for the phosphine ligand. The simple NMR spectra suggest the presence of only one complex in solution. We anticipate that upon dissolution in coordinating CD_3CN, **4c** is cleaved to form the mononuclear complex $[PdI(NCCH_3)(^i\text{Pr}_2\text{-}r\text{NHC})(PPh_3)]^+BF_4^-$ ($^i\text{Pr}_2$-*r*NHC = 3,5-diisopropyl-2-methyl-1-phenylpyrazolin-4-ylidene). At the moment, we are still not certain about the exact configuration of the four different ligands in this complex. However, it is expected that the $^i\text{Pr}_2$-*r*NHC and PPh_3 ligands are *cis* to each other, in line with the transphobia effect. The cleavage of **4c** by the solvent is also supported by the positive ESI mass spectrum measured of a CH_3CN solution, which shows a base peak at $m/z = 778$ corresponding to the $[PdI(NCCH_3)(^i\text{Pr}_2\text{-}r\text{NHC})(PPh_3)]^+$ cation and a smaller peak at $m/z = 737$ corresponding to the $[PdI(^i\text{Pr}_2\text{-}r\text{NHC})(PPh_3)]^+$ fragment.

X-ray diffraction analysis on single crystals of **4c** obtained by diffusion of diethyl ether into a concentrated CH_3CN solution of **4c** revealed an iodo-bridged dinuclear structure (Figure 4). The reversible decoordination of CH_3CN and formation of dimeric species under the influence of diethyl ether has been reported by us previously.[10] The molecular structure shows two essentially square-planar Pd(II) centers each coordinated by one phosphine and one *r*NHC ligand and bridged by two iodo ligands. The two $^i\text{Pr}_2$-*r*NHC ligands are oriented in a *trans-syn* fashion to each other. The $[Pd_2I_2]$ rhombus in **4c** is slightly bent with a hinge angle of ∼153°. Furthermore, the two Pd−I bonds *trans* to the *r*NHC ligand are notably longer than those *trans* to the PPh_3 ligand, confirming a stronger *trans* influence of the former. Efforts to obtain single crystals of the mononuclear complex $[PdI(NCCH_3)(^i\text{Pr}_2\text{-}r\text{NHC})(PPh_3)]^+BF_4^-$ in pure CH_3CN were unsuccessful.

The preferable formation of dinuclear **4c** over the hypothetical mononuclear $[PdI(^i\text{Pr}_2\text{-}r\text{NHC})(PPh_3)_2]^+BF_4^-$ complex could be explained by the strong electron-donating ability as well as the pronounced steric bulk of the 3,5-diisopropyl-2-methyl-1-phenylpyrazolin-4-ylidene ligand.

Synthesis and Characterizations of Pd(II) Pyrazolin-4-ylidene-Pyridine Complexes. To date, all known *r*NHC complexes contain PPh_3 as a co-ligand due to the ready availability of low-valent $[M(PPh_3)_4]$ (M = Ni, Pd, and Pt) as metal precursors. In an attempt to extend the scope of *r*NHC complexes we studied the feasibility of incorporating other donors such as pyridine. Hence, 2 equiv of pyrazolium precur-

(10) Han, Y.; Hong, Y.-T.; Huynh, H. V. *J. Organomet. Chem.* **2008**, *693*, 3159.

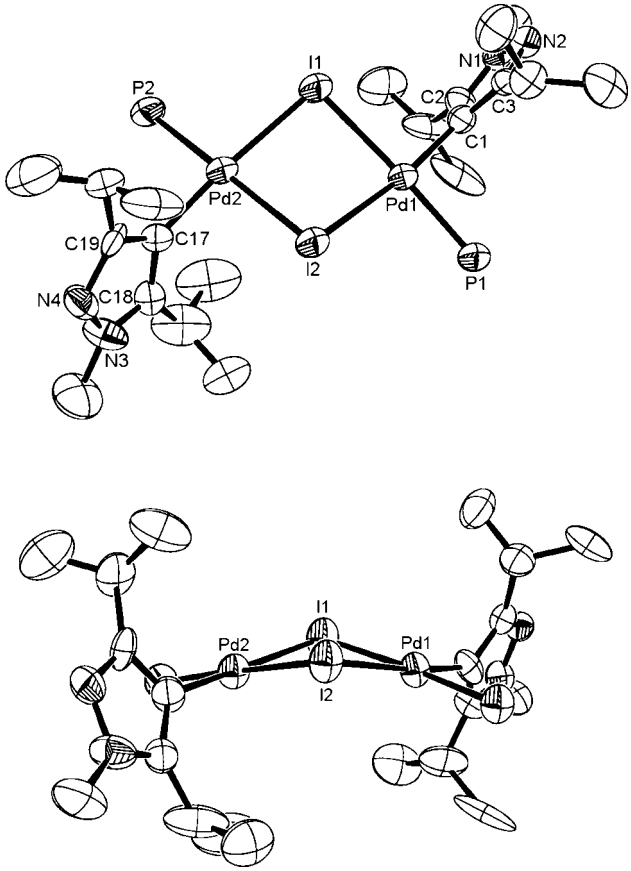
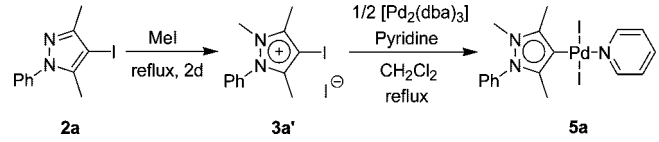


Figure 4. Molecular structure of complex **4c** showing 50% probability ellipsoids (upper: top view; lower: side view). BF_4^- counterion, hydrogen atoms, and all phenyl substituents are omitted for clarity. Selected bond lengths (Å) and angles (deg): Pd(1)−C(1) 2.023(16), Pd(1)−P(1) 2.267(5), Pd(1)−I(1) 2.6534(17), Pd(1)−I(2) 2.6783(17), Pd(2)−C(17) 1.998(17), Pd(2)−P(2) 2.283(5), Pd(2)−I(2) 2.6304(17), Pd(2)−I(1) 2.6825(17), C(1)−C(2) 1.36(2), C(1)−C(3) 1.35(2), N(1)−C(2) 1.36(2), N(2)−C(3) 1.351(17), N(1)−N(2) 1.323(18), C(17)−C(18) 1.43(2), C(17)−C(19) 1.41(2), N(3)−C(18) 1.307(19), N(4)−C(19) 1.41(2), N(3)−N(4) 1.378(19); C(1)−Pd(1)−P(1) 93.7(5), C(1)−Pd(1)−I(1) 88.3(4), P(1)−Pd(1)−I(2) 93.52(12), I(1)−Pd(1)−I(2) 84.56(5), C(17)−Pd(2)−P(2) 91.4(5), C(17)−Pd(2)−I(2) 88.6(5), P(2)−Pd(2)−I(1) 95.08(13), I(2)−Pd(2)−I(1) 84.92(5), C(3)−C(1)−C(2) 106.0(15), C(19)−C(17)−C(18) 104.5(15).

sors **3a/b/c** were reacted with $Pd_2(dba)_3$ and 4 equiv of pyridine in order to obtain cationic mixed *r*NHC-pyridine complexes of the type $[PdI(rNHC)(pyridine)_2]^+BF_4^-$. Surprisingly, these reactions afforded neutral diiodo complexes of the type $[PdI_2(rNHC)(pyridine)]$ (**5a**−**c**) in moderate to low yields of 48%, 65%, and 4%,[11] respectively (Scheme 3), and no cationic complex could be detected. In this series, the bulkiest and electron-richest precursor **3c** gave rise to a rather sluggish reaction, again highlighting the influence of 3,5-substituents on complexation reactions.

