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Heteroleptic Bis(N-heterocyclic carbene)Copper(I) Complexes: Highly Efficient Systems for the [3+2] Cycloaddition of Azides and Alkynes

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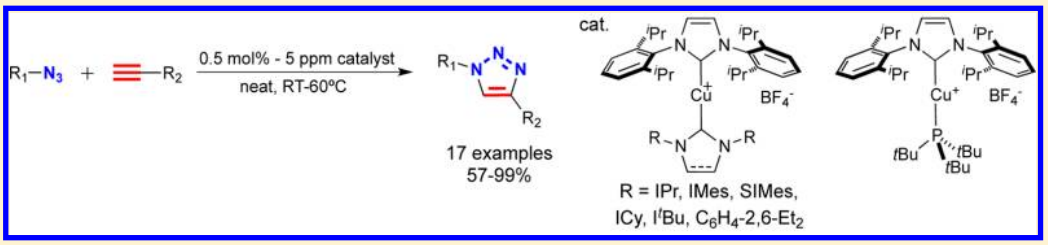
Supporting Information



ABSTRACT: The first examples of heteroleptic bis-N-heterocyclic carbene (NHC) copper(I) complexes and a mixed NHC−phosphine Cu complex are reported. These complexes are easily synthesized from the reaction of [Cu(OH)(NHC)] with various imidazol(idin)ium or phosphonium tetrafluoroborate salts. These cationic heteroleptic bis-NHC Cu complexes are highly active systems for the azide−alkyne cycloaddition leading to the formation of 1,2,3-triazoles. The mechanism of this transformation was investigated, and information gathered suggests that only one NHC remains coordinated to the metal center during catalysis.

INTRODUCTION

Functionalized triazoles have rapidly become a very common molecular construct, finding applications ranging from biology to material science.[1] The popularity of this approach has been driven by the ease with which the basic architecture can be assembled using "click" chemistry.[2] Of the various reactions falling under the click appellation, the 1,3 dipolar cycloaddition of alkynes and azides (the Huisgen reaction)[3] represents the flag-bearer for the reaction class. Whether metal catalyzed[4] or not,[5] it represents a very simple experimental protocol to assemble the triazole core.

Among the most active single-component systems enabling the Huisgen reaction,[6] copper N-heterocyclic carbene (NHC) complexes stand at the head of the class in terms of activity and productivity.[7] These copper complexes usually have a [CuX-(NHC)] (X = halide) or the homoleptic $[Cu(NHC)_2]Y$ (e.g., Y = BF_4 or PF_6) formulation.[8] As the proposed mechanism, described by Nolan and co-workers,[8b] using the homoleptic systems involves decoordination of one of the NHC ligands,[8b] we reasoned that heteroleptic complexes bearing two different ligands (with one of these being more labile than the other) may lead to an interesting activity in the Huisgen reaction leading to triazoles. We now report a straightforward synthetic approach leading to the first examples of heteroleptic bis-NHC copper complexes and examine the activity of these novel compositions in alkyne−azide cycloaddition reactions.

RESULTS AND DISCUSSION

Synthesis and Characterization of [Cu(NHC)(NHC′)]-BF_4 Complexes. Heteroleptic bis-NHC complexes of copper were obtained by reaction of a hydroxide complex of the type [Cu(OH)(NHC)], **1**,[9] with tetrafluororoborate imidazol(idin)-ium salts **2**. The sole side-product formed being water, this reaction is very straightforward and most atom economical.

In order to assess the viability of this synthetic pathway, [Cu(OH)(IPr)] (IPr = *N*,*N*′-bis{2,6-(di-isopropyl)phenyl}-imidazol-2-ylidene) was reacted with IPr·HBF_4, and the NMR spectra of the product of the reaction were compared with data reported for $[Cu(IPr)_2]BF_4$.[8c] As NMR data indicated an essentially quantitative conversion to the homoleptic bis-NHC complex **3a** had occurred, we tested the viability of this new route to access heteroleptic bis-NHC Cu complexes (Scheme 1). A series of heteroleptic bis-carbene copper(I) complexes bearing saturated and unsaturated NHCs was synthesized in this manner. These colorless complexes (**3b**−**f**) were isolated microanalytically pure in excellent yields (90−99%) (Scheme 1).

The ^{1}H NMR spectra of complexes of type **3** contain two singlets corresponding to the imidazolylidene protons. These are shifted to higher field for the saturated ligands (3.68−3.75 ppm) compared to the unsaturated ones (6.88−7.34 ppm). The isopropyl groups of the IPr ligand are seen as two doublets (CH_3 groups) and a septet (CH proton), with a coupling constant near 7 Hz. In the ^{13}C-{^{1}H} NMR spectrum, the backbone carbon atoms are seen as two singlets, one per imidazolylidene carbon atoms, while the most characteristic peaks, corresponding to the carbene carbon atoms, are shifted to lower field, between 171.6 and 200.8 ppm. As expected, the saturated NHCs give rise to the lowest field signals (200 ppm).[10,11]

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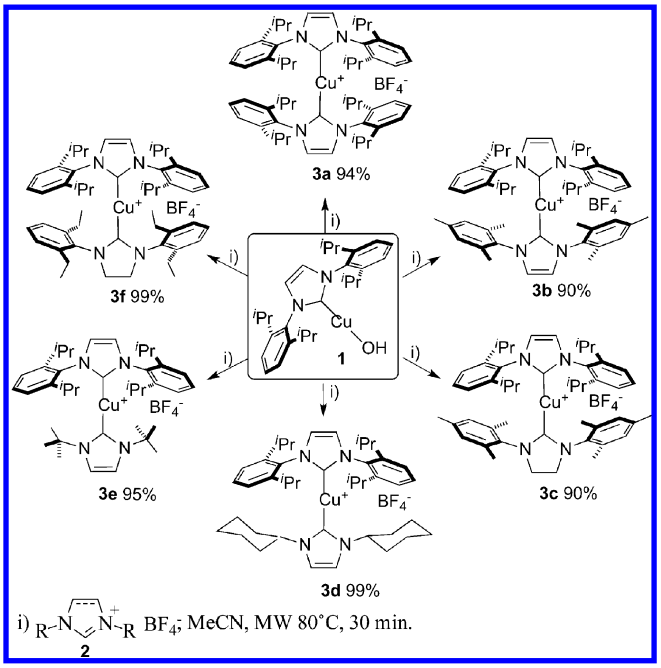
Scheme 1. [Cu(IPr)(NHC)]BF_4 Complexes Synthesized in This Study



