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A Bis (BICAAC) Palladium(II) Complex: Synthesis and Implementation as Catalyst in Heck-Mizoroki and Suzuki-Miyaura Cross Coupling Reactions

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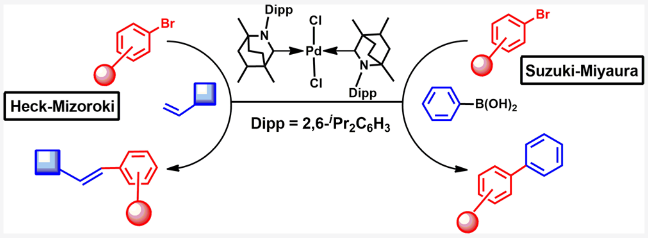

ABSTRACT: Carbenes are one of the most appealing, well-explored, and exciting ligands in modern chemistry due to their tunable stereoelectronic properties and a wide area of applications. A palladium complex (BICAAC)$_2$PdCl$_2$ with a recently discovered cyclic (alkyl)(amino)carbene having bicyclo[2.2.2] octane skeleton (BICAAC) was synthesized and characterized. The enhanced σ-donating and π-accepting ability of this carbene lend a hand to form a robust Pd-carbene bond, which allowed us to probe its reactivity as a precatalyst in Heck-Mizoroki and Suzuki-Miyaura cross-coupling reactions with low catalyst loading in open-air conditions. The diverse range of substrates was explored for both the cross-coupling reactions. To get a better understanding of the catalytic reactions, several analytical techniques such as field-emission scanning electron microscopy, high-resolution transmission electron microscopy, and powder X-ray diffraction were employed in a conclusive manner.

INTRODUCTION

Transition-metal-catalyzed cross-coupling reactions are one of the most efficient and versatile methods for the formation of C−C, C−O, C−N, C−S, and C−B bonds. Particularly, the case of C−C bond-forming processes such as Heck−Mizoroki (HM), Negishi, Suzuki−Miyaura (SM), Kumada, and Stille reactions catalyzed by Pd complexes have gained prominence.[1a] Palladium complexes by far dominate this research area, followed by other precious transition metals (Rh, Ru, Ir, Cu, Ni, and Fe).[1b,f] These advancements of transition-metal catalysis have largely been facilitated by the rational design of supporting ligands. Typically, sterically demanding and electronically rich phosphines,[1g,l] various pincer ligands,[1m] and stable heterocyclic carbenes have been employed as the supportive ligands.[2,3] In this regard, the application of N-heterocyclic carbene-palladium (NHC-Pd) complexes has made a paradigm change in the homogeneous catalysis for C−C bond-forming reactions.

In 1995, Hermann and co-workers reported the first Pd-NHC complexes as highly active and robust catalysts for cross-coupling reactions.[4] Since then, Pd-NHC complexes came into the limelight, and subsequently groups of Caddick,[5] Gade,[6] Nolan,[7] Beller,[8] Herrmann,[9] and Organ[10] have made a significant breakthrough in the Pd-carbene catalyzed C−C coupling reactions. In fact, various mono- and bis-NHC-Pd complexes were synthesized and found to have a potent activity in homogeneous catalysis (Figure 1).[11] In 2002, Gade and co-workers synthesized a palladium complex of oxazolinyl-carbene and exploited its catalytic application for HM and SM cross-coupling reactions.[6] In 2003, Gregory et al. first reported the Sonogashira reaction between alkyl electrophile and alkyl bromide under ambient conditions supported by the Pd-NHC complex;[11b] subsequently, Nolan and co-workers in 2004 demonstrated the reactivity of an “unusual” N-heterocyclic carbene palladium complex toward the C−C coupling reaction using a 2 mol % catalyst loading.[12] An elegant report by Organ and co-workers in 2006 on the Pd-PEPPSI complex as an excellent catalyst for different cross-coupling reactions clearly authenticated the potential and suitability of carbenes as a spectator ligand in such reactions.[10]

In 2005, Bertrand and co-workers reported on cyclic (alkyl)(amino)carbenes (cAACs), which exhibit improved nucleophilicity and electrophilicity as compared to typical NHCs.[13] The better σ-donation and π-acceptor properties of cAACs make them a superior ligand for the stabilization of unstable chemical species[14] and elements in their unusual oxidation states,[15] although relatively few cAAC-metal complexes were investigated for their catalytic applications as compared to a plethora of catalysts based on NHC-metal complexes. Nevertheless, the cAAC-metal complexes of Ru for olefin metathesis[16] and Au complexes for the coupling of

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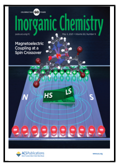

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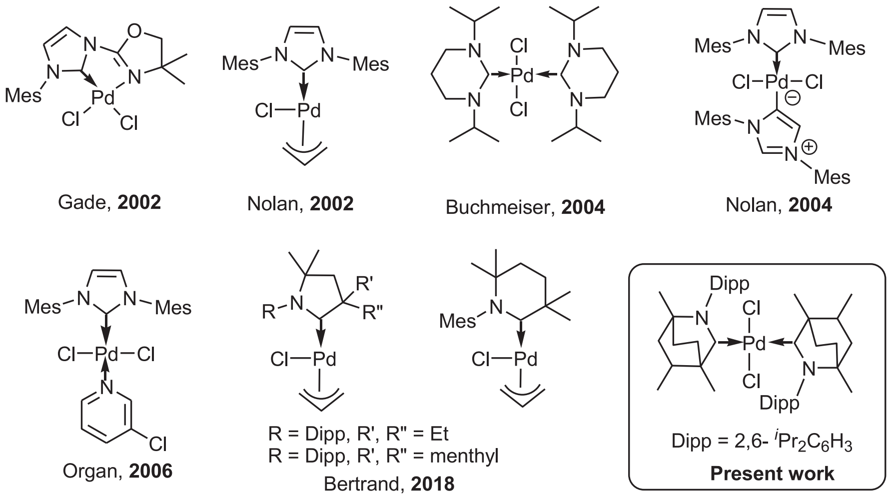


Figure 1. A selection of carbene palladium chloride complexes used in C−C bond-formation reactions.

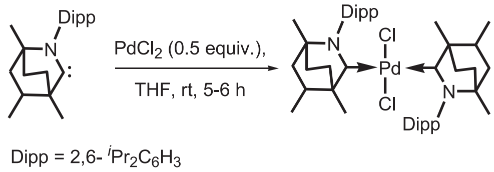
enamines and terminal alkyne and intramolecular hydroamination of alkyne are some prominent examples.[17] Recently, Bertrand and co-workers introduced bicyclic (alkyl)(amino)-carbenes (BICAACs), as new members to the family of stable carbenes, that have a bicyclo[2.2.2]octane framework.[18a] The greater electrophilic and nucleophilic nature of BICAAC in comparison to that of CAAC and NHC is experimentally supported by ligand exchange reactions at the metal center and the lower CO frequency of the metal carbonyl complex of BICAAC.[18a] Further, these electronic factors are confirmed from a computational study, and the calculated singlet−triplet energy gap for BICAAC is smaller (45.7 kcal/mol) than that of cAAC (49.2 kcal/mol) and NHC (68 kcal/mol)[18b,c] indicating that BICAAC has superior ambiphilic characteristics than NHC and is marginally better than cAACs. Because of these features, BICAAC-metal complexes can be extrapolated as potential catalysts to compare with the known metal-carbene catalysts to pursue applications in homogeneous catalysis.