Scheme 4. Improved Synthesis of Complex 5a



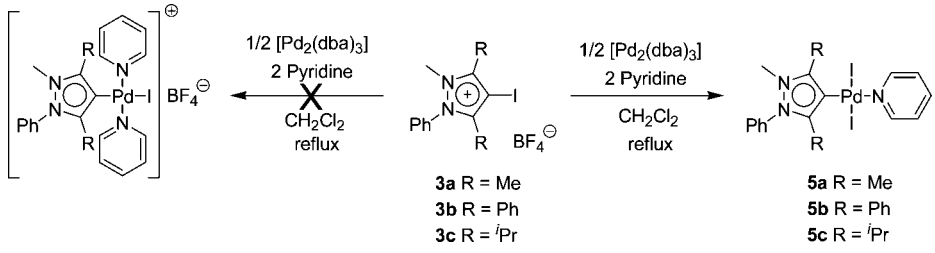
Since no additional iodide source was added, the formation of the neutral diiodo complexes **5a**−**c** required the sacrifice of 1 equiv of salt precursor **3a**−**c**, which explains their generally low yields. We anticipated that the use of 4-iodopyrazolium iodides instead of the BF_4^- salts would lead to an improvement. Hence, 4-iodo-2,3,5-trimethyl-1-phenylpyrazolium iodide (**3a′**) was prepared by refluxing **2a** in iodomethane to test this possibility. Indeed, by oxidative addition of 2 equiv of **3a′** to $Pd_2(dba)_3$ in the presence of pyridine the yield of complex **5a** could be improved from initially 48% to 75% (Scheme 4).

Positive mode ESI-MS spectra of complexes **5a**−**c** revealed isotopic clusters centered at $m/z = 498$ (**5a**), 622 (**5b**), and 553 (**5c**), respectively, corresponding to the $[M - I]^+$ fragment. Their ^1H NMR spectra corroborate the presence of the coordinated pyridine with the 2,6-py-H resonance shifted downfield by ∼0.5 ppm compared to the analogous signal for free pyridine. More importantly, the ^{13}C NMR signal of the carbenoid carbon is observed at 99.3 (**5a**), 104.5 (**5b**), and 95.0 (**5c**) ppm, respectively. These chemical shifts decrease in the order **5b** > **5a** > **5c**, which correlates to the electron-donating ability of the R substituents Ph (**5b**) < Me (**5a**) < ^{i}Pr (**5c**). The same trend was also observed when comparing the chemical shifts of the CI carbon atoms in their ligand precursors **3a**−**c** (vide supra).

Single-crystal X-ray diffraction analysis revealed that complexes **5a**−**c** all adopt a *trans* arrangement around the palladium center. Two molecules were found in the unit cell of **5c**, and one of them is depicted in Figure 5 as a representative. The carbene ring planes of all complexes are oriented almost perpendicularly to the $PdCNI_2$ coordination plane with dihedral angles ranging from 73.36^o to 87.32^o. On the other hand, the pyridine ring planes in **5a** and **5b** deviate from the perpendicular orientation with respect to the $PdCNI_2$ coordination plane with torsion angles of 66.75^o for **5a** and 64.34^o for **5b**. As an exception, that in **5c** adopts a nearly right angle (88.92^o and 89.22^o) to the coordination plane. The Pd−$C_{carbene}$ bonds of **5a**−**c** fall in a narrow range of 1.981(7)−1.987(4) Å, and the Pd−N bonds amounting to 2.121(6) (**5a**), 2.119(4) (**5b**), 2.116 (4), and 2.117(4) Å (**5c**), respectively, are comparable to those reported for analogues containing normal NHC ligands.[12]

Catalysis. The precatalysts **4a/b** and **5a/b** have been tested for their catalytic activities in Suzuki−Miyaura and Mizoroki−Heck cross-coupling reactions. Complexes **4c** and **5c** are excluded in these studies due to their generally low yields. The results summarized in Tables 1 and 2, respectively, involve coupling of simple substrates in order to gain some insight on the influence of 3,5-substituents in pyrazolin-4-ylidene ligands on the catalytic activity of their complexes. The Suzuki−Miyaura

Scheme 3. Synthesis of Pyrazolin-4-ylidene−Pyridine Complexes 5a−c



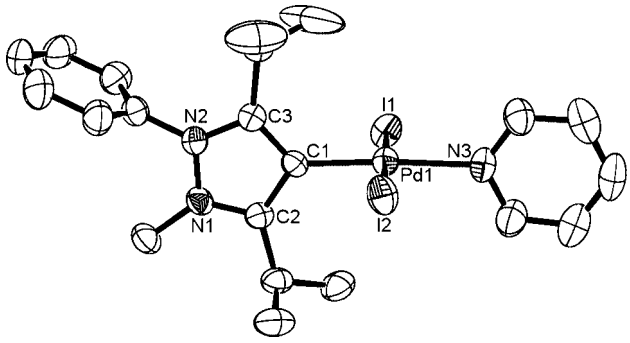
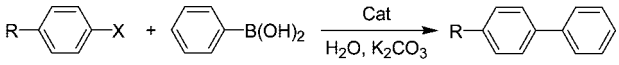


Figure 5. Molecular structure of complex **5c**·0.5H_2O showing 50% probability ellipsoids. The other molecule, hydrogen atoms, and solvent molecules are omitted for clarity. Selected bond lengths (Å) and angles (deg): Pd(1)−C(1) 1.983(5), Pd(1)−N(3) 2.116(4), Pd(1)−I(1) 2.6303(6), Pd(1)−I(2) 2.6268(6), C(1)−C(2) 1.405(7), C(1)−C(3) 1.390(7), N(1)−C(2) 1.346(6), N(2)−C(3) 1.355(6), N(1)−N(2) 1.358(6); C(1)−Pd(1)−I(2) 88.78(13), N(3)−Pd(1)−I(2) 89.10(12), C(1)−Pd(1)−I(1) 90.27(13), N(3)−Pd(1)−I(1) 91.86(12), C(3)−C(1)−C(2) 104.5(4).