Crystallographic studies were carried out to unambiguously establish the structural features of these complexes (Figure 1).[12]

All complexes present a linear geometry with $C_{(IPr)}$–Cu–$C_{(NHC)}$ angles between 178.55(19)° and 180.0(2)° (Table 1). The Cu–$C_{carbene}$ bond lengths for the heteroleptic complexes lie in the range 1.897(6) to 1.908(7) Å, which is shorter than the Cu–$C_{carbene}$ length measured for the homoleptic analogue **3a** (1.938(18) and 1.926(19) Å).[8c] This is in agreement with the steric hindrance of IPr (%V_{Bur} IPr of **3a** is 36.9). The steric bulk of the NHC ligands of complexes **3b–f** was assessed using the Samb*V*ca application.[13] The %V_{Bur} values obtained show that I*t*Bu is the most sterically demanding NHC in the study, ICy the less congested, and the saturated SIMes more hindered than its unsaturated analogue. This is in accordance with previous observations made for these ligands.[8d] Complexes bearing two aryl-*N*-substituted NHCs (complexes **3b**, **3c**, **3f**) display a twist between the NHCs five-membered rings (Table 1). In contrast, complexes **3d** and **3e**, which bear a NHC with *N*-alkyl substituents, do not present such a twist. This shows the flexibility of alkyl groups compared to aryl ones, the former having the ability to modulate its bulkiness in response to the steric requirement of IPr.

Catalysis. The catalytic activity of this novel series of cationic copper complexes was first examined for the [3+2] cycloaddition of heptyl azide and phenylacetylene. At room temperature, in neat substrate, with a catalyst loading of 0.5 mol %, all complexes of type **3** permitted complete conversion to the triazole product.[14] However, a divergence between the complexes in terms of rate of reaction is observed, **3d** and **3e** reaching completion within 2 h (Table 2, entries 4 and 5), while **3a–c** and **3f** require between 20 and 36 h to attain quantitative conversion (Table 2, entries 1–3 and 6). This observation cannot be rationalized using steric arguments alone based on %V_{Bur}, as the two fastest systems, **3d** and **3e**, bear the smallest and the largest NHC of the study (ICy and I*t*Bu) (Table 1). However, a common feature of the two *N*-alkyl-