Herein, we report on the synthesis and characterization of a (BICAAC)$_2$PdCl$_2$ complex and also evaluate the catalytic activity of this complex in HM and SM cross-coupling reactions under ambient conditions. The present complex, (BICAAC)$_2$PdCl$_2$, showed good activity with catalyst loadings lower than known biscarbene-PdCl$_2$ complexes such as "unusual"-NHC-PdCl$_2$ and tetracyclic-NHC-PdCl$_2$ complexes.[12,19] In addition, we also examined the fate of the catalyst by recovering it after the completion of the reaction using various analytical techniques to satisfy the curiosity to check the robustness of the carbene-Pd bond and for any further applications. This aspect was pursued keeping in view that many cross-coupling reactions require the in situ generation of catalytically active Pd (0) species of sufficient stability and exclusion of air and moisture from the system to prevent the irreversible formation of unreactive Pd-peroxo species[20] or precipitation of inactive Pd black.[21]

■ RESULTS AND DISCUSSION

Synthesis and Characterization of (BICAAC)$_2$PdCl$_2$. The synthesis of the (BICAAC)$_2$PdCl$_2$ complex was performed in a straightforward manner by the treatment of a BICAAC solution in dry cold tetrahydrofuran (THF) with PdCl$_2$ under the exclusion of light at room temperature for 5−6 h (Scheme 1). The complex (BICAAC)$_2$PdCl$_2$ was obtained in 78% yield.

Scheme 1. Synthesis of the (BICAAC)$_2$PdCl$_2$ Complex



The product obtained was characterized by ^{1}H and ^{13}C{^{1}H} NMR spectroscopy. In the ^{1}H NMR spectrum of (BICAAC)$_2$PdCl$_2$ two broad septets corresponding to the 2,6-C*H*(CH$_3$)$_2$C$_6$H$_3$ group of carbene ligand appeared at 3.22 and 3.09 ppm. In the ^{13}C{^{1}H} NMR spectrum of Pd complex, the signal for the carbene carbon nucleus was observed at 262.9 ppm, which is significantly upfield-shifted as compared to BICAAC (334 ppm) and can be attributed to the strong electrophilic nature of BICAAC in the Pd complex. The high-resolution mass spectrometry (AP$^+$) of the product showed a signal at m/z = 763.3917 (calcd 763.3962 for C$_{44}$H$_{66}$N$_2$PdCl), which is attributed to [M-Cl]$^+$.

The formation of the (BICAAC)$_2$PdCl$_2$ complex was confirmed by single-crystal X-ray diffraction studies. The suitable crystals of the Pd complex were grown by layering its dichloromethane solution with diethyl ether. The (BICAAC)$_2$PdCl$_2$ complex crystallized in the monoclinic crystal system with the $P2_1/n$ space group (Table S1). The molecular structure depicted in Figure 2 revealed the trans form of (BICAAC)$_2$PdCl$_2$, and the Pd center adopted the square-planar geometry. The metal center bound to two carbene units through carbon C1 and C1′, and the remaining sites were completed by two chloride groups. The Pd1−C1 (2.0297(3) Å) and Pd1−Cl1(2.3247(8) Å) bond distances are almost similar to the reported carbene-palladium-chloride complexes, [(ethyl-cAAC-5)Pd(allyl)Cl][22] (Pd−C 2.030(2), Pd−Cl 2.374(1) Å); [(ethyl-cAAC-6)Pd(allyl)Cl][22] (Pd−C 2.058(2), Pd−Cl 2.397(1) Å); and [(NHC)$_2$PdCl$_2$] (Pd−C 2.019(13), Pd−Cl 2.289(4) Å).[12] The Cl1−Pd1−C1′ and Cl1−Pd1−Cl1′ bond angles in trans-(BICAAC)$_2$PdCl$_2$ are 90.90(4)° and 180.00(4)°, respectively, and stipulate the square-planar geometry around the Pd(II) center in trans-(BICAAC)$_2$PdCl$_2$ isomer.

The UV−vis spectrum of (BICAAC)$_2$PdCl$_2$ in acetonitrile showed two absorptions centered at 290 nm (4 × 10^2 L mol^{-1}

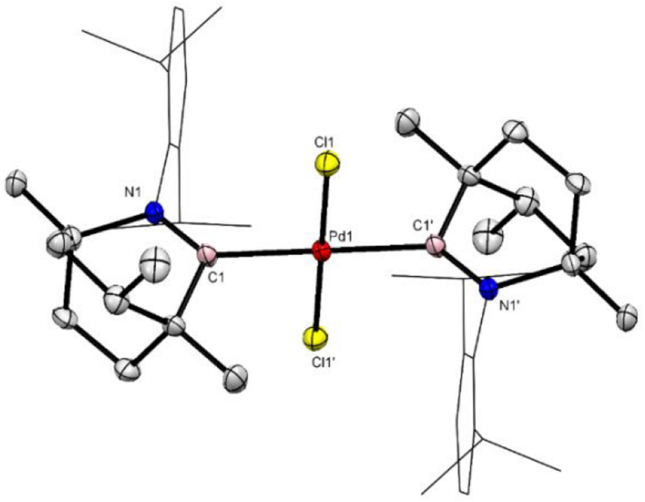


Figure 2. Single-crystal X-ray structure of trans-$(BICAAC)_2PdCl_2$. Ellipsoids are shown at 50% probability levels. All hydrogen atoms are omitted for clarity. Selected bond lengths [Å] and bond angles [deg]: Pd1−C1 2.0297(3), Pd1−Cl1 2.3247(8), N1−C1 1.309(4); Cl1−Pd1−C1 90.90(4), Cl1−Pd1−Cl1′ 180.00(4), Cl1−Pd1−C1′ 89.10(5), C1′−Pd1−C1 180.0(4).

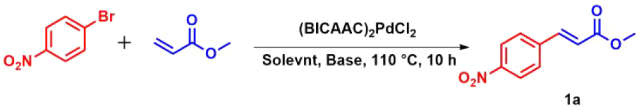
cm^{-1}) and 435 nm (1.9×10^2 L mol^{-1} cm^{-1}), which correspond to the intraligand charge transfer (ILCT) and metal-to-ligand charge transfer (MLCT), respectively (see Figure S4 in the Supporting Information). No d−d transition was observed as expected. The field emission scanning electron microscopic (FE-SEM) and energy-dispersive X-ray spectroscopic (EDX) measurements were also performed with the $(BICAAC)_2PdCl_2$ complex to observe the surface morphology and composition of the material. The crystallinity of the material was also observed in the SEM images (see Figure S5 in the Supporting Information). The Pd/Cl ratio of the complex was found to be 1:2 via an EDX analysis (Figure 3, Table S2) consistent with the $(BICAAC)_2PdCl_2$ composition of the complex.

Catalytic Applications of the $(BICAAC)_2PdCl_2$ Complex in C−C Coupling Reactions. The palladium-catalyzed C−C cross-coupling reactions and C−H bond activation are the most coherent and effective methods, which led to the vast improvement to the methodologies applied in synthetic organic chemistry.[23] In this aspect, aryl-substituted *α*,*β*-unsaturated esters, olefins, and biaryl systems having *ortho*, *meta*, or *para* functionalities are supposed to be the key intermediates in the synthesis of natural products, pharmaceuticals, and precursors for material chemistry.[23c] Hence, the development of suitable catalysts that work under ambient conditions has been a challenging task for the chemists in the past decades.[24] Along with that, the stability, sustainability, and utilization of catalysts in low quantity have been key factors that were taken into consideration.