Table 1. Suzuki−Miyaura Cross-Coupling Reactions Catalyzed by 4a/b and 5a/b in Aqueous Media[a]



X = Br, Cl
R = $COCH_3$, CHO, OCH_3

entry	catalyst	aryl halide	*t* [h]	temp [°C]	yield [%][b]
1	**4a**	4-bromobenzaldehyde	19	RT	96
2	**4b**	4-bromobenzaldehyde	19	RT	97
3	**5a**	4-bromobenzaldehyde	19	RT	55
4	**5b**	4-bromobenzaldehyde	19	RT	100
5	**4a**	4-bromoacetophenone	19	RT	94
6	**4b**	4-bromoacetophenone	19	RT	96
7	**5a**	4-bromoacetophenone	19	RT	31
8	**5b**	4-bromoacetophenone	19	RT	70
9	**4a**	4-bromoanisole	21	80	95[c]
10	**4b**	4-bromoanisole	21	80	98[c]
11	**5a**	4-bromoanisole	21	80	100[c]
12	**5b**	4-bromoanisole	21	80	100[c]
13	**4a**	4-chlorobenzaldehyde	21	80	39[c]
14	**4b**	4-chlorobenzaldehyde	21	80	50[c]
15	**5a**	4-chlorobenzaldehyde	21	80	21[c]
16	**5b**	4-chlorobenzaldehyde	21	80	52[c]

[a] Reaction conditions: 1 mmol of aryl halide; 1.2 mmol of phenylboronic acid; 3 mL of water; 1.5 equiv of K_2CO_3; 1 mol % of catalyst. [b] Yields were determined by ^1H NMR spectroscopy for an average of two runs. [c] With addition of 1.5 equiv of $[N(n\text{-}C_4H_9)_4]Br$.

cross-coupling reactions were performed in water under aerobic conditions employing 1 mol % catalyst loading to allow a direct comparison with our previously reported Pd(II) pyrazolin-4-ylidene complexes.[6b] All four complexes are able to couple activated aryl bromides at ambient temperature, affording moderate to good yields (entries 1−8, Table 1). As for the deactivated substrate 4-bromoanisole, very good yields could be achieved by increasing temperature and adding $[N(n\text{-}C_4H_9)_4]Br$ (TBAB) (entries 9−12, Table 1). However, these precatalysts are not very active toward the more difficult substrate 4-chlorobenzaldehyde, giving rise to only low to moderate yields (entries 13−16, Table 1) under the given conditions. Overall, it was found that complexes with the bulkier 3,5-diphenyl substituents are generally more active in the coupling of electron-poor aryl halides compared to their counterparts bearing 3,5-dimethyl substituents. Notably, such a substituent effect is more pronounced for the pyridine

Table 2. Mizoroki−Heck Cross-Coupling Reactions Catalyzed by 4a/b and 5a/b[a]

X=Br,Cl
R=CHO,CH_3CO, OCH_3

entry	catalyst	aryl halide	temp [°C]	*t* [h]	yield (%)[b]
1	**4a**	4-bromobenzaldehyde	120	5	100
2	**4b**	4-bromobenzaldehyde	120	5	100
3	**5a**	4-bromobenzaldehyde	120	5	92
4	**5b**	4-bromobenzaldehyde	120	5	100
5	**4a**	4-bromoacetophenone	120	22	82
6	**4b**	4-bromoacetophenone	120	22	85
7	**5a**	4-bromoacetophenone	120	22	36
8	**5b**	4-bromoacetophenone	120	22	31
9	**4a**	4-bromoanisole	140	24	33[c]
10	**4b**	4-bromoanisole	140	24	51[c]
11	**5a**	4-bromoanisole	140	24	20[c]
12	**5b**	4-bromoanisole	140	24	16[c]
13	**4a**	4-chlorobenzaldehyde	140	24	45[c]
14	**4b**	4-chlorobenzaldehyde	140	24	55[c]
15	**5a**	4-chlorobenzaldehyde	140	24	0[c]
16	**5b**	4-chlorobenzaldehyde	140	24	0[c]

[a] Reaction conditions: 1 mmol of aryl halide; 1.5 mmol of *tert*-butyl acrylate; 3 mL of DMF; 1.5 equiv of NaOAc; 1 mmol % of catalyst. [b] Yields were determined by ^1H NMR spectroscopy for an average of two runs. [c] With addition of 1.5 equiv of $[N(n\text{-}C_4H_9)_4]Br$.

complexes **5a/b** than for the phosphine complexes **4a/b**. A comparison among the phosphine complexes **4a/b** and the previously reported analogues with triflate counteranion[6b] revealed that **4b** performs slightly better than all the other complexes with 3,5-dimethyl substituents for all four substrates investigated here.

Table 2 shows the results obtained for Mizoroki−Heck cross-coupling reactions. The coupling of aryl halides with *tert*-butyl acrylate with 1 mol % catalyst loading in DMF under aerobic conditions was chosen as a standard test reaction in this study. Entries 1−4 show that all four precatalysts can couple activated 4-bromobenzaldehyde in quantitative or nearly quantitative yields at 120 °C within 5 h. However, the coupling reactions with 4-bromoacetophenone are much slower, affording yields ranging from 31% to 85% even after 22 h (entries 5−8). Furthermore, in cases of the more difficult substrates, e.g., 4-bromoanisole (entries 9−12) and 4-chlorobenzaldehyde (entries 13−16), only very low to moderate yields are obtained even at elevated temperature of 140 °C and with addition of TBAB. Again, it was found that complex **4b**, with the bulky 3,5-diphenyl substituents, shows overall the best performance in Mizoroki−Heck cross-coupling reactions. Moreover, the phosphine complexes **4a/b** are generally more active than their counterparts with pyridine bearing the same pyrazolin-4-yl ligands **5a/b**.

Conclusion

Three 4-iodopyrazolium salts with 3,5-dimethyl (**3a**), 3,5-diphenyl (**3b**), and 3,5-diisopropyl (**3c**) substituents, respectively, were prepared in good yields in an attempt to tune the sterics and electronics around the carbene center in the resulting pyrazolin-4-ylidene ligands. Oxidative addition of **3a−c** to $Pd_2(dba)_3/PPh_3$ afforded products (*trans*-**4a**, *cis*-/*trans*-**4b** and **4c**) different in geometry or connectivity, highlighting the dramatic influence of the 3,5-substituents in pyrazolin-4-ylidene

ligands on complexation. A detailed study on isomerization of complex **4b** revealed that *trans*-**4b** is the thermodynamically more stable isomer, in line with the transphobia effect. In addition, a series of new mixed *r*NHC-pyridine complexes derived from **3a**−**c** were also synthesized, which again demonstrates the substituent effect on complexation. The substituent effect on catalytic activities of complexes **4a/b** and **5a/b** was also observed in both Suzuki−Miyaura and Mizoroki−Heck cross-coupling reactions. Current research in our laboratory is ongoing to extend the scope of *r*NHCs to functionalized pyrazolin-4-ylidene complexes and their applications.