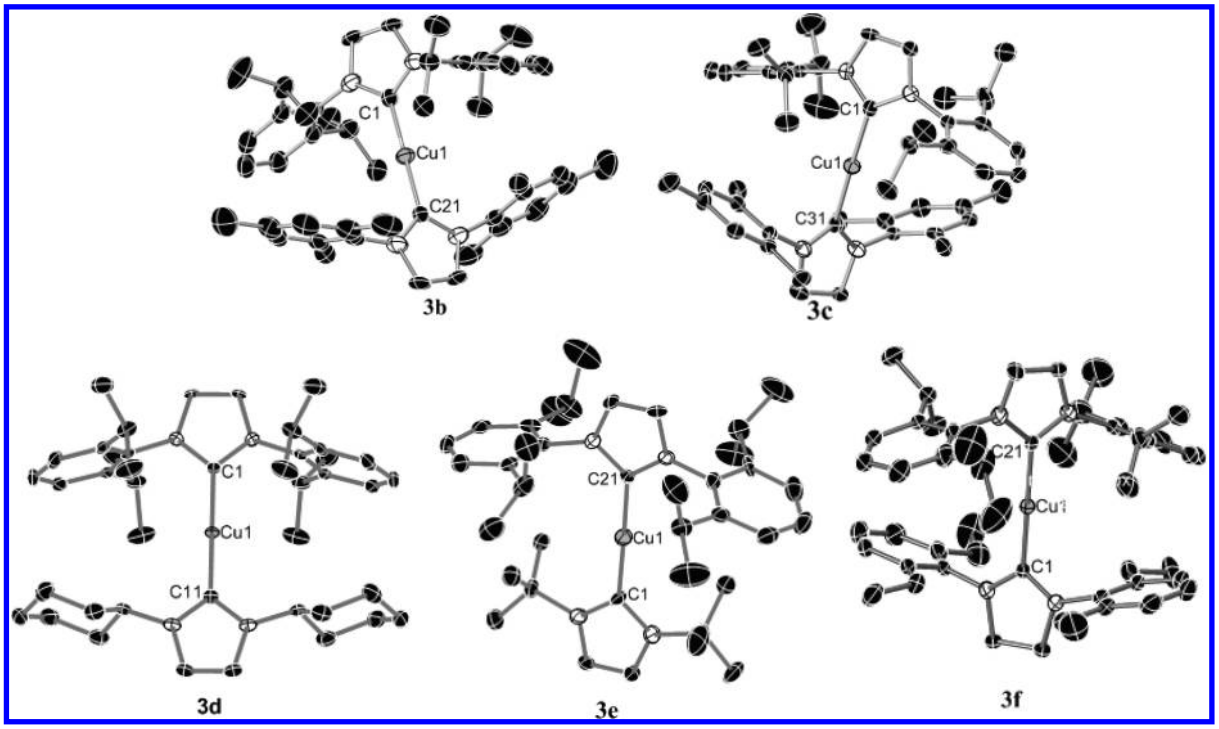


Figure 1. ORTEP plots of [Cu(IPr)(IMes)]BF_4, **3b**, [Cu(IPr)(SIMes)]BF_4, **3c**, [Cu(IPr)(ICy)]BF_4, **3d**, [Cu(IPr)(I*t*Bu)]BF_4, **3e**, and [Cu(IPr)(NHC′)]BF_4, **3f**.[12] (NHC′ = *N*,*N*′-bis[2,6-(diethyl)phenyl]imidazolidin-2-ylidene.) Ellipsoids are represented at the 50% probability level. Hydrogen atoms and anion are omitted for clarity. Selected bond lengths (Å) and angles (deg) (esd): **3b**: Cu(1)–C(1) 1.905(5), Cu(1)–C(21) 1.902(5), C(1)–Cu(1)–C(21) 180.0(2); **3c**: Cu(1)–C(1) 1.899(5), Cu(1)–C(31) 1.900(4), C(1)–Cu(1)–C(31) 178.55(19); **3d**: Cu(1)–C(1) 1.898(6), Cu(1)–C(11) 1.897(6), C(1)–Cu(1)–C(11) 180.0(1); **3e**: Cu(1)–C(1) 1.906(6), Cu(1)–C(21) 1.903(6), C(1)–Cu(1)–C(21) 178.8(3); **3f**: Cu(1)–C(1) 1.906(7), Cu(1)–C(21) 1.908(7), C(1)–Cu(1)–C(21) 180.0(1).

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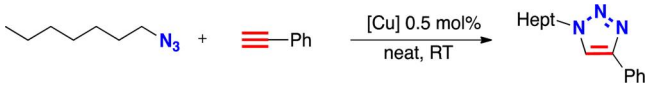
Table 1. $\%V_{Bur}$ and Selected Bond Lengths (Å) and Angles (deg) (esd) for Complexes 3a−f

	IPr/IPr **3a**[8c]	IPr/IMes **3b**	IPr/SIMes **3c**	IPr/ICy **3d**	IPr/ItBu **3e**	IPr/NHC′[a] **3f**
$\%V_{Bur}$	36.9	45.7/32.3	44.2/35.1	42/25.5	38.9/37.2	43.6/33.2
$Cu-C_{IPr}$	1.938(18)	1.905(5)	1.899(5)	1.898(6)	1.903(6)	1.908(7)
$Cu-C_{NHC}$	1926(19)	1.902(5)	1.900(4)	1.897(6)	1.906(6)	1.906(7)
$C_{IPr}-Cu-C_{NHC}$	177.1(9)	180.0(2)	178.55(19)	180.0(1)	178.8(3)	180.0(1)
NHC−NHC′[b]	49.72	136(1)	55(1)	0(1)	2(1)	47(1)

[a]NHC′ = *N*,*N*′-bis[2,6-(diethyl)phenyl]imidazolidin-2-ylidene. [b]Angle between five-membered rings.

Table 2. Catalyst Optimization[a]



entry	complex	cat loading (mol %)	time[c] (h)	conv[d] (%)
1	$[Cu(IPr)_2]BF_4$, **3a**	0.5	20	100 (97)
2	$[Cu(IPr)(IMes)]BF_4$, **3b**	0.5	25	100 (97)
3	$[Cu(IPr)(SIMes)]BF_4$, **3c**	0.5	24	100 (95)
4	$[Cu(IPr)(ICy)]BF_4$, **3d**	0.5	2.1	100 (98)
5	$[Cu(IPr)(ItBu)]BF_4$, **3e**	0.5	1.8	100 (97)
6	$[Cu(IPr)(NHC')]BF_4$, **3f**[b]	0.5	36	100 (96)
7	$[Cu(IPr)(ICy)]BF_4$, **3d**	0.25	2.25	100 (97)
8	$[Cu(IPr)(ItBu)]BF_4$, **3e**	0.25	2	100 (97)
9	$[Cu(IPr)(ICy)]BF_4$, **3d**	0.1	3	100 (98)
10	$[Cu(IPr)(ItBu)]BF_4$, **3e**	0.1	2.5	100 (98)
11	$[Cu(IPr)(ICy)]BF_4$, **3d**	0.02	16	100 (97)[e]
12	$[Cu(IPr)(ItBu)]BF_4$, **3e**	0.02	24	71 (65)

[a]Reaction conditions: azide (1.00 mmol), alkyne (1.05 mmol), catalyst (0.5 mol %), RT, neat. [b]NHC′ = *N*,*N*′-bis[2,6-(diethyl)phenyl]-imidazolidin-2-ylidene. [c]Optimized reaction time; see Supporting Information for kinetic profiles of entries 4, 5, 11, and 12. [d]Conversion determined by GC, based on azide, minimum average of 4 reactions. Isolated yields are given in parentheses. [e]Turnover number (TON) = 5000.

substituted ligands ICy and I*t*Bu is the fact that, in complexes of type **3**, the planes containing the two five-membered NHC rings are nearly parallel, which is in contrast with all *N*-aryl analogues (Table 1, NHC−NHC′ angle). In terms of electronics, both NHCs are better donors than the *N*-aryl-substituted NHCs studied here.[15] Therefore, it appears that the key to catalytic activity within the series is to ally strong donor ability with ligand flexibility.

At lower catalyst loadings (0.25 and 0.1 mol %), the system based on I*t*Bu (**3e**) reached completion faster than the system based on ICy (**3d**) (Table 2, entries 7−10). However, lowering the catalyst loading showed that complex **3d** is more active than its I*t*Bu analogue (Table 2, entries 11 and 12), and at 0.02 mol % Cu, quantitative conversion to the triazole is obtained within 16 h. Of note is the fact that the homoleptic complex $[Cu(ICy_2)]PF_6$, under the same reaction conditions, led to only 72% of product after 20 h.[8b]

The scope of the reaction was next examined using **3d** (Scheme 2). Alkyl-/Aryl-substituted and functionalized azides and alkynes were successfully reacted, leading to a range of 1,4-disubstitued-1,2,3-triazoles in high yields. The range of functionalities tolerated is very broad and includes amines, esters, alcohols, ketones, and halides. At room temperature using 0.5 mol % catalyst loading, the reaction reached completion within 20 min to 7 h, with isolated yields of triazoles in the 97−99% range. Studies performed at low catalyst loadings further highlight the high efficiency of the heteroleptic bis-NHC system **3d**. All substrates proved to lead to the desired product with the exception of **6j**, which proved difficult to form at low catalyst loading. All other compounds could be obtained in excellent yields using loading below 500 ppm. At 40 °C, most products could be obtained using only 100−200 ppm of catalyst. The exceptional catalytic activity of **3d** was further revealed in the formation of **6m**, **6n**, and **6o**. Compounds **6m** and **6n** were obtained with a turnover number of 28 400 and 32 400, respectively, and for **6o**, *an outstanding TON of 194 000 was achieved!*