To explore the properties of BICAAC, previously we reported its reactivity with different hydroboranes.[25] Very recently, we reported the synthesis of two coordinated complexes of Cu(I) and Au(I) with BICAAC ligand.[26] As a part of our continued interest in this direction, we evaluated the Pd complex reported herein, $(BICAAC)_2PdCl_2$, as a catalyst in Heck-Mizoroki (HM) and Suzuki-Miyaura cross-coupling (SMCC) reactions under ambient conditions.

During optimizations for Heck-Mizoroki reaction, we used 4 mol % of catalyst and chose 4-bromo nitrobenzene and methyl acrylate as model substrates in the presence of 1 mmol of K_2CO_3 and 10 mol % of tetrabutylammonium bromide (TBAB) at 110 °C in dimethylacetamide (DMA) as the commonly used solvent for this rection (Table 1, entry 1). The

Table 1. Optimization Table for the Heck-Mizoroki Reaction[a]



entry	catalyst (mol %)	solvent	base	time	yield[b] (%)
1	4	DMA	K_2CO_3	6 h	82
2	2	DMA	K_2CO_3	10 h	78
3	0.5	DMA	K_2CO_3	10 h	78
4	0.1	DMA	K_2CO_3	10 h	45
5	0.1	DMA	K_2CO_3	24 h	52
6	0.5	DMF	K_2CO_3	10 h	75
7	0.5	DCE	K_2CO_3	10 h	70
8	0.5	toluene	K_2CO_3	10 h	42
9	0.5	1,4-dioxane	K_2CO_3	10 h	22
10	0.5	H_2O	K_2CO_3	10 h	NR[c]
11	0.5	DMA	NEt_3	10 h	50
12	0.5	DMA	NaH	10 h	61
13	0.5	DMA	^tBuOK	10 h	30
14	0.5	DMA	KOH	10 h	48
15	0.5	DMA	NaOAc	10 h	42
16	0.5	DMA	Na_2CO_3	10 h	35

[a]Typical reaction conditions: catalyst $(BICAAC)_2PdCl_2$, 1.0 mmol 4-bromonitrobenezene, 1.1 mmol methyl acrylate, 1.0 mmol base, 10 mol % TBAB. [b]Isolated yield. [c]NR = No reaction.

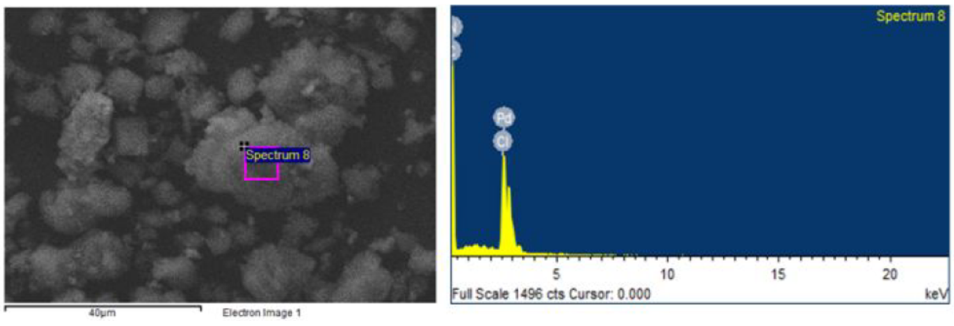
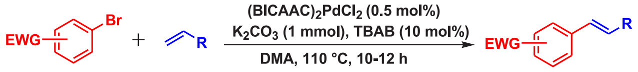


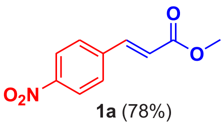
Figure 3. EDX spectrum of $(BICAAC)_2PdCl_2$.

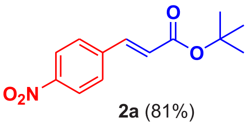
Table 2. Heck-Mizoroki Reaction (Substrate Scope and Yields)

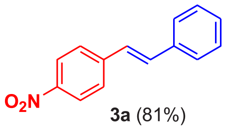


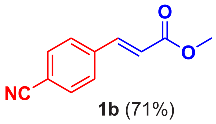
EWG = NO$_2$, CHO, CN, F
R = CO$_2$Me, CO$_2${}^tBu, Ph

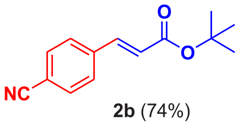
Substrate scope[a]

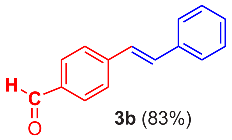

1a (78%)

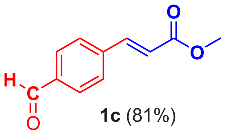

2a (81%)

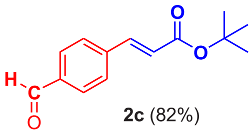

3a (81%)

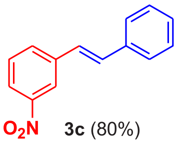

1b (71%)

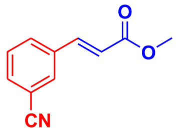

2b (74%)

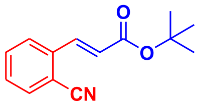

3b (83%)

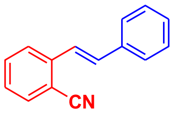

1c (81%)

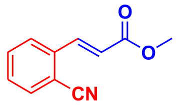

2c (82%)

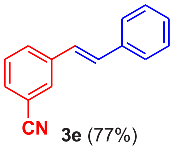

3c (80%)

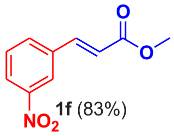

1d (76%)

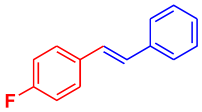

2d (75%)


3d (75%)


1e (78%)


3e (77%)


1f (83%)

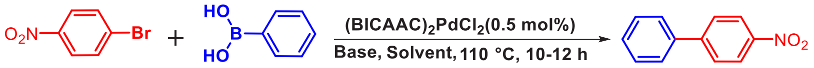

3f (73%)

[a]Aryl bromide (1.0 mmol), substituted olefin (1.1 mmol), catalyst 0.5 mol %; K$_2$CO$_3$ (1.0 mmol), TBAB (10 mol %), dimethylacetamide (4 mL), 10−12 h.

progress of the reactions was monitored by thin-layer chromatography (TLC), and the product was characterized by ^{1}H and ^{13}C{^{1}H} NMR spectra. The expected product **1a** was obtained with 82% isolated yield after 6 h. Decreasing the catalyst loading to 2 mol % resulted in the formation of **1a** in 78% yield after 10 h (Table 1, entry 2). Rewardingly, lowering the catalyst loading to 0.5 mol % did not affect the yield of **1a** (Table 1, entry 3) and resulted in turnover number (TON) value of 156. However, the use of 0.1 mol % catalyst gave **1a** in 45% yield after 10 h, and with extended time of 24 h the yield reached up to 52% (Table 1, entries 4 and 5). The obtained turnover number (TON) value with our catalyst is slightly better and comparable to the previously reported catalysts.[12,19,24a,27a,b]