Experimental Section

General Considerations. Unless otherwise noted all operations were performed without taking precautions to exclude air and moisture. All solvents and chemicals were used as received without any further treatment if not noted otherwise. CH_2Cl_2 was dried with CaH_2 and distilled under nitrogen using standard Schlenk techniques. Tris(dibenzylideneacetone)dipalladium(0) was received from Alfa Aesar. 3,5-Dimethyl-1-phenylpyrazole (**1a**) and 4-iodo-3,5-dimethyl-1-phenylpyrazole (**2a**) were synthesized following reported procedures.[6b] 1,3,5-Triphenylpyrazole (**1b**) and 3,5-diisopropyl-1-phenylpyrazole (**1c**) were prepared in analogy with **1a**. 4-Iodo-1,3,5-triphenylpyrazole (**2b**) and 4-iodo-3,5-diisopropyl-1-phenylpyrazole (**2c**) were synthesized in analogy with **2a**. ^{1}H, ^{13}C, ^{31}P, and ^{19}F NMR spectra were recorded on Bruker ACF 300 and AMX 500 spectrometers, and the chemical shifts (δ) were internally referenced to the residual solvent signals relative to tetramethylsilane (^{1}H, ^{13}C) or externally to 85% H_3PO_4 (^{31}P) and CF_3CO_2H (^{19}F). Mass spectra were measured using a Finnigan MAT LCQ (ESI) spectrometer. Elemental analyses were performed on a Perkin-Elmer PE 2400 elemental analyzer at the Department of Chemistry, National University of Singapore.

1,3,5-Triphenylpyrazole (1b). 1b was synthesized from dibenzoylmethane (2.242 g, 10.0 mmol) and phenylhydrazinium chloride (1446 mg, 10.0 mmol). Yield: 2.542 g, 8.58 mmol, 86%. The purity of **1b** was verified by spectroscopic comparison with an authentic sample from Sigma-Aldrich.

3,5-Diisopropyl-1-phenylpyrazole (1c). 1c was synthesized from 2,2,6,6-tetramethyl-3,5-heptanedione (1.716 mL, 10.0 mmol) and phenylhydrazinium chloride (1.446 g, 10.0 mmol). Yield: 1.864 g, 8.16 mmol, 82%. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.47−7.33 (m, 5 H, Ar-H), 6.03 (s, 1 H, CH), 3.01 (m, ^3J(H,H) = 6.9 Hz, 2 H, C*H*(CH$_3$)$_2$), 1.30 (d, ^3J(H,H) = 6.9 Hz, 6 H, CH(C*H*$_3$)$_2$), 1.17 (d, ^3J(H,H) = 6.9 Hz, 6 H, CH(C*H*$_3$)$_2$). ^{13}C(^{1}H) NMR (75.47 MHz, $CDCl_3$): 159.9, 151.5 (s, CN), 140.8, 129.7, 128.4, 126.7 (s, Ar-C), 100.2 (s, CH), 28.6, 26.2 (s, *C*H(CH$_3$)$_2$), 23.7, 23.6 (s, CH(*C*H$_3$)$_2$). Anal. Calcd for $C_{15}H_{20}N_2$: C, 78.90; H, 8.83; N, 12.27. Found: C, 78.10; H, 8.39; N, 12.05. MS (ESI): *m*/*z* 229 [M + H]$^+$.

4-Iodo-1,3,5-triphenylpyrazole (2b). 2b was synthesized from **1b** (2.345 g, 7.91 mmol). Slow evaporation of a diethyl ether solution of the crude product afforded the pure product as colorless crystals. Yield: 1.455 g, 3.45 mmol, 43%. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.02−7.30 (m, 15 H, Ar-H). ^{13}C(^{1}H) NMR (75.47 MHz, $CDCl_3$): 153.7, 146.1 (s, CN), 140.6, 133.5, 131.2, 130.9, 129.7, 129.5, 129.3, 129.2, 129.1, 128.9, 128.2, 125.5 (s, Ar-C), 64.3 (s, CI). Anal. Calcd for $C_{21}H_{15}IN_2$: C, 59.73; H, 3.58; N, 6.63. Found: C, 59.56; H, 3.63; N, 6.65. MS (ESI): *m*/*z* 423 [M + H]$^+$.

4-Iodo-3,5-diisopropyl-1-phenylpyrazole (2c). 2c was synthesized. from **1c** (1.864 g, 8.16 mmol). Yield: 2.553 g, 7.21 mmol, 88%. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.49−7.31 (m, 5 H, Ar-H), 3.10 (m, ^3J(H,H) = 6.9 Hz, 1 H, C*H*(CH$_3$)$_2$), 3.04 (m, ^3J(H,H) = 6.9 Hz, 1 H, C*H*(CH$_3$)$_2$), 1.32 (d, ^3J(H,H) = 6.9 Hz, 6 H, CH(C*H*$_3$)$_2$), 1.31 (d, ^3J(H,H) = 6.9 Hz, 6 H, CH(C*H*$_3$)$_2$). ^{13}C(^{1}H) NMR (75.47 MHz, $CDCl_3$): 159.6, 148.0 (s, CN), 140.9, 129.8, 129.2, 127.4 (s, Ar-C), 59.2 (s, CI), 28.7, 27.3 (s, *C*H(CH$_3$)$_2$), 22.5, 21.4 (s, CH(*C*H$_3$)$_2$). Anal. Calcd for $C_{15}H_{19}IN_2$: C, 50.86; H, 5.41; N, 7.91. Found: C, 51.02; H, 5.24; N, 7.91. MS (ESI): *m*/*z* = 355 [M + H]$^+$.

4-Iodo-2,3,5-trimethyl-1-phenylpyrazolium Tetrafluoroborate (3a). 2a (597 mg, 2.0 mmol) was dissolved in dry CH_2Cl_2 (10 mL), and the resulting solution was transferred to a suspension of trimethyloxonium tetrafluoroborate (355 mg, 2.4 mmol) in dry CH_2Cl_2 (10 mL) via cannula. The reaction mixture was stirred at ambient temperature overnight under nitrogen. All volatiles were removed under reduced pressure, and the off-white solid was washed with diethyl ether (3 × 20 mL). The residue was dried in vacuo to give the product as a white powder. Yield: 761 mg, 1.9 mmol, 95%. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.61−7.75 (m, 5 H, Ar-H), 3.79 (s, 3 H, NCH$_3$), 2.63 (s, 3 H, CH$_3$), 2.29 (s, 3 H, CH$_3$). ^{13}C(^{1}H) NMR (75.48 MHz, $CDCl_3$): 150.8, 149.4 (s, *C*CH$_3$), 133.6, 132.0, 131.7, 129.4 (s, Ar-C), 67.4 (s, CI), 36.8 (s, NCH$_3$), 14.7, 14.4 (s, C*C*H$_3$). ^{19}F(^{1}H) NMR (282 MHz, $CDCl_3$): −77.94, −77.89 (s, 4 F, BF_4). Anal. Calcd for $C_{12}H_{14}BF_4IN_2$: C, 36.04; H, 3.53; N, 7.00. Found: C, 35.84; H, 3.50; N, 6.92. MS (ESI): *m*/*z* 313 [M − BF_4]$^+$.