Comparing the hetero- with the homoleptic system leads to the observation of some differing reactivity trends. Most notably, for **6b**, **6m**, **6o**, **6p**, and **6q** at 0.5 mol % catalyst, less than 3 h is required to reach complete conversion, whereas the system described by Nolan required 5 to 9 h.[8b] For **6a** and **6b**, the same reaction time at 0.5 mol % is observed to reach full conversion, whereas the homoleptic systems require 5 min for **6a** but 9 h for **6b**. The methoxy group in the *para* position does not change the reactivity at high catalyst loading. Even if for "easy" substrates the homoleptic systems present high reactivity, the heteroleptic system shows very high activity especially at low catalyst loadings.

Mechanistic Considerations. A catalytic cycle was proposed by Nolan for homoleptic bis-NHC complexes.[8b] The complex is believed to react with the azide to form a copper-acetylide. One NHC is released and an imidazolium salt is formed. To understand if the heteroleptic and homoleptic complexes presented the same activation, simple stoichiometric reactions were conducted. The copper complex $[Cu(IPr)(ICy)]BF_4$, **3d**, was exposed to phenylacetylene and heated overnight at 80 °C. The formation of two new species was observed. The new products were separated and identified as $[Cu(IPr)(C{\equiv}CPh)]$ and $ICy{\cdot}HBF_4$. The same reaction was performed at RT, and the same products were isolated, highlighting a low activation pathway for click using these heteroleptic complexes. Using the Cu-acetylide intermediate $[Cu(IPr)(C{\equiv}CPh)]$, a stoichiometric reaction was conducted on an NMR tube scale in CD_3CN with 1 equiv of heptyl azide. The reaction leads to the formation of an unstable complex, presumably a copper-triazolyl intermediate, as diagnosed by the characteristic CH_2 group bound to azide. Finally, to confirm the catalytic relevancy of the $[Cu(IPr)(C{\equiv}CPh)]$, it was used as catalyst (1 mol %) in a reaction involving heptylazide (1.00 mmol) and phenylacetylene (1.05 mmol) without solvent. The reaction was stirred at RT, and after 130 min, complete conversion was reached and the desired product was isolated in 95% yield, confirming the active role of $[Cu(IPr)(C{\equiv}CPh)]$ in the catalytic cycle. It is essential to release a carbene ligand for catalytic activity, as shown by an experiment in which $ICy{\cdot}HBF_4$ was added to the catalyst system. This inhibited the catalyst, as, at room temperature, with 0.5 mol % of

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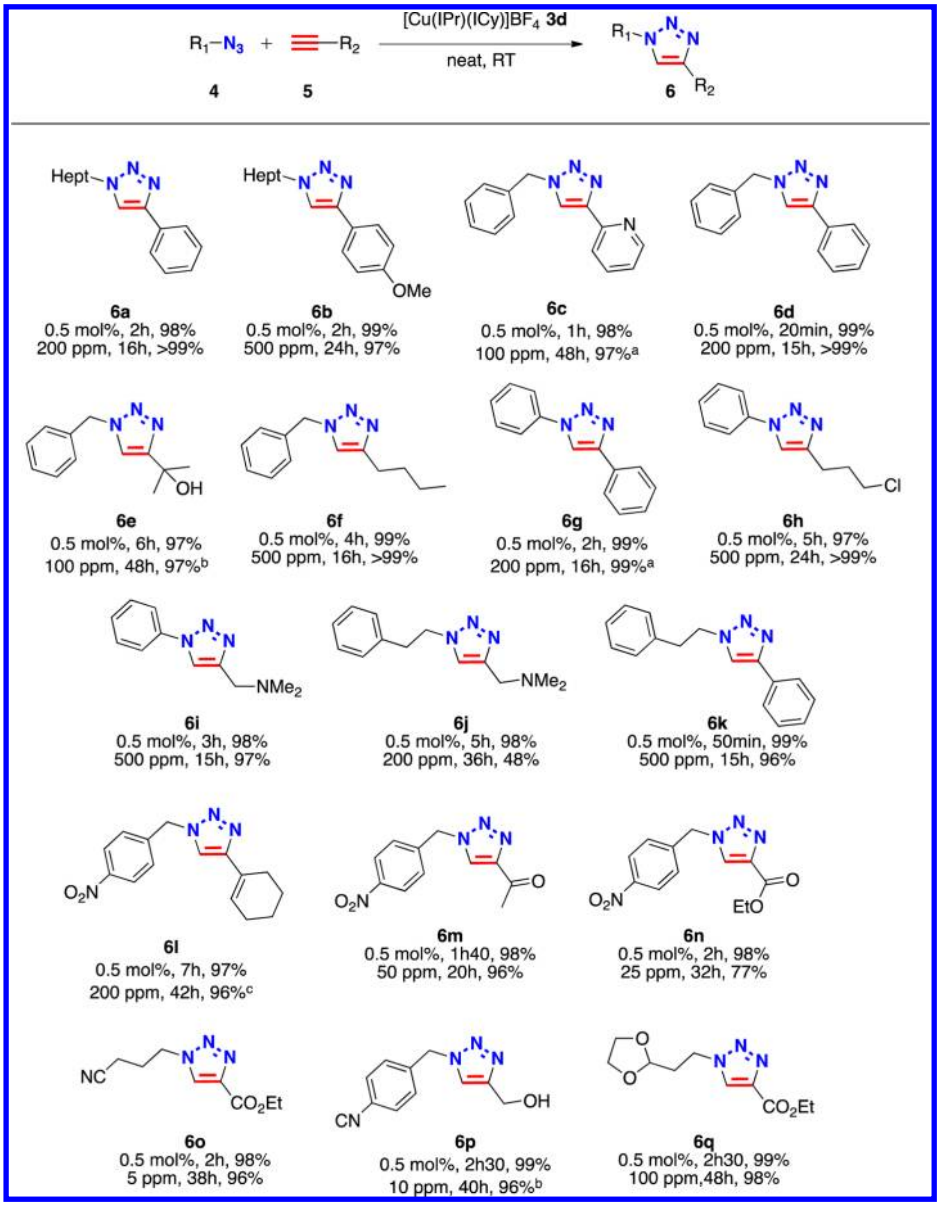
Scheme 2. Scope of the Reaction at RT and at Low Catalyst Loading[a]



[a]Reaction conditions: azide (1.00 mmol), alkyne (1.05 mmol), **3d** (5 ppm−0.5 mol %), neat, RT to 60 °C, 20 min to 48 h. Isolated yield (average of reactions): [a]40 °C; [b]50 °C; [c]60 °C.