Taken together, we chose the catalyst loading of 0.5 mol % and the reaction time of 10 h for further optimization. Screening of the model reaction in different solvent mediums (dimethylformamide (DMF), 1,2-dichloroethane (DCE), toluene, 1,4-dioxane, and H$_2$O) led to the observation that DMA is the most suitable solvent (Table 1, entries 6−10). Next, optimizations were performed by changing bases (such as NEt$_3$, NaH, ^{t}BuOK, KOH, NaOAc, and Na$_2$CO$_3$) with DMA as the solvent under the above reaction conditions that revealed K$_2$CO$_3$ as the appropriate base (Table 1, entries 11−16). Overall, we found the best-optimized reaction protocol with a combination of 0.5 mol % (BICAAC)$_2$PdCl$_2$, 1 mmol K$_2$CO$_3$, and 10 mol % TBAB as an additive in DMA for 1 mmol of 4-bromonitrobenzene. Not surprisingly, when the reaction was performed with lower than 10 mol % TBAB (or in its absence) only traces of **1a** formed along with deposition of Pd black. In the literature, it has been well-documented that the presence of TBAB suppresses the catalyst degradation and inhibits the formation of Pd black.[28a,d] Noticeably, the report by Ananikov and co-workers employed higher amounts of TBAB as an additive (1 equiv with respect to the substrate) for a Pd-NHC complex for the HM reaction.[29] To extend the substrate scope for the catalyst, reactions were performed by varying the olefinic as well as the aryl bromide part having

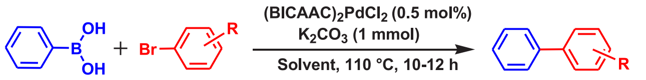
Table 3. Optimization Table for the Suzuki-Miyaura Cross-Coupling Reaction[a]



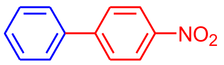
entry	catalyst (mol %)	solvent	base	yield[b] (%)
1	0.5	DMA	K_2CO_3	85
2	0.5	DMA	NEt_3	10
3	0.5	DMA	^tBuOK	67
4	0.5	DMA	KOH	51
5	0.5	DMA	NaOAc	50
6	0.5	DMF	K_2CO_3	90
7	0.5	toluene	K_2CO_3	60
8	0.5	DME	K_2CO_3	73
9	0.5	1,4-dioxane	K_2CO_3	56
10	0.5	H_2O	K_2CO_3	97

[a] Typical reaction conditions: catalyst (BICAAC)$_2$PdCl$_2$ 0.5 mol %, 1.0 mmol 4-bromonitrobenezene, 1.1 mmol phenylboronic acid, 1.0 mmol base. [b] Isolated yield.

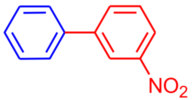
Table 4. Suzuki-Miyaura Cross-Coupling Reaction (Substrate Scope and Yields)



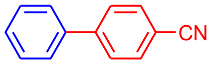
Substrate scope[a]



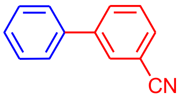
4a (85%)[b,c]



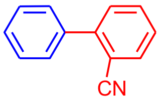
4b (82%)[b]



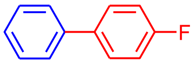
4c (88%)[b,c]



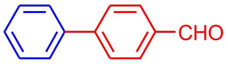
4d (85%)[b]



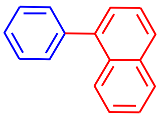
4e (82%)[b]



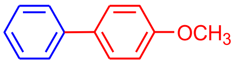
4f (79%)[b]



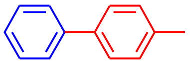
4g (83%)[b]



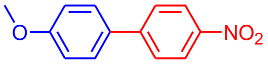
4h (72%)[b]



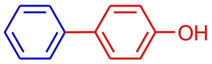
4i (85%)[c]



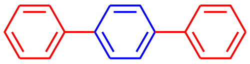
4j (80%)[c]



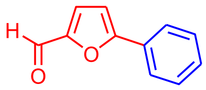
4k (91%)[c]



4l (84%)[c]



4m (83%)[c]



4n (84%)[c]

[a] Aryl bromide (1.0 mmol), boronic acid (1.1 mmol), catalyst 0.5 mol %; K$_2$CO$_3$ (1.0 mmol), solvent (4 mL), 10–12 h. [b] DMA as reaction medium. [c] Water as the reaction medium.

different positional substituents (*ortho*, *meta*, and *para*). The substrates with electron-withdrawing groups such as NO$_2$, CN, and CHO on aryl bromide led to the desired products with a high yield (71–83%) (Table 2, **1a**–**1f**). Gratifyingly, *tert*-butyl acrylate and styrene as the coupling partners were also investigated, which led to the formation of the respective products (**2a**–**2d** and **3a**–**3f**) (Table 2). In all the cases of **1a**–**1f** and **2a**–**2d** the (*E*)-methyl cinnamates and for **3a**–**3f** (*E*)-stilbene derivatives were the only products, confirmed by the trans coupling constant ($^3J_{H-H}$ = 16 Hz) of the olefinic hydrogens that appeared at ~6.0–7.5 ppm in the ^{1}H NMR spectra. Interestingly, no significant difference in the catalytic performance was observed among the *ortho*-, *meta*-, and *para*-substituted aryl bromide substrates under the same reaction conditions, and good to moderate product yields were obtained.

Encouraged with the results of the HM reaction, we further evaluated the catalytic activity of (BICAAC)$_2$PdCl$_2$ for the SMCC reaction keeping in view that the SM reaction has previously been studied well with NHC-Pd catalysts.[7e,12,19] The reaction between phenylboronic acid and 4-nitrobromobenzene in the presence of K$_2$CO$_3$ as the base with 0.5 mol % of the catalyst gave the desired product **4a** in 85% yield (Table 3, entry 1) with a TON of 194. The use of other bases such as Cs$_2$CO$_3$, CsF, or K$_3$PO$_4$ failed to activate the catalyst, as no product formed in these reactions.

Further, bases such as NEt$_3$, ^{t}BuOK, KOH, and NaOAc were found to be less efficient than K$_2$CO$_3$ (Table 3, entries 2−5). To identify the suitable reaction medium, we examined the reaction in different solvents like DMA, DMF, toluene, DME, and 1,4-dioxane and found DMA as the appropriate reaction medium (Table 3, entries 6−9). Interestingly, during the revision of the manuscript, we found water as the best solvent for this reaction (Table 3, entry 10).

The substrate scope for SMCC was elaborated with aryl bromide bearing different electron-withdrawing and electron-donating substituents (Table 4). All the aryl bromides containing electron-withdrawing substituents (NO$_2$, CN, F, CHO) at *ortho*, *meta*, or *para* positions afforded the respective products in good yields (72−85%) (Table 4, **4a**−**4g**). Of note, no significant dissimilarity in the catalytic activity was noticed with respect to the positional substitution. In addition, 2-bromonaphthalene also afforded C−C coupled product **4h** with 72% yield. The *p*-OCH$_3$- and *p*-CH$_3$-substituted aryl bromides also furnished the desired products **4i** and **4j** in high yields of 85% and 80%, respectively. Also, the coupling of *p*-OCH$_3$-substituted phenyl boronic acid with 4-nitrobromobenzene gave **4k** in 91% yield. *p*-OH and 1,4-dibromo-substituted aryl bromides gave the corresponding products **4l** and **4m** in good yields. The heterocyclic substrate 5-bromo-2-furaldehyde also smoothly afforded **4n** in 84% yield. We compared the catalytic activity of the present complex, (BICAAC)$_2$PdCl$_2$, with some of the notable examples of NHC-PdCl$_2$ complexes known to catalyze Heck-Mizoroki and Suzuki-Miyaura cross-coupling reactions (see Figure S6 in the Supporting Information).