4-Iodo-2,3,5-trimethyl-1-phenylpyrazolium Iodide (3a′). 2a (1.475 g, 4.95 mmol) was dissolved in iodomethane (2 mL) and heated under reflux for 2 days shielded from light. The reaction mixture was cooled to ambient temperature, and all volatiles were removed under reduced pressure. The residue was washed with diethyl ether and dried in vacuo to give the product as an off-white powder. Yield: 1.097 g, 2.49 mmol, 50%. ^{1}H NMR (500 MHz, d_6-DMSO): δ 7.81−7.70 (m, 5 H, Ar-H), 3.69 (s, 3 H, NCH$_3$), 2.56 (s, 3 H, CH$_3$), 2.21 (s, 3 H, CH$_3$). ^{13}C(^{1}H) NMR (125.76 MHz, d_6-DMSO): 148.8, 148.2 (s, *C*CH$_3$), 132.5, 131.4, 130.5, 128.7 (s, Ar-C), 70.2 (s, CI), 36.0 (s, NCH$_3$), 13.7, 13.4 (s, C*C*H$_3$). Anal. Calcd for $C_{12}H_{14}I_2N_2$: C, 32.75; H, 3.21; N, 6.37. Found: C, 32.71; H, 3.25; N, 6.25. MS (ESI): *m*/*z* 313 [M − I]$^+$.

4-Iodo-2-methyl-1,3,5-triphenylpyrazolium Tetrafluoroborate (3b). 2b (718 mg, 1.7 mmol) was dissolved in dry CH_2Cl_2 (10 mL), and the resulting solution was transferred to a suspension of trimethyloxonium tetrafluoroborate (281 mg, 1.9 mmol) in dry CH_2Cl_2 (10 mL) via cannula. The reaction mixture was stirred at ambient temperature for a day and then under reflux for another day under an inert nitrogen atmosphere. After cooling to ambient temperature, all volatiles were removed in vacuo. The residue was washed with diethyl ether (3 × 20 mL) and dried under vacuum to afford the product as a white powder. Yield: 873 mg, 1.66 mmol, 98%. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.79−7.24 (m, 15 H, Ar-H), 3.72 (s, 3 H, NCH$_3$). ^{13}C(^{1}H) NMR (75.48 MHz, $CDCl_3$): 152.6, 151.9 (s, CN), 132.9, 132.8, 132.1, 131.5, 131.0, 130.9, 130.1, 130.0, 129.3, 127.0, 126.9 (s, Ar-C), 68.5 (s, CI), 38.0 (s, NCH$_3$). ^{19}F(^{1}H) NMR (282 MHz, $CDCl_3$): −77.09, −77.14 (s, 4 F, BF_4). Anal. Calcd for $C_{22}H_{18}BF_4IN_2$: C, 50.42; H, 3.46; N, 5.35. Found: C, 50.41; H, 3.53; N, 5.34. MS (ESI): *m*/*z* 437 [M − BF_4]$^+$.

4-Iodo-3,5-diisopropyl-2-methyl-1-phenylpyrazolium Tetrafluoroborate (3c). 3c was prepared from **2c** (1.806 g, 5.1 mmol) in analogy with **3b** except that the residue was washed with ethyl acetate (4 × 20 mL) instead of diethyl ether (3 × 20 mL). Yield: 1.768 g, 3.88 mmol, 76%. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.71−7.61 (m, 5 H, Ar-H), 3.70 (s, 3 H, NCH$_3$), 3.44 (m, ^3J(H,H) = 7.1 Hz, 1 H, C*H*(CH$_3$)$_2$), 2.96 (m, ^3J(H,H) = 7.1 Hz, 1 H, C*H*(CH$_3$)$_2$), 1.51 (d, ^3J(H,H) = 7.1 Hz, 6 H, CH(C*H*$_3$)$_2$), 1.25 (d, ^3J(H,H) = 7.1 Hz, 6 H, CH(C*H*$_3$)$_2$). ^{13}C(^{1}H) NMR (75.47 MHz, $CDCl_3$): 155.8, 155.3 (s, CN), 133.7, 132.0, 131.5, 130.1 (s, Ar-C), 60.7 (s, CI), 36.4 (s, NCH$_3$), 29.2, 29.0 (s, *C*H(CH$_3$)$_2$), 20.0, 19.7 (s, CH(*C*H$_3$)$_2$). ^{19}F(^{1}H) NMR (282 MHz, $CDCl_3$): −77.32,

−77.38 (s, 4 F, BF_4). Anal. Calcd for $C_{16}H_{22}BF_4IN_2$: C, 42.14; H, 4.86; N, 6.14. Found: C, 41.96; H, 4.79; N, 6.08. MS (ESI): *m/z* = 369 $[M - BF_4]^+$.

***trans*-Iodo-(2,3,5-trimethyl-1-phenylpyrazolin-4-ylidene)bis(triphenylphosphine)palladium(II) Tetrafluoroborate (4a).** Tris(dibenzylideneacetone)dipalladium(0) (92 mg, 0.1 mmol) and triphenylphosphine (105 mg, 0.4 mmol) were dissolved in dry CH_2Cl_2 (20 mL) and stirred at ambient temperature for 10 min under nitrogen. To the resulting dark red solution was added a solution of **3a** (80 mg, 0.2 mmol) in dry CH_2Cl_2 (10 mL) via cannula. The reaction mixture was heated under reflux for 6 h in an inert nitrogen atmosphere and then cooled to ambient temperature. The resulting mixture was filtered through Celite, and the filtrate was extracted with H_2O (4 × 30 mL). The CH_2Cl_2 layer was dried over Na_2SO_4, and the solvent was reduced under vacuum to 1 mL. Adding diethyl ether to the concentrated solution resulted in an off-white precipitate, which was collected and washed with diethyl ether again (4 × 30 mL) to give the product as a light yellow powder. Yield: 204 mg, 0.2 mmol, 99%. ^{1}H NMR (500 MHz, CD_2Cl_2): δ 7.63−7.44 (m, 33 H, Ar-H), 6.77−6.76 (m, 2 H, Ar-H), 3.07 (s, 3 H, NCH_3), 2.00 (s, 3 H, CH_3), 1.73 (s, 3 H, CH_3). ^{31}P(^{1}H) NMR (202.45 MHz, CD_2Cl_2): 22.9 (s, 2 P, PPh_3). ^{19}F(^{1}H) NMR (282 MHz, CD_2Cl_2): −77.44, −77.38 (s, 4 F, BF_4). ^{13}C(^{1}H) NMR (125.77 MHz, CD_2Cl_2): 145.6 (t, ^3J(P,C) = 3.2 Hz, CN), 145.1 (t, ^3J(P,C) = 3.2 Hz, CN), 135.0 (t, $^{2/3}J$(P,C) = 6.0 Hz, Ar-C), 132.3 (s, Ar-C), 131.7 (t, ^1J(P,C) = 24.7 Hz, Ar-C), 131.5, 131.1, 130.8 (s, Ar-C), 128.6 (t, $^{2/3}J$(P,C)= 5.0 Hz, Ar-C), 128.3 (t, ^2J(P,C) = 7.3 Hz, $C_{carbene}$), 127.7 (s, Ar-C), 34.9 (s, NCH_3), 14.8, 14.8 (s, CH_3). Anal. Calcd for $C_{48}H_{44}BF_4IN_2P_2Pd$: C, 55.92; H, 4.30; N, 2.72. Found: C, 57.03; H, 4.61; N, 2.97 (better values could not be obtained with spectroscopically pure samples). MS (ESI): *m/z* 943 $[M - BF_4]^+$.