$[Cu(IPr)(ICy)]BF_4$ (**3d**) and 1 mol % of ICy·HBF_4, after 7 h, no conversion was observed. This system required 16 h to reach quantitative conversion, which is in contrast with the performance observed with **3d** (Table 2, entry 4). The catalytic cycle is therefore likely to proceed as in the case of the homoleptic system $[Cu(ICy)_2]BF_4$ (Scheme 3).[8b,16]

The fact that the leaving NHC is ICy and not IPr is counterintuitive. Indeed, ICy is less sterically demanding, is a better donor,[15] and has been shown to bind more strongly than IPr.[17] However, it should be kept in mind that the simple difference in bond dissociation energies of Cu−ICy and Cu−IPr is not the only thermodynamic term to be considered, as the formation of a stronger ICy−H vs IPr−H bonds in formation of the imidazolium salt product also contributes to the overall reaction enthalpy.

Finally, the mechanistic study directed us toward the examination of a mixed ligand system, NHC/phosphine, which might enable a better understanding of the catalytic manifold. For this reason, complex **3g**, bearing P*t*Bu_3, was synthesized. The synthetic route makes use of the general route developed above for NHC-based systems and requires the use of the phosphonium salt $[HPtBu_3]BF_4$. The reaction of the latter with $[Cu(OH)(IPr)]$ (**1**) at room temperature leads to the formation of $[Cu(IPr)(PtBu_3)]BF_4$, **3g**, in quantitative yield. The structure of **3g** was confirmed by X-ray diffraction on single crystals (Figure 2).

The $^{31}P\{^1H\}$ NMR spectrum of **3g** displays a singlet at 66.9 ppm, corresponding to the phosphine ligand. In the ^1H NMR spectrum, the protons of the latter are seen as a doublet shifted at δ_H 1.06 ppm ($^3J_{HP}$ = 13.3 Hz). The *i*Pr groups of the NHC are seen as two doublets and a septuplet ($^3J_{HH}$ = 6.9 Hz), and the NHC backbone protons as a singlet at 7.39 ppm. In the $^{13}C\{^1H\}$ NMR, the most characteristic peaks for the NHC are a singlet at 124.6 ppm (backbone carbon atoms) and a doublet

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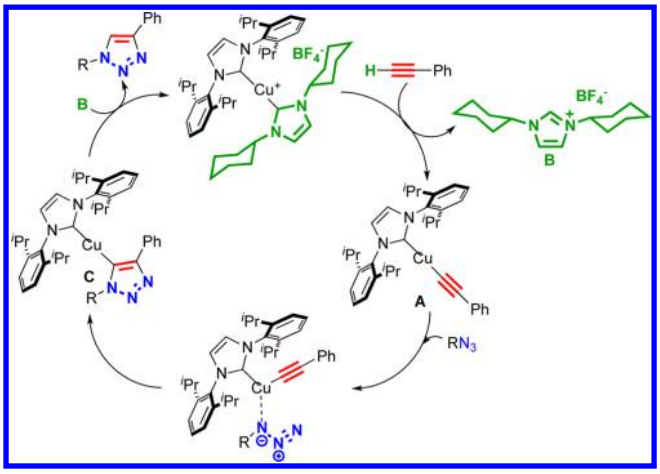
Scheme 3. Catalytic Cycle Leading to the Formation of 1,2,3-Triazole



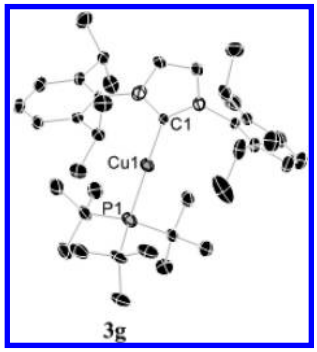
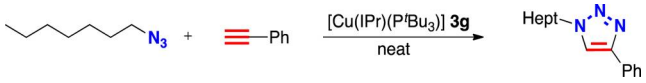


Figure 2. Crystal structure of $[Cu(IPr)(PtBu_3)]BF_4$, **3g**.[12] Ellipsoids are represented at the 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (deg) (esd): Cu(1)−C(1) 1.918(5), Cu(1)−P(1) 2.2147(15), C(1)−Cu(1)−P(1) 178.38(17).

at 178.6 ppm with a C−P coupling constant of 61.0 Hz, corresponding to the carbene carbon atom. Doublets at 32.2 and 37.3 ppm were assigned to the *t*Bu carbon atoms.

Catalytic testing was performed on the model reaction (1-azidoheptane, phenylacetylene, neat) and shows that $[Cu(IPr)(PtBu_3)]BF_4$, **3g**, at 0.5 mol % loading, leads to a catalytic system faster than all heteroleptic bis-NHC complexes, with the exception of $[Cu(IPr)(ICy)]BF_4$, **3d** (Table 2, entries 1−6, and Table 3, entry 1). At lower catalyst loading, $[Cu(IPr)(ICy)]BF_4$, **3d**, still displays a catalytic activity superior to that of $[Cu(IPr)(PtBu_3)]BF_4$, **3g** (Table 2, entry 11, and Table 3, entries 2 and 3).[18] Increasing the temperature shows that $[Cu(IPr)(PtBu_3)]BF_4$, **3g**, is a high-performance catalyst, as 5000 TONs can be reached (Table 3, entry 5); however, this result can be compared to the performance of $[Cu(IPr)(ICy)]BF_4$, **3d**, which performs equally well but at room temperature. This appears to indicate that $[Cu(IPr)(ICy)]BF_4$, **3d**, bears ligands that have the right balance in terms of electronic and steric effects to ensure optimum performance under click conditions, i.e., at room temperature and under solvent-free (or neat) conditions.