Notably, when some of these catalytic reactions were performed for durations longer than specified in Tables 2 and 4, the formation of trace quantities of gray precipitate was observed for Heck-Mizoroki and Suzuki-Miyaura reactions. Such observations motivated us to investigate if the catalyst operated in a heterogeneous manner. For this purpose, a mercury drop test was performed for the reaction between *p*-nitrobromobenzene and methyl acrylate in a model reaction (see Figure S10 in the Supporting Information). The absence of a significant effect of mercury on the metal-catalyzed reaction indicated the homogeneous nature of the reaction.[30] A similar observation was found in the case of Suzuki-Miyaura coupling between *p*-nitrobromobenzene and phenylboronic acid. We recovered the gray material from a scaled-up reaction employed to prepare **1a** and used it as a catalyst for the fresh HM and SMCC reactions to check the activity of this material for the scope of catalyst recyclability. Unfortunately, no catalytic activity was detected under the optimized reaction condition. In view of this, we were prompted to check whether the BICAAC ligand was still associated with the Pd centers in the recovered material, but due to the poor solubility of the material, we used the techniques such as field emission scanning electron microscopy (FE-SEM), EDX, and HR-TEM to characterize this material.

The SEM images of the recovered material showed a block-shaped morphology (see Figure S7 in the Supporting Information), which is not akin to the SEM images of (BICAAC)$_2$PdCl$_2$ (see Figure S5 and Table S2). In addition, the EDX analysis in conjunction with SEM confirmed the presence of palladium in the gray material (see Figure S8 in the Supporting Information). The HR-TEM images of the material clearly depicted the formation of fine, uniform, and small-sized palladium nanoparticles of 5−8 nm average diameter (Figure 4), which was further confirmed by the powder X-ray diffraction pattern of the gray material where Pd(111) and Pd(200) planes of the material were found (see Figure S9 in the Supporting Information).[31] On the basis of these results, we infer that, once (BICAAC)$_2$PdCl$_2$ catalyzed the coupling reactions, it does not stay as the BICAAC-coordinated palladium complex; rather, it slowly formed fine catalytically inactive palladium nanoparticles. These observations indirectly support the homogeneous reaction, where the catalyst lived sufficiently long to complete the reaction, and the degenerated catalyst at the completion of the reaction did not show any reactivity.

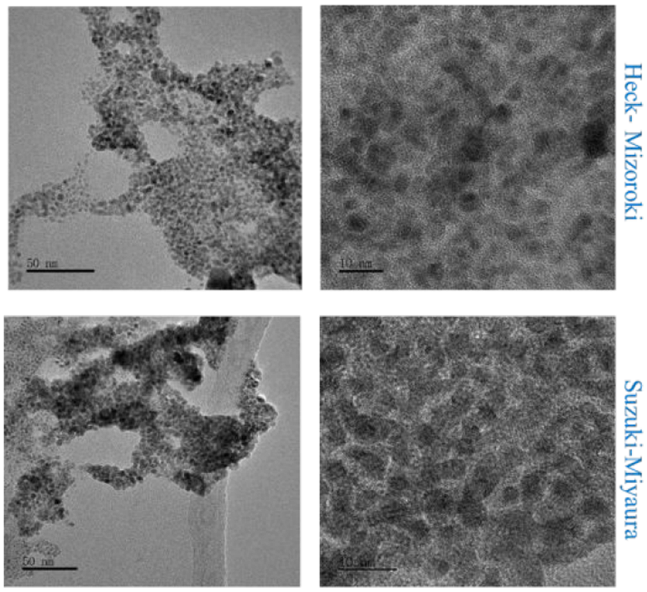


Figure 4. HR-TEM images of the material recovered after the completion of catalysis.

■ CONCLUSION

In summary, we have demonstrated the synthesis and characterization of the first BICAAC-palladium complex, (BICAAC)$_2$PdCl$_2$. This complex is stable under ambient conditions without the exclusion of moisture or oxygen. Moreover, this complex acts as a potential catalyst in cross-coupling reactions (Suzuki-Miyaura and Heck-Mizoroki). All the catalytic reactions were performed under open-air conditions, and broad substrates scope (irrespective of the *ortho*, *meta*, and *para* substitution pattern) of aryl bromides were demonstrated with good to moderate yields of the products. This complex is found to have better catalytic activity with a low catalyst loading as compared to a few previously reported carbene-$PdCl_2$ complexes.[12,19] The homogeneous process for the catalytic reaction was supported by the Hg-drop test. Other evidence from FE-SEM, HR-TEM, and PXRD indirectly support the homogeneous reaction pathway for these reactions. At present, our attention is focused on the synthesis of new metal complexes of BICAAC ligand to explore their reactivity studies and catalytic applications in organic transformations.

EXPERIMENTAL SECTION

Materials and Methods. The synthesis of $(BICAAC)_2PdCl_2$ was performed under an inert atmosphere of dry nitrogen using standard Schlenk techniques or a glovebox, where O_2 and H_2O levels were maintained below 1 ppm. All other reactions were performed under ambient atmospheric conditions in glassware dried at 150 °C in a hot air oven. Solvents were purified by an MBRAUN solvent purification system MB SPS-800 and were used directly from the SPS system. All chemicals were purchased from Merck and used without further purification. The bicyclic (alkyl)(amino) carbene (BICAAC) was prepared following the literature procedure reported by Bertrand and co-workers.[18a] and was characterized using ^1H and $^{13}C\{^1H\}$ NMR methods. High-resolution mass spectrometry (HRMS) for $(BICAAC)_2PdCl_2$ was performed with a Waters SYNAPT G2-S instrument. The ^1H and $^{13}C\{^1H\}$ NMR spectra were recorded with Bruker 400 MHz spectrometer with tetramethylsilane (TMS) as an external reference; chemical shift values are reported in parts per million. For absorption spectroscopy measurements, an LABINDIA UV−vis spectrophotometer 3000+ was used. FE-SEM and EDX analyses were performed with a JEOL JSM 7600F field emission electron microscope. The HR-TEM measurement was done with a JEOL F200 with an electron acceleration energy of 200 kV.

Synthesis of $(BICAAC)_2PdCl_2$. BICAAC (**0.31 g, 1.00 mmol**) was dissolved in cold THF (10 mL), and subsequently solid palladium chloride (**0.09 g, 0.50 mmol**) was added to this solution. The resulting mixture was stirred for ∼5−6 h **in the exclusion of light**. This was followed by the removal of all volatiles under vacuum. Further, the brown powder residues were dissolved in 1 mL of dichloromethane, and then 10 mL of diethyl ether was added to precipitate the impurities. The colored solution was filtered and evaporated, which afforded the $[(BICAAC)_2PdCl_2]$ complex in 78% yield (0.3 g). The crystals were obtained after $[(BICAAC)_2PdCl_2]$ was dissolved in the dichloromethane and diethyl ether layered onto this solution. mp 240 °C. ^1H NMR (400 MHz, $CDCl_3$) δ = 7.40−7.31 (m, 3H, Ar−H), 3.22 (sept, 1H, $CH(CH_3)_2$, $^3J_{H-H}$ = 8 Hz), 3.09 (sept, 1H, $CH(CH_3)_2$, $^3J_{H-H}$ = 8 Hz), 1.82−1.69 (m, 3H), 1.61 (s, 1H), 1.46−1.42 (m, 10H), 1.33−1.30 (m, 1H), 1.22−1.18 (m, 7H), 1.00−0.98 (m, 3H), 0.93−0.92 (m, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ = 262.9, 146.4, 146.3, 140.6, 128.4, 125.1, 125.0, 65.5, 65.3, 52.8, 52.7, 43.7, 40.8, 37.5, 36.9, 33.5, 32.9, 32.8, 32.4, 28.7, 28.6, 28.4, 27.6, 27.5, 26.6, 26.5, 23.8, 23.5, 20.7, 20.4. HRMS (AP^+) m/z calculated for $C_{44}H_{66}N_2PdCl$: 763.3962 $[M-Cl]^+$; found: 763.3917.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.inorgchem.0c03614.