***cis*-Iodo-(2-methyl-1,3,5-triphenylpyrazolin-4-ylidene)bis(triphenylphosphine)palladium(II) Tetrafluoroborate (*cis*-4b).** Tris(dibenzylideneacetone)dipalladium(0) (92 mg, 0.1 mmol) and triphenylphosphine (105 mg, 0.4 mmol) were dissolved in dry CH_2Cl_2 (20 mL) and stirred at ambient temperature for 10 min under nitrogen. To the resulting dark red solution was added a solution of **3b** (105 mg, 0.2 mmol) in dry CH_2Cl_2 (10 mL) via cannula. The reaction mixture was heated under reflux for 6 h in an inert nitrogen atmosphere and then cooled to ambient temperature. The resulting mixture was filtered through Celite, and the solvent of the filtrate was removed in vacuo. The residue was washed with diethyl ether (4 × 30 mL) and then recrystallized by slow evaporation of a concentrated CH_2Cl_2/hexane solution. The resultant yellow crystals were collected by filtration and washed with small portions of acetone to afford the analytically pure product. Yield: 95 mg, 0.08 mmol, 40%. ^{1}H NMR (500 MHz, CD_2Cl_2): δ 8.24−6.94 (m, 45 H, Ar-H), 3.50 (s, 3 H, NCH_3). ^{13}C(^{1}H) NMR (125.76 MHz, CD_2Cl_2): 150.5, 148.5 (dd, ^3J(P,C) = 7.3 Hz, ^3J(P,C) = 3.7 Hz, CN), 135.5, 134.0, 133.1, 132.3, 132.0, 131.9, 131.8, 131.7, 131.2, 130.8, 130.5, 130.3, 130.1, 130.0, 129.0, 128.8, 128.6, 128.5, 128.4, 128.3, 128.2, 128.1, 128.0 (Ar-C, coupling to phosphorus is not considered), 125.0 (dd, $^2J(P,C)_{trans}$ = 143.9 Hz, $^2J(P,C)_{cis}$ = 5.5 Hz, $C_{carbene}$), 37.5 (s, NCH_3). ^{31}P(^{1}H) NMR (202.45 MHz, CD_2Cl_2): 28.7 (d, ^2J(P,P) = 24.8 Hz, 1 P, PPh_3), 16.3 (d, ^2J(P,P) = 24.8 Hz, 1 P, PPh_3). ^{19}F(^{1}H) NMR (282 MHz, CD_2Cl_2): −77.65, −77.70 (s, 4 F, BF_4). Anal. Calcd for $C_{58}H_{48}BF_4IN_2P_2Pd$: C, 60.31; H, 4.19; N, 2.43. Found: C, 60.04; H, 4.22; N, 2.49. MS (ESI): *m/z* 1067 $[M - BF_4]^+$.

***trans*-Iodo-(2-methyl-1,3,5-triphenylpyrazolin-4-ylidene)bis(triphenylphosphine)palladium(II) Tetrafluoroborate (*trans*-4b).** *cis*-**4b** (58 mg, 0.05 mmol) was dissolved in acetonitrile (5 mL) and kept for 3 days. Upon evaporation of acetonitrile at ambient temperature, the product was obtained as yellow crystals in a quantitative yield. ^{1}H NMR (500 MHz, d_6-DMSO): δ 7.71−6.52 (m, 45 H, Ar-H), 3.50 (s, 3 H, NCH_3). ^{13}C(^{1}H) NMR (125.76 MHz, d_6-DMSO): 149.8 (t, ^3J(P,C) = 3.7 Hz, CN), 148.6 (t, ^3J(P,C) = 3.7 Hz, CN), 135.5, 133.1, 132.3, 132.0, 131.5, 131.4, 131.2, 131.1, 131.0, 130.5, 130.3, 130.0, 129.9, 128.8, 128.7, 128.6, 128.5, 128.4, 128.3, 128.2, 1281.1, 128.0, 127.8 (Ar-C and $C_{carbene}$, coupling to phosphorus is not considered), 36.8 (s, NCH_3). ^{31}P(^{1}H) NMR (202.45 MHz, d_6-DMSO): 20.6 (s, 2 P, PPh_3). ^{19}F(^{1}H) NMR (282 MHz, d_6-DMSO): −72.30, −72.35 (s, 4 F, BF_4). Anal. Calcd for $C_{58}H_{48}BF_4IN_2P_2Pd$: C, 60.31; H, 4.19; N, 2.43. Found: C, 60.25; H, 4.35; N, 2.39. MS (ESI): *m/z* 1067 $[M - BF_4]^+$.