Table 3. Catalysis Using $[Cu(IPr)(P^tBu_3)]BF_4$, 3g[a]



entry	cat loading (mol %)	temp (°C)	time (h)	conversion (%)[b]
1	0.5	RT	<4	100
2	0.05	RT	20	90
3	0.02	RT	20	48
4	0.02	40	24	88
5	0.02	50	<15	100

[a]Reaction conditions: azide (1.00 mmol), alkyne (1.05 mmol), neat. [b]Conversion determined by GC, minimum average of 4 reactions.

In order to find out which of the NHC or phosphine is released in the course of catalysis, simple stoichiometric reactions were conducted. The copper complex $[Cu(IPr)(PtBu_3)]BF_4$, **3g**, was exposed to phenylacetylene and heated overnight at 80 °C. The formation of two new species was observed. The new products were separated and identified as $[Cu(PtBu_3)(C{\equiv}CPh)]$ and $IPr{\cdot}HBF_4$. The same reaction was performed at RT, and the same products were isolated, indicating the facile nature of the reaction. This catalytic step hints at the importance of the basicity of the NHC (or of that of the other ligand) attached to the metal center. This might indicate that the NHC that is released acts as a base to the alkyne substrate to initiate the catalytic cycle, while the less basic NHC or PR_3 species remains coordinated to copper. This highlights the interest of having heteroleptic or mixed ligand complexes, as each ligand can be separately tuned to reach optimum catalytic performance.

CONCLUSION

A novel and straightforward synthetic route leading to moisture- and air-stable homoleptic and (the first isolation of) heteroleptic bis-NHC copper(I) complexes has been developed. This versatile synthetic methodology also allows access to a mixed NHC/PR_3 complex. The structural studies of a number of these complexes indicate the presence of significant torsion angles of ligands about the copper center that, in essence, encapsulate the metal, rendering it less accessible. Catalytic studies with these complexes highlight a very good catalytic activity in the Huisgen cycloaddition reaction. The structure−activity relationship within this series appears to be guided by a flexibility of the coligand. With $[Cu(IPr)(ICy)]BF_4$, **3d**, reactions can reach completion with only a few ppm of catalyst. The access to the metal clearly appears important, and mechanistic studies suggest that only one NHC remains on copper during the catalytic transformation.

EXPERIMENTAL SECTION

General Procedure. For the synthesis of heteroleptic bis-carbene complexes of type **3**, a vial was charged with $[Cu(OH)(IPr)]$[9] (200 mg, 0.426 mmol), the appropriate imidazol(idin)ium salt (0.426 mmol), and acetonitrile (2 mL). The reaction mixture was heated at 80 °C in a microwave oven for 30 min. The reaction mixture was concentrated *in vacuo* (1 mL), and diethyl ether (2 mL) was added. The product was collected by filtration.

N,N′-Bis{2,6-(di-isopropyl)phenyl}imidazol-2-ylidene-{N,N′-bis-(2,4,6-trimethylphenyl)imidazol-2-ylidene}copper(I) Tetrafluoroborate, [Cu(IPr)(IMes)]BF4, ***3b.*** Colorless solid, 320.7 mg, 90%. ^{1}H NMR (400 MHz, CD_2Cl_2, 298 K): δ 0.82 (d, 12H, $^3J_{HH}$ = 6.9 Hz, $CHCH_3$), 1.10 (d, 12H, $^3J_{HH}$ = 6.9 Hz, $CHCH_3$), 1.66 (s, 12H, CH_3 Mes), 2.31 (septet, 4H, $^3J_{HH}$ = 6.9 Hz, $CHCH_3$), 2.39 (s, 6H, CH_3 Mes), 6.80 (s, 4H, Ar IMes), 6.88 (s, 2H, H^4 and H^5), 7.11 (s, 2H, $H^{4'}$ and $H^{5'}$), 7.20 (d, 4H, $^3J_{HH}$ = 7.8 Hz, Ar IPr), 7.57 (t, 2H, $^3J_{HH}$ = 7.8 Hz, Ar IPr). $^{13}C\{^1H\}$ NMR (75 MHz, CD_2Cl_2, 298 K): δ 17.3 (s, CH_3

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Mes), 21.3 (s, CH_3 Mes), 23.6 (s, $CHCH_3$), 24.5 (s, $CHCH_3$), 28.9 (s, $CHCH_3$), 123.9 (s, C^4 and C^5), 124.3 (s, $C^{4\prime}$ and $C^{5\prime}$), 124.5 (s, Ar IPr), 130.1 (s, Ar IMes), 131.0 (s, Ar IPr), 134.5 (s, C^{IV}), 134.6 (s, C^{IV}), 134.8 (s, C^{IV}), 139.6 (s, C^{IV}), 145.4 (s, C^{IV}), 176.2 (s, C^2 carbene), 179.3 (s, C^2 carbene). Anal. Calcd for $C_{48}H_{60}BCuF_4N_4$: C, 68.36; H, 7.17; N, 6.64. Found: C, 68.09; H, 7.24; N, 6.61.