> Information on catalytic reactions and characterization (NMR, UV−vis, FE-SEM, EDX, HR-TEM graphics) (PDF)

Accession Codes

CCDC 2003312 contain the supplementary crystallographic data for this paper. This data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: + 44 1223 336033.

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) (a) Colacot, T. J., Ed. *New Trends in Cross-Coupling: Theory and Applications;* RSC: Cambridge, U.K., 2015. (b) Colby, D. A.; Bergman, R. G.; Ellman, J. A. Rhodium-Catalyzed C-C Bond Formation via Heteroatom-Directed C-H Bond Activation. *Chem. Rev.* **2010**, *110*, 624−655. (c) Arockiam, P. B.; Bruneau, C.; Dixneuf, P. H. Ruthenium(II)-Catalyzed C-H Bond Activation and Functionalization. *Chem. Rev.* **2012**, *112*, 5879−5918. (d) Jana, R.; Pathak, T. P.; Sigman, M. S. Advances in Transition Metal (Pd, Ni, Fe)-Catalyzed Cross-Coupling Reactions Using Alkyl-organometallics as Reaction Partners. *Chem. Rev.* **2011**, *111*, 1417−1492. (e) Han, F.-S. Transition-Metal-Catalyzed Suzuki-Miyaura Cross-Coupling Reactions: A Remarkable Advance from Palladium to Nickel Catalysts. *Chem. Soc. Rev.* **2013**, *42*, 5270−5298. (f) Hatakeyama, T.; Hashimoto, T.; Kondo, Y.; Fujiwara, Y.; Seike, H.; Takaya, H.; Tamada, Y.; Ono, T.; Nakamura, M. Iron-Catalyzed Suzuki-Miyaura Coupling of Alkyl Halides. *J. Am. Chem. Soc.* **2010**, *132*, 10674−10676. (g) Chan, K. T.; Tsai, Y. H.; Lin, W. S.; Wu, J. R.; Chen, S. J.; Liao, F. X.; Hu, C. H.; Lee, H. M. Palladium Complexes with Carbene and Phosphine Ligands: Synthesis, Structural Characterization, and Direct Arylation Reactions between Aryl Halides and Alkynes.

Organometallics **2010**, *29*, 463−472. (h) Kumar, P. V.; Lin, W. S.; Shen, J. S.; Nandi, D.; Lee, H. M. Direct C5-Arylation Reaction between Imidazoles and Aryl Chlorides Catalyzed by Palladium Complexes with Phosphines and N-Heterocyclic Carbenes. *Organometallics* **2011**, *30*, 5160−5169. (i) Schmid, T. E.; Jones, D. C.; Songis, O.; Diebolt, O.; Furst, M. R. L.; Slawin, A. M. Z.; Cazin, C. S. J. Mixed Phosphine/N-Heterocyclic Carbene Palladium Complexes: Synthesis, Characterization and Catalytic use in Aqueous Suzuki-Miyaura Reactions. *Dalton Trans.* **2013**, *42*, 7345−7353. (j) Bernhammer, J. C.; Chong, N. X.; Jothibasu, R.; Zhou, B.; Huynh, H. V. Palladium(II) Complexes Bearing an Indazole-Derived N-Heterocyclic Carbene and Phosphine Coligands as Catalysts for the Sonogashira Coupling and the Hydroamination of Alkynes. *Organometallics* **2014**, *33*, 3607−3617. (k) Boubakri, L.; Yasar, S.; Dorcet, V.; Roisnel, T.; Bruneau, C.; Hamdi, N.; Ozdemir, I. Synthesis and Catalytic Applications of Palladium N-heterocyclic Carbene Complexes as Efficient Pre-catalysts for Suzuki-Miyaura and Sonogashira Coupling Reactions. *New J. Chem.* **2017**, *41*, 5105−5113. (l) de Meijere, A., Diedrich, F., Eds. *Metal-Catalyzed Cross-Coupling Reactions;* Wiley-VCH: 399, 2004; Vols. *1* & *2*. (m) Rishu; Prashanth, B.; Bawari, D.; Mandal, U.; Verma, A.; Choudhury, A. R.; Singh, S. Hg(II) and Pd(II) Complexes with a New Selenoether Bridged Biscarbene Ligand: Efficient Mono- and Bis-arylation of Methyl Acrylate with a Pincer Biscarbene Pd(II) Precatalyst. *Dalton Trans.* **2017**, *46*, 6291−6302.

(2) (a) Campeau, L.-C.; Hazari, N. Cross-Coupling and Related Reactions: Connecting Past Success to the Development of New Reactions for the Future. *Organometallics* **2019**, *38*, 3−35. (b) Wang, D.; Weinstein, A. B.; White, P. B.; Stahl, S. S. Ligand-Promoted Palladium-Catalyzed Aerobic Oxidation Reactions. *Chem. Rev.* **2018**, *118*, 2636−2679. (c) Li, H.; Johansson Seechurn, C. C. C.; Colacot, T. J. Development of Preformed Pd Catalysts for Cross-Coupling Reactions, Beyond the 2010 Nobel Prize. *ACS Catal.* **2012**, *2*, 1147−1164. (d) Gildner, P. G.; Colacot, T. J. Reactions of the 21st Century: Two Decades of Innovative Catalyst Design for Palladium-Catalyzed Cross-Couplings. *Organometallics* **2015**, *34*, 5497−5508.

(3) Fu, G. C. The Development of Versatile Methods for Palladium-Catalyzed Coupling Reactions of Aryl Electrophiles Through the Use of $P(t\text{-}Bu)_3$ and PCy_3 as Ligands. *Acc. Chem. Res.* **2008**, *41*, 1555−1564.

(4) Herrmann, W. A.; Elison, M.; Fischer, J.; Köcher, C.; Artus, G. R. J. Metal Complexes of N-Heterocyclic Carbenes-A New Structural Principle for Catalysts in Homogeneous Catalysis. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2371−2374.

(5) Titcomb, L. R.; Caddick, S.; Cloke, F. G. N.; Wilson, D. J.; McKerrecher, D. Unexpected Reactivity of Two-coordinate Palladium-Carbene Complexes; Synthetic and Catalytic Implications. *Chem. Commun.* **2001**, 1388−1389.

(6) César, V.; Bellemin-Laponnaz, S.; Gade, L. H. Direct Coupling of Oxazolines and N-Heterocyclic Carbenes: A Modular Approach to a New Class of C-N Donor Ligands for Homogeneous Catalysis. *Organometallics* **2002**, *21*, 5204−5208.