Di-μ-iodobis(3,5-diisopropyl-2-methyl-1-phenylpyrazolin-4-ylidene)bis(triphenylphosphine)dipalladium(II) Ditetrafluoroborate (4c). Tris(dibenzylideneacetone)dipalladium(0) (137 mg, 0.15 mmol) and triphenylphosphine (79 mg, 0.3 mmol) were dissolved in dry CH_2Cl_2 (20 mL) and stirred at ambient temperature for 10 min under nitrogen. To the resulting dark red solution was added a solution of **3c** (137 mg, 0.3 mmol) in dry CH_2Cl_2 (15 mL) via cannula. The reaction mixture was heated under reflux for 6 h in an inert nitrogen atmosphere and then cooled to ambient temperature. The resulting mixture was filtered through Celite, and the solvent of the filtrate was removed in vacuo. The residue was washed with diethyl ether (4 × 30 mL) and then recrystallized by slow evaporation of a concentrated methanol solution. The resultant crystals were collected by filtration and washed with ice-cold methanol. The remaining crystals were recrystallized twice by diffusing diethyl ether into a concentrated acetonitrile solution to afford the analytically pure product. Yield: 20 mg, 0.012 mmol, 8%. ^{1}H NMR (500 MHz, CD_2Cl_2): δ 7.71−7.01 (m, 40 H, Ar-H), 3.72−3.63 (m, 2 H, C*H*$(CH_3)_2$), 3.45−3.41 (m, 6 H, NCH_3), 3.38−3.26 (m, 2 H, C*H*$(CH_3)_2$), 1.48−1.38 (m, 6 H, CH(C*H*$_3)_2$), 1.19−1.11 (m, 6 H, CH(C*H*$_3)_2$), 1.05−0.97 (m, 6 H, CH(C*H*$_3)_2$), 0.53−0.46 (m, 6 H, CH(C*H*$_3)_2$). ^{31}P(^{1}H) NMR (202.45 MHz, CD_2Cl_2): 27.4, 27.3, 24.0, 23.9 (s, PPh_3). ^{19}F(^{1}H) NMR (282 MHz, CD_2Cl_2): −77.45, −77.50 (s, 4 F, BF_4). ^{13}C(^{1}H) NMR (125.77 MHz, CD_2Cl_2): 155.2−154.8 (m, CN), 135.0, 133.1, 133.0, 132.3, 132.2, 131.05, 131.01, 130.99, 130.8, 129.7, 129.50, 129.47, 129.27, 129.23, 129.19, 129.15, 129.09, 129.06 (Ar-C), 118.8 (d, ^2J(P,C) = 8.2 Hz, $C_{carbene}$), 35.5, 35.4 (s, NCH_3), 30.81, 30.80, 30.78, 30.49, 30.46, 30.41 (s, *C*H$(CH_3)_2$), 21.7, 21.60, 21.57, 20.68, 20.66, 20.61, 20.56, 20.55, 20.06, 20.00, 19.94, 19.92 (s, CH(*C*H$_3)_2$). Anal. Calcd for $C_{68}H_{74}B_2F_8I_2N_4P_2Pd_2$: C, 49.51; H, 4.52; N, 3.40. Found: C, 49.17; H, 4.70; N, 3.33. MS (ESI): *m/z* 738 $[M - 2BF_4]^{2+}$.

***trans*-Diiodo-(2,3,5-trimethyl-1-phenylpyrazolin-4-ylidene)(pyridine)palladium(II) (5a).** Method A: Tris(dibenzylideneacetone)-dipalladium(0) (247 mg, 0.27 mmol) and pyridine (88 μL, 1.09 mmol) were dissolved in dry CH_2Cl_2 (20 mL) and stirred at ambient temperature for 10 min under nitrogen. To the resulting dark red solution was added a solution of **3a** (216 mg, 0.54 mmol) in dry CH_2Cl_2 (10 mL) via cannula. The reaction mixture was heated under reflux for 6 h in an inert nitrogen atmosphere and then cooled to ambient temperature. The resulting mixture was filtered through Celite, and the filtrate was extracted with H_2O (4 × 30 mL). The CH_2Cl_2 layer was dried over Na_2SO_4, and the solvent was removed under vacuum. The residue was washed with hexane (4 × 30 mL) and then recrystallized by slow evaporation of a concentrated acetone solution to afford the product as orange crystals. Yield: 84 mg, 0.13 mmol, 48%. Method B: The procedure is similar to that of method A except that in method B tris(dibenzylideneacetone)-dipalladium(0) (183 mg, 0.2 mmol), pyridine (32 μL, 0.4 mmol), and **3a′** (176 mg, 0.4 mmol) were used. Yield: 189 mg, 0.3 mmol, 75%. ^{1}H NMR (500 MHz, CD_2Cl_2): δ 9.06−9.05 (m, 2 H, Ar-H), 7.73−7.69 (m, 1 H, Ar-H), 7.65−7.61 (m, 3 H, Ar-H), 7.33−7.28 (m, 4 H, Ar-H), 3.47 (s, 3 H, NCH_3), 2.66 (s, 3 H, CH_3), 2.37 (s, 3 H, CH_3). ^{13}C(^{1}H) NMR (125.76 MHz, CD_2Cl_2): 153.9 (s, Ar-C), 149.3, 148.7 (s, *C*CH_3), 137.3, 133.4, 131.8, 130.7, 128.7, 124.2

(s, Ar-C), 99.3 (s, $C_{carbene}$), 34.4 (s, NCH_3), 16.9, 16.8 (s, CCH_3). Anal. Calcd for $C_{17}H_{19}I_2N_3Pd$: C, 32.64; H, 3.06; N, 6.72. Found: C, 32.20; H, 3.04; N, 6.36. MS (ESI): *m*/*z* 498 $[M - I]^+$.

***trans*-Diiodo-(2-methyl-1,3,5-triphenylpyrazolin-4-ylidene)(pyridine)palladium(II) (5b).** Tris(dibenzylideneacetone)dipalladium(0) (183 mg, 0.2 mmol) and pyridine (65 μL, 0.8 mmol) were dissolved in dry CH_2Cl_2 (20 mL) and stirred at ambient temperature for 10 min under nitrogen. To the resulting dark red solution was added a solution of **3b** (210 mg, 0.4 mmol) in dry CH_2Cl_2 (10 mL) via cannula. The reaction mixture was heated under reflux for 6 h in an inert nitrogen atmosphere and then cooled to ambient temperature. The resulting mixture was filtered through Celite, and the solvent of the filtrate was removed under vacuum. The residue was washed with hexane (4 × 30 mL) and then recrystallized by slow evaporation of a concentrated CH_2Cl_2 solution. The resultant orange crystals were collected and dissolved in a minimal amount of CH_2Cl_2. Passing the CH_2Cl_2 solution through a short plug of silica gel followed by removal of the solvent in vacuo afforded the product as an orange solid. Yield: 95 mg, 0.13 mmol, 65%. ^{1}H NMR (500 MHz, CD_2Cl_2): δ 8.79−8.77 (m, 2 H, Ar-H), 8.20−8.19 (m, 2 H, Ar-H), 8.03 −8.00 (m, 2 H, Ar-H), 7.66−7.33 (m, 12 H, Ar-H), 7.20−7.17 (m, 2 H, Ar-H), 3.59 (s, 3 H, NCH_3). ^{13}C(^{1}H) NMR (125.76 MHz, CD_2Cl_2): 153.8 (s, Ar-C), 152.4, 151.1 (s, CN), 137.2, 134.5, 131.9, 131.7, 131.6, 131.2, 130.5, 130.1, 129.4, 129.3, 128.6, 128.0, 124.2 (s, Ar-C), 104.5 (s, $C_{carbene}$), 36.4 (s, NCH_3). Anal. Calcd for $C_{27}H_{23}I_2N_3Pd$: C, 43.25; H, 3.09; N, 5.60. Found: C, 43.24; H, 3.18; N, 5.53. MS (ESI): *m*/*z* 622 $[M - I]^+$.