N,N′-Bis{2,6-(di-isopropyl)phenyl}imidazol-2-ylidene-N,N′-bis-{2,4,6-(trimethyl)phenyl}imidazolidin-2-ylidene Copper(I) Tetrafluoroborate, [Cu(IPr)(SIMes)]BF$_4$, ***3c***. Colorless solid, 320 mg, 90%. ^{1}H NMR (400 MHz, CD_2Cl_2, 298 K): δ 0.81 (d, 12H, $^3J_{HH}$ = 6.9 Hz, $CHCH_3$), 1.08 (d, 12H, $^3J_{HH}$ = 6.9 Hz, $CHCH_3$), 1.86 (s, 12H, CH_3 Mes), 2.28 (septet, 4H, $^3J_{HH}$ = 6.9 Hz, $CHCH_3$) overlapping with 2.33 (s, 6H, CH_3 Mes), 3.68 (s, 4H, H^4 and H^5 SIMes), 6.74 (s, 4H, Ar SIMes), 7.07 (s, 2H, $H^{4\prime}$ and $H^{5\prime}$ IPr), 7.21 (d, 4H, $^3J_{HH}$ = 7.8 Hz, Ar IPr), 7.58 (t, 2H, $^3J_{HH}$ = 7.8 Hz, Ar IPr). $^{13}C\{^1H\}$ NMR (CD_2Cl_2, 75 MHz, 298 K): δ 17.6 (s, CH_3 Mes), 21.2 (s, CH_3 Mes), 23.6 (s, $CHCH_3$), 24.4 (s, $CHCH_3$), 28.9 (s, $CHCH_3$), 51.8 (s, C^4 and C^5 SIMes), 124.3 (s, $C^{4\prime}$ and $C^{5\prime}$ IPr), 124.6 (s, Ar IPr), 130.4 (s, Ar SIMes), 131.0 (s, Ar IPr), 134.4 (s, C^{IV}), 134.7 (s, C^{IV}), 135.4 (s, C^{IV}), 138.7 (s, C^{IV}), 145.3 (s, C^{IV}), 179.0 (s, C^2 carbene), 200.2 (s, C^2 carbene). Anal. Calcd for $C_{48}H_{62}BCuF_4N_4$: C, 68.20; H, 7.39; N, 6.63. Found: C, 68.19; H, 7.53; N, 6.71.

N,N′-Bis{2,6-(di-isopropyl)phenyl}imidazol-2-ylidene-N,N′-(dicyclohexyl)imidazol-2-ylidene Copper(I) Tetrafluoroborate, [Cu(IPr)(ICy)]BF$_4$, ***3d***. Colorless solid, 306 mg, 99%. ^{1}H NMR (400 MHz, CD_2Cl_2, 298 K): δ 0.89−1.12 (m, 6H, CH_2 cyclohexyl), 1.24 (d, 12H, $^3J_{HH}$ = 6.8 Hz, $CHCH_3$), 1.29 (d, 12H, $^3J_{HH}$ = 6.8 Hz, $CHCH_3$), 1.31−1.42 (m, 4H, CH_2 cyclohexyl), 1.56−1.71 (m, 10H, CH_2 cyclohexyl), 2.59 (septet, 4H, $^3J_{HH}$ = 6.8 Hz, $CHCH_3$), 3.10 (tt, 2H, $^3J_{HH}$ = 12.2 Hz, $^3J_{HH}$ = 4 Hz, CH cyclohexyl), 6.89 (s, 2H, H^4 and H^5), 7.29 (s, 2H, $H^{4\prime}$ and $H^{5\prime}$), 7.44 (d, 4H, $^3J_{HH}$ = 7.8 Hz, Ar), 7.64 (t, 2H, $^3J_{HH}$ = 7.8 Hz, Ar). $^{13}C\{^1H\}$ NMR (CD_2Cl_2, 75 MHz, 298 K): δ 23.5 (s, $CHCH_3$), 24.9 (s, CH_2 cyclohexyl), 25.1 (s, CH_2 cyclohexyl), 25.7 (s, $CHCH_3$), 29.2 (s, $CHCH_3$), 34.5 (s, CH_2 cyclohexyl), 61.3 (s, CH cyclohexyl), 118.6 (s, C^4 and C^5), 124.3 (s, $C^{4\prime}$ and $C^{5\prime}$), 125.0 (s, Ar), 131.6 (s, Ar), 134.6 (s, C^{IV}), 146.4 (s, C^{IV}), 171.7 (s, C^2 carbene), 179.3 (s, C^2 carbene). Anal. Calcd for $C_{42}H_{60}BCuF_4N_4$: C, 65.40; H, 7.84; N, 7.26. Found: C, 65.37; H, 7.84; N, 7.17.

N,N′-Bis{2,6-(di-isopropyl)phenyl}imidazol-2-ylidene-N,N′-(di-tert-butyl)imidazol-2-ylidene copper(I) Tetrafluoroborate, [Cu(IPr)(ItBu)]BF$_4$, ***3e***. Colorless solid, 274 mg, 95%. ^{1}H NMR (400 MHz, CD_2Cl_2, 298 K): δ 1.19 (s, 18H, CH_3 *tert*-butyl), 1.22 (d, 12H, $^3J_{HH}$ = 7.1 Hz, $CHCH_3$) overlapping with 1.24 (d, 12H, $^3J_{HH}$ = 7.1 Hz, $CHCH_3$), 2.71 (septet, 4H, $^3J_{HH}$ = 7.1 Hz, $CHCH_3$), 6.98 (s, 2H, H^4 and H^5), 7.34 (s, 2H, H^4 and H^5), 7.36 (d, 4H, $^3J_{HH}$ = 7.5 Hz, Ar IPr), 7.54 (t, 2H, $^3J_{HH}$ = 7.5 Hz, Ar IPr). $^{13}C\{^1H\}$ NMR (CD_2Cl_2, 75 MHz, 298 K): δ 24.0 (s, $CHCH_3$), 25.0 (s, $CHCH_3$), 29.1 (s, $CHCH_3$), 29.9 (s, C^{IV}), 31.9 (s, CH_3 *tert*-butyl), 57.3 (s, C^{IV} mesityl), 117.6 (s, C^4 and C^5), 124.9 (s, C^4 and C^5), 125.2 (s, Ar), 131.3 (s, Ar), 135.1 (s, C^{IV} phenyl), 145.8 (s, C^{IV} phenyl), 171.6 (s, C^2 carbene), 179.6 (s, C^2 carbene). Anal. Calcd for $C_{38}H_{56}BCuF_4N_4$: C, 63.46; H, 7.85; N, 7.79. Found: C, 63.55; H, 7.74; N, 7.82.