(7) (a) Viciu, M. S.; Germaneau, R. F.; Navarro-Fernandez, O.; Stevens, E. D.; Nolan, S. P. Activation and Reactivity of (NHC)Pd(allyl)Cl (NHC = N-Heterocyclic Carbene) Complexes in Cross-Coupling Reactions. *Organometallics* **2002**, *21*, 5470−5472. (b) Viciu, M. S.; Kelly, R. A.; Stevens, E. D.; Naud, F.; Studer, M.; Nolan, S. P. Synthesis, Characterization, and Catalytic Activity of N-Heterocyclic Carbene (NHC) Palladacycle Complexes. *Org. Lett.* **2003**, *5*, 1479−1482. (c) Navarro, O.; Marion, N.; Scott, N. M.; González, J.; Amoroso, D.; Bell, A.; Nolan, S. P. Synthesis of Novel (NHC)Pd(acac)Cl Complexes (acac = acetylacetonate) and their Activity in Cross-Coupling Reactions. *Tetrahedron* **2005**, *61*, 9716−9722. (d) Marion, N.; Navarro, O.; Mei, J.; Stevens, E. D.; Scott, N. M.; Nolan, S. P. Modified (NHC)Pd(allyl)Cl (NHC = N-Heterocyclic Carbene) Complexes for Room-Temperature Suzuki-Miyaura and Buchwald-Hartwig Reactions. *J. Am. Chem. Soc.* **2006**, *128*, 4101−4111. (e) Fortman, G. C.; Nolan, S. P. N-Heterocyclic Carbene (NHC) Ligands and Palladium in Homogeneous Cross-Coupling Catalysis: A Perfect Union. *Chem. Soc. Rev.* **2011**, *40*, 5151−5169.

(8) Jackstell, R.; Gomez Andreu, M.; Frisch, A.; Selvakumar, K.; Zapf, A.; Klein, H.; Spannenberg, A.; Rottger, D.; Briel, O.; Karch, R.; Beller, M. A Highly Efficient Catalyst for the Telomerization of 1,3-Dienes with Alcohols: The First Synthesis of a Monocarbenepalladium(0)-Olefin Complex. *Angew. Chem., Int. Ed.* **2002**, *41*, 986−989.

(9) Schneider, S. K.; Herrmann, W. A.; Herdtweck, E. Active Catalysts for the Suzuki Coupling: Palladium Complexes of Tetrahydropyrimid-2-ylidenes. *J. Mol. Catal. A: Chem.* **2006**, *245*, 248−254.

(10) O'Brien, C. J.; Kantchev, E. A. B.; Valente, C.; Hadei, N.; Chass, G. A.; Lough, A.; Hopkinson, A. C.; Organ, M. G. Easily Prepared Air- and Moisture-Stable Pd-NHC (NHC = N-Heterocyclic Carbene) Complexes: A Reliable, User-Friendly, Highly Active Palladium Precatalyst for the Suzuki-Miyaura Reaction. *Chem. - Eur. J.* **2006**, *12*, 4743−4748.

(11) (a) Kantchev, E. A. B; O'Brien, C. J.; Organ, M. G. Palladium Complexes of N-Heterocyclic Carbenes as Catalysts for Cross-Coupling Reactions-A Synthetic Chemist's Perspective. *Angew. Chem., Int. Ed.* **2007**, *46*, 2768−2813. (b) Eckhardt, M.; Fu, G. C. The First Applications of Carbene Ligands in Cross-Couplings of Alkyl Electrophiles: Sonogashira Reactions of Unactivated Alkyl Bromides and Iodides. *J. Am. Chem. Soc.* **2003**, *125*, 13642−13643.

(12) Lebel, H.; Janes, M. K.; Charette, A. B.; Nolan, S. P. Structure and Reactivity of "Unusual" N-Heterocyclic Carbene (NHC) Palladium Complexes Synthesized from Imidazolium Salts. *J. Am. Chem. Soc.* **2004**, *126*, 5046−5047.

(13) Lavallo, V.; Canac, Y.; Prasang, C.; Donnadieu, B.; Bertrand, G. Stable Cyclic (Alkyl)(amino)carbenes as Rigid or Flexible, Bulky, Electron-rich Ligands for Transition-metal Catalysts: A Quaternary Carbon Atom Makes the Difference. *Angew. Chem., Int. Ed.* **2005**, *44*, 5705−5709.

(14) (a) Martin, D.; Soleilhavoup, M.; Bertrand, G. Stable Singlet Carbenes as Mimics for Transition Metal Centers. *Chem. Sci.* **2011**, *2*, 389−399. (b) Mondal, K. C.; Roesky, H. W.; Schwarzer, M. C.; Frenking, G.; Niepötter, B.; Wolf, H.; Herbst-Irmer, R.; Stalke, D. A Stable Singlet Biradicaloid Siladicarbene: $(L:)_2Si$. *Angew. Chem., Int. Ed.* **2013**, *52*, 2963−2967. (c) Niepötter, B.; Herbst-Irmer, R.; Kratzert, D.; Samuel, P. P.; Mondal, K. C.; Roesky, H. W.; Jerabek, P.; Frenking, G.; Stalke, D. Experimental Charge Density Study of a Silylone. *Angew. Chem., Int. Ed.* **2014**, *53*, 2766−2770.

(15) (a) Mondal, K. C.; Samuel, P. P.; Roesky, H. W.; Carl, E.; Herbst-Irmer, R.; Stalke, D.; Schwederski, B.; Kaim, W.; Ungur, L.; Chibotaru, L. F.; Hermann, M.; Frenking, G. Stabilization of a Cobalt-Cobalt Bond by Two Cyclic Alkyl Amino Carbenes. *J. Am. Chem. Soc.* **2014**, *136*, 1770−1773. (b) Kretschmer, R.; Ruiz, D. A.; Moore, C. E.; Rheingold, A. L.; Bertrand, G. One-, Two-, and Three-electron Reduction of a Cyclic Alkyl(amino)carbene-$SbCl_3$ Adduct. *Angew. Chem., Int. Ed.* **2014**, *53*, 8176−8179.

(16) Gawin, R.; Kozakiewicz, A.; Guńka, P. A.; Dąbrowski, P.; Skowerski, K. Bis(Cyclic Alkyl Amino Carbene) Ruthenium Complexes: A Versatile, Highly Efficient Tool for Olefin Metathesis. *Angew. Chem., Int. Ed.* **2017**, *56*, 981−986.

(17) (a) Lavallo, V.; Frey, G. D.; Kousar, S.; Donnadieu, B.; Bertrand, G. Allene Formation by Gold Catalyzed Cross-coupling of Masked Carbenes and Vinylidenes. *Proc. Natl. Acad. Sci. U. S. A.* **2007**, *104*, 13569−13573. (b) Zeng, X.; Frey, G. D.; Kousar, S.; Bertrand, G. A Cationic Gold(I) Complex as a General Catalyst for the Intermolecular Hydroamination of Alkynes: Application to the One-Pot Synthesis of Allenes from Two Alkynes and a Sacrificial Amine. *Chem. - Eur. J.* **2009**, *15*, 3056−3060.

(18) (a) Tomas-Mendivil, E.; Hansmann, M. M.; Weinstein, C. M.; Jazzar, R.; Melaimi, M.; Bertrand, G. Bicyclic (Alkyl)(amino)carbenes (BICAACs): Stable Carbenes More Ambiphilic than CAACs. *J. Am. Chem. Soc.* **2017**, *139*, 7753−7756. (b) Lavallo, V.; Canac, Y.; Donnadieu, B.; Schoeller, W. W.; Bertrand, G. CO Fixation to Stable Acyclic and Cyclic Alkyl Amino Carbenes: Stable Amino Ketenes with a Small HOMO-LUMO Gap. *Angew. Chem., Int. Ed.* **2006**, *45*, 3488−

3491. (c) Frey, G. D.; Lavallo, V.; Donnadieu, B.; Schoeller, W. W.; Bertrand, G. Facile Splitting of Hydrogen and Ammonia by Nucleophilic Activation at a Single Carbon Center. *Science* **2007**, *316*, 439−441.