***trans*-Diiodo-(3,5-diisopropyl-2-methyl-1-phenylpyrazolin-4-ylidene)(pyridine)palladium(II) (5c).** Tris(dibenzylideneacetone)-dipalladium(0) (183 mg, 0.2 mmol) and pyridine (65 μL, 0.8 mmol) were dissolved in dry CH_2Cl_2 (20 mL) and stirred at ambient temperature for 10 min under nitrogen. To the resulting dark red solution was added a solution of **3c** (182 mg, 0.4 mmol) in dry CH_2Cl_2 (10 mL) via cannula. The reaction mixture was heated under reflux for 6 h in an inert nitrogen atmosphere and then cooled to ambient temperature. The resulting mixture was filtered through Celite, and the solvent of the filtrate was removed under vacuum. The residue was washed with hexane (4 × 30 mL) and then subjected to column chromatography (SiO_2, diethyl ether). The third band ($R_f = 0.5$) was collected and dried in vacuo to give an orange solid, which was recrystallized by diffusing pentane into a concentrated CH_2Cl_2 solution to afford the product as orange crystals. Yield: 6 mg, 0.01 mmol, 4%. ^{1}H NMR (500 MHz, CD_2Cl_2): δ 9.07−9.06 (m, 2 H, Ar-H), 7.72−7.60 (m, 4 H, Ar-H), 7.38−7.37 (m, 2 H, Ar-H), 7.31−7.28 (m, 2 H, Ar-H), 3.91 (m, ^3J(H,H) = 6.9 Hz, 1 H, $CH(CH_3)_2$), 3.44 (s, 3 H, NCH_3), 3.44 (m, ^3J(H,H) = 6.9 Hz, 1 H, $CH(CH_3)_2$), 1.70 (d, ^3J(H,H) = 6.9 Hz, 6 H, $CH(CH_3)_2$), 1.45 (d, ^3J(H,H) = 6.9 Hz, 6 H, $CH(CH_3)_2$). ^{13}C(^{1}H) NMR (125.76 MHz, CD_2Cl_2): 155.5, 155.3 (s, CN), 154.1 (s, Ar-C), 137.2, 133.8, 132.1, 130.5, 129.8, 124.3 (s, Ar-C), 95.0 (s, $C_{carbene}$), 34.5 (s, NCH_3), 30.2, 29.8 (s, $CH(CH_3)_2$), 22.2, 21.0 (s, $CH(CH_3)_2$). Elemental analysis could not be obtained due to the low yield of the product. MS (ESI): *m*/*z* 553 $[M - I]^+$.

General Procedure for the Suzuki−Miyaura Cross-Coupling Reaction. In a typical run, a test tube was charged with a mixture of aryl halide (1.0 mmol), phenylboronic acid (1.2 mmol), potassium carbonate (1.5 mmol), precatalyst (0.01 mmol), and $[N(n\text{-}C_4H_9)_4]Br$ (1.5 mmol) (for entries 9−16 in Table 1). To the mixture was added H_2O (3 mL). The reaction mixture was vigorously stirred at the appropriate temperature. After the desired reaction time, the solution was allowed to cool. A 10 mL amount of dichloromethane was added to the reaction mixture, and the organic phase was extracted with water (6 × 5 mL) and dried over $MgSO_4$. The solvent was removed by evaporation to give a crude product, which was analyzed by ^{1}H NMR spectroscopy.

General Procedure for the Mizoroki−Heck Cross-Coupling Reaction. In a typical run, a test tube was charged with a mixture of aryl halide (1.0 mmol), *tert*-butyl acrylate (1.5 mmol), anhydrous sodium acetate (1.5 mmol), catalyst (0.01 mmol), and $[N(n\text{-}C_4H_9)_4]Br$ (1.5 mmol) (for entries 9−16 in Table 2). To the mixture was then added DMF (3 mL). The reaction mixture was vigorously stirred at the appropriate temperature. After the desired reaction time, the solution was allowed to cool. A 10 mL amount of dichloromethane was added to the reaction mixture, and the organic phase was extracted with water (6 × 5 mL) and dried over $MgSO_4$. The solvent was removed by evaporation to give a crude product, which was analyzed by ^{1}H NMR spectroscopy.

X-ray Diffraction Studies. X-ray data were collected with a Bruker AXS SMART APEX diffractometer, using Mo Kα radiation at 295 K (**4a**) or 223 K (**4b/c** and **5a−c**), with the SMART suite of programs.[13] Data were processed and corrected for Lorentz and polarization effects with SAINT[14] and for absorption effect with SADABS.[15] Structural solution and refinement were carried out with the SHELXTL suite of programs.[16] The structure was solved by direct methods to locate the heavy atoms, followed by difference maps for the light, non-hydrogen atoms. All hydrogen atoms were put at calculated positions. All non-hydrogen atoms were generally given anisotropic displacement parameters in the final model. In the structure of **4c**, one methyl group of each isopropyl substituent is disordered into two positions with occupancy ratio 46:54 and 76:34, respectively, and the fluorine atoms of one BF_4^- are also disordered into two positions with occupancy 55:45. A summary of the most important crystallographic data of **4a−c** and **5a−c** is given in the Supporting Information.

Acknowledgment. We thank the National University of Singapore for financial support (Grant No. R 143-000-327-133) and the CMMAC staff of our department for technical assistance.

Supporting Information Available: Crystallographic data and CIF files for complexes **4a−c** and **5a−c** and ORTEP plots with selected bond lengths and angles for complexes **5a/b**. This material is available free of charge via the Internet at http://pubs.acs.org.

OM8010849

(11) Yields are calculated on the basis of the pyrazolium precursors **3a/b/c**, which are the limiting reagents in these reactions.

(12) (a) O'Brien, C. J.; Kantchev, E. A. B.; Valente, C.; Hadei, N.; Chass, G. A.; Lough, A.; Hopkinson, A. C.; Organ, M. G. *Chem.−Eur. J.* **2006**, *12*, 4743. (b) Kantchev, E. A. B.; O'Brien, C. J.; Organ, M. G. *Aldrichim. Acta* **2006**, *39*, 97. (c) Han, Y.; Huynh, H. V.; Tan, G. K. *Organometallics* **2007**, *26*, 6447.

(13) *SMART version 5.628*; Bruker AXS Inc.: Madison, WI, 2001.

(14) *SAINT+ version 6.22a*; Bruker AXS Inc.: Madison, WI, 2001.

(15) Sheldrick, G. W. *SADABS version 2.10*; University of Göttingen, 2001.

(16) *SHELXTL version 6.14*; Bruker AXS Inc.: Madison, WI, 2000.