N,N′-Bis{2,6-(di-isopropyl)phenyl}imidazol-2-ylidene-N,N′-bis-{2,6-(diethyl)phenyl}imidazolidin-2-ylidene Copper(I) Tetrafluoroborate, [Cu(IPr)(NHC′)]BF$_4$, ***3f***. Colorless solid, 346 mg, 99%. ^{1}H NMR (400 MHz, CD_2Cl_2, 298 K): δ 0.78 (d, 12H, $^3J_{HH}$ = 7.2 Hz, $CHCH_3$), 1.05 (d, 12H, $^3J_{HH}$ = 7.2 Hz, $CHCH_3$), 1.13 (t, 12H, $^3J_{HH}$ =7.6 Hz, CH_2CH_3 ethyl), 2.12 (dq, 4H, $^3J_{HH}$ = 7.6 Hz, CH_2CH_3 ethyl), 2.25 (septet, 4H, $^3J_{HH}$ = 7.2 Hz, $CHCH_3$) overlapping with 2.33 (dq, 4H, $^3J_{HH}$ = 7.6 Hz, CH_2CH_3 ethyl), 3.75 (s, 4H, H^4 and H^5), 7.00 (d, 4H, $^3J_{HH}$ = 7.7 Hz, Ar), overlapping with 7.02 (s, 2H, $H^{4\prime}$ and $H^{5\prime}$), 7.19 (d, 4H, $^3J_{HH}$ = 7.8 Hz, Ar), 7.29 (t, 2H, $^3J_{HH}$ = 7.7 Hz, Ar), 7.57 (t, 2H, $^3J_{HH}$ = 7.8 Hz, Ar). $^{13}C\{^1H\}$ NMR (CD_2Cl_2, 75 MHz, 298 K): δ 14.6 (s, CH_2CH_3 ethyl), 23.7 (s, $CHCH_3$), 24.0 (s, $CHCH_3$), 24.4 (s, CH_2CH_3), 28.9 (s, $CHCH_3$), 53.1 (s, C^4 and C^5), 124.6 (s, $C^{4\prime}$ and $C^{5\prime}$), 124.8 (s, Ar), 127.4 (s, Ar), 129.5 (s, Ar), 130.9 (s, Ar), 134.4 (s, C^{IV}), 136.2 (s, C^{IV}), 141.1 (s, C^{IV}), 145.3 (s, C^{IV}), 178.5 (s, C^2 carbene), 200.8 (s, C^2 carbene). Anal. Calcd for $C_{50}H_{66}BCuF_4N_4$: C, 68.76; H, 7.62; N, 6.4. Found: C, 68.83; H, 7.71; N, 6.37.

N,N′-Bis{2,6-(di-isopropyl)phenyl}imidazol-2-ylidene-tri(tert-butyl)phosphine Copper(I) Tetrafluoroborate, [Cu(IPr)(PtBu$_3$)]BF$_4$, ***3g***. A vial was charged with [Cu(OH)(IPr)][9] (200 mg, 0.426 mmol), the phosphonium salt (124 mg, 0.426 mmol), and THF (2 mL). The reaction mixture was stirred at RT for 12 h. The solution was concentrate *in vacuo* (1 mL), and diethyl ether (2 mL) was added. The product was collected by filtration and obtained as a colorless solid (294 mg, 99%). ^{1}H NMR (400 MHz, CD_2Cl_2, 298 K): δ 1.06 (d, 27H, $^3J_{HP}$ = 13.3 Hz, $C(CH_3)_3$), 1.23 (d, 12H, $^3J_{HH}$ = 6.9 Hz, $CHCH_3$), 1.28 (d, 12H, $^3J_{HH}$ = 6.9 Hz, $CHCH_3$), 2.61 (septet, 4H, $^3J_{HH}$ = 6.9 Hz, $CHCH_3$), 7.35 (d, 4H, $^3J_{HH}$ = 7.9 Hz, CH Ar), 7.39 (s, 2H, H^4 and H^5), 7.54 (t, 2H, $^3J_{HH}$ = 7.9 Hz, CH Ar). $^{13}C\{^1H\}$ NMR (CD_2Cl_2, 75 MHz, 298 K): δ 24.3 (s, $CHCH_3$), 24.8 (s, $CHCH_3$), 29.2 (s, $CHCH_3$), 32.2 (d, $^2J_{CP}$ = 5.2 Hz, CH_3 *tert*-butyl), 37.3 (d, $^1J_{CP}$ = 12.6 Hz, CCH_3 *tert*-butyl), 124.6 (s, C^4 and C^5) 124.8 (s, Ar), 131.3 (s, Ar), 134.7 (s, C^{IV}), 145.8 (s, C^{IV}), 178.6 (d, $^2J_{CP}$ = 61.0 Hz, C^2 carbene). $^{31}P\{^1H\}$ NMR (400 MHz, CD_2Cl_2, 298 K): δ 66.9 ppm. Anal. Calcd for $C_{39}H_{63}BCuF_4N_4$: C, 63.19; H, 8.57; N, 3.78. Found: C, 63.12; H, 8.71; N, 3.66.

General Procedure for Catalytic Testing. A vial was charged with the azide (1.00 mmol), the alkyne (1.05 mmol), and the appropriate amount of catalyst. The reaction mixture was stirred without solvent (when substrates were liquids) at the indicated temperature for the specified amount of time. The progress of the reaction was monitored by GC, and when completion was reached, the product was collected by filtration and washed with pentane (2 × 3 mL). For low catalyst loading experiments, in a vial, the required amount of a freshly prepared stock solution (4 mg of [Cu(IPr)(ICy)] in 1 mL of CH_2Cl_2) was introduced, and the solvent was evaporated *in vacuo*. Azide (1.00 mmol) and alkyne (1.05 mmol) were then charged in turn into the vial. The reaction mixture was stirred without added solvent at the indicated temperature for the specified amount of time. Once the reaction reached completion, the product was collected by filtration and washed with pentane (2 × 3 mL).

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Crystallographic data for **3b−g**, procedure for the preparation of azides, mechanistic studies, spectroscopic data, and NMR spectra for all complexes and compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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