(19) Metallinos, C.; Barrett, F. B.; Chaytor, J. L.; Heska, M. E. A. A Benzimidazole-Based N-Heterocyclic Carbene Derived from 1,10-Phenanthroline. *Org. Lett.* **2004**, *6*, 3641−3644.

(20) (a) Fantasia, S.; Nolan, S. P. A General Synthetic Route to Mixed NHC-Phosphane Palladium(0) Complexes (NHC = N-Heterocyclic Carbene). *Chem.-Eur. J.* **2008**, *14*, 6987−6993. (b) Konnick, M. M.; Guzei, I. A.; Stahl, S. S. Characterization of Peroxo and Hydroperoxo Intermediates in the Aerobic Oxidation of *N*-Heterocyclic-Carbene-Coordinated Palladium(0). *J. Am. Chem. Soc.* **2004**, *126*, 10212−10213. (c) Yamashita, M.; Goto, K.; Kawashima, T. Fixation of Both O_2 and CO_2 from Air by a Crystalline Palladium Complex Bearing *N*-Heterocyclic Carbene Ligands. *J. Am. Chem. Soc.* **2005**, *127*, 7294−7295.

(21) Marion, N.; Nolan, S. P. Well-Defined N-Heterocyclic Carbenes-Palladium(II) Precatalysts for Cross-Coupling Reactions. *Acc. Chem. Res.* **2008**, *41*, 1440−1449.

(22) Weinstein, C. M.; Junor, G. P.; Tolentino, D. R.; Jazzar, R.; Melaimi, M.; Bertrand, G. Highly Ambiphilic Room Temperature Stable Six-Membered Cyclic (Alkyl)(amino)carbenes. *J. Am. Chem. Soc.* **2018**, *140*, 9255−9260.

(23) (a) Yamaguchi, J.; Yamaguchi, A. D.; Itami, K. C-H Bond Functionalization: Emerging Synthetic Tools for Natural Products and Pharmaceuticals. *Angew. Chem., Int. Ed.* **2012**, *51*, 8960−9009. (b) Le Bras, J.; Muzart, J. Intermolecular Dehydrogenative Heck Reactions. *Chem. Rev.* **2011**, *111*, 1170−1214. (c) Smith, C. A.; Narouz, M. R.; Lummis, P. A.; Singh, I.; Nazemi, A.; Li, C.-H.; Crudden, C. M. N-Heterocyclic Carbenes in Materials Chemistry. *Chem. Rev.* **2019**, *119*, 4986−5056.

(24) (a) Inomata, S.; Hiroki, H.; Terashima, T.; Ogata, K.; Fukuzawa, S. I. 1,2,3-Triazol-5-Ylidene-Palladium Complex Catalyzed Mizoroki-Heck and Sonogashira Coupling Reactions. *Tetrahedron* **2011**, *67*, 7263−7267. (b) Pawar, G. M.; Buchmeiser, M. R. Polymer-Supported, Carbon Dioxide-Protected N-Heterocyclic Carbenes: Synthesis and Application in Órgano- and Organometallic Catalysis. *Adv. Synth. Catal.* **2010**, *352*, 917−928. (c) Mayr, M.; Wurst, K.; Ongania, K. H.; Buchmeiser, M. R. 1,3-Dialkyl- and 1,3-Diaryl-3,4,5,6-Tetrahydropyrimidin-2-Ylidene Rhodium(I) and Palladium(II) Complexes: Synthesis, Structure, and Reactivity. *Chem. - Eur. J.* **2004**, *10*, 1256−1266. (d) Nakamura, T.; Ogata, K.; Fukuzawa, S. I. Synthesis of Dichlorobis(1,4-Dimesityl-1*H*-1,2,3-Triazol-5-Ylidene)Palladium [$PdCl_2(TMes)_2$] and Its Application to Suzuki-Miyaura Coupling Reaction. *Chem. Lett.* **2010**, *39*, 920−922.

(25) Manar, K. K.; Porwal, V. K.; Kamte, R. S.; Adhikari, M.; Thakur, S. K.; Bawari, D.; Choudhury, A. R.; Singh, S. Reactions of a BICAAC with Hydroboranes: Propensity for Lewis Adduct Formation and Carbene Insertion into the B-H Bond. *Dalton Trans.* **2019**, *48*, 17472−17478.

(26) Manar, K. K.; Chakrabortty, S.; Porwal, V. K.; Prakash, D.; Thakur, S. K.; Choudhury, A. R.; Singh, S. Two-Coordinate Cu(I) and Au(I) Complexes Supported by BICAAC and CAAC Ligands. *ChemistrySelect* **2020**, *5*, 9900−9907.

(27) (a) Han, Y.; Lee, L. J.; Huynh, H. V. Palladium(II) Pyrazolin-4-ylidenes: Substituent Effects on the Formation and Catalytic Activity of Pyrazole-Based Remote NHC Complexes. *Organometallics* **2009**, *28*, 2778−2786. (b) Guest, D.; Menezes da Silva, V. H.; de Lima Batista, A. P.; Roe, S. M.; Braga, A. A.; Navarro, O. (N-Heterocyclic Carbene)-Palladate Complexes in Anionic Mizoroki-Heck Coupling Cycles: A Combined Experimental and Computational Study. *Organometallics* **2015**, *34*, 2463−2470.

(28) (a) Weck, M.; Jones, C. W. Mizoroki-Heck Coupling Using Immobilized Molecular Precatalysts: Leaching Active Species from Pd Pincers, Entrapped Pd Salts, and Pd NHC Complexes. *Inorg. Chem.* **2007**, *46*, 1865−1875. (b) Muimhneachain, E. O.; McGlacken, G. P. Pd(0) nanoparticles (NPs) as catalysts in cross-coupling reactions and the homogeneous vs. heterogeneous debate. In *Organometallic Chemistry;* The Royal Society of Chemistry: Cambridge, U.K., 2016; Vol. *40*, pp 33−53. (c) Bej, A.; Ghosh, K.; Sarkar, A.; Knight, D. W. Palladium Nanoparticles in the Catalysis of Coupling Reactions. *RSC Adv.* **2016**, *6*, 11446−11453. (d) de Vries, J. G. A Unifying Mechanism for all High-Temperature Heck Reactions. The Role of Palladium Colloids and Anionic Species. *Dalton Trans.* **2006**, 421−429.

(29) Astakhov, A. V.; Khazipov, O. V.; Chernenko, A. Y.; Pasyukov, D. V.; Kashin, A. S.; Gordeev, E. G.; Khrustalev, V. N.; Chernyshev, V. M.; Ananikov, V. P. A New Mode of Operation of Pd-NHC Systems Studied in A Catalytic Mizoroki-Heck Reaction. *Organometallics* **2017**, *36*, 1981−1992.

(30) Chernyshev, V. M.; Astakhov, A. V.; Chikunov, I. E.; Tyurin, R. V.; Eremin, D. B.; Ranny, G. S.; Khrustalev, V. N.; Ananikov, V. P. Pd and Pt Catalyst Poisoning in the Study of Reaction Mechanisms: What Does the Mercury Test Mean for Catalysis? *ACS Catal.* **2019**, *9*, 2984−2995.

(31) Wojcieszak, R.; Genet, M. J.; Eloy, P.; Ruiz, P.; Gaigneaux, E. M. Determination of the Size of Supported Pd Nanoparticles by X-ray Photoelectron Spectroscopy. Comparison with X-ray Diffraction, Transmission Electron Microscopy, and H_2 Chemisorption Methods. *J. Phys. Chem. C* **2010**, *114*, 16677−16684.