Catalytic Carbon−Hydrogen Bond Functionalization in an Ionic Liquid Medium

Pilar Rodríguez,† Eleuterio Álvarez,‡ M. Carmen Nicasio,*,† and Pedro J. Pérez*,†

Laboratorio de Catálisis Homogénea, Departamento de Química y Ciencia de los Materiales, Unidad Asociada al CSIC, Campus de El Carmen s/n, Universidad de Huelva, 21007 Huelva, Spain, and Instituto de Investigaciones Químicas, CSIC-Universidad de Sevilla, Avenida Américo Vespucio 49, 41092 Sevilla, Spain

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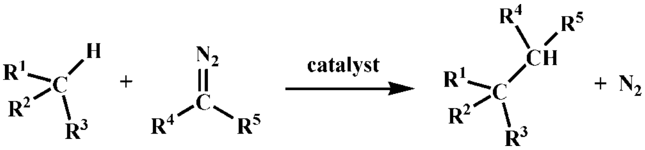
The functionalization of unreactive C−H bonds of several hydrocarbons has been achieved at room temperature by the formal insertion of carbene/$CHCO_2Et$ units (from ethyl diazoacetate) into such bonds, using copper-based catalysts in a biphasic reaction medium (ionic liquid-hydrocarbon). Catalyst and product separation has been carried out easily, and the recycle of the catalyst for five cycles has been achieved without any loss of catalytic activity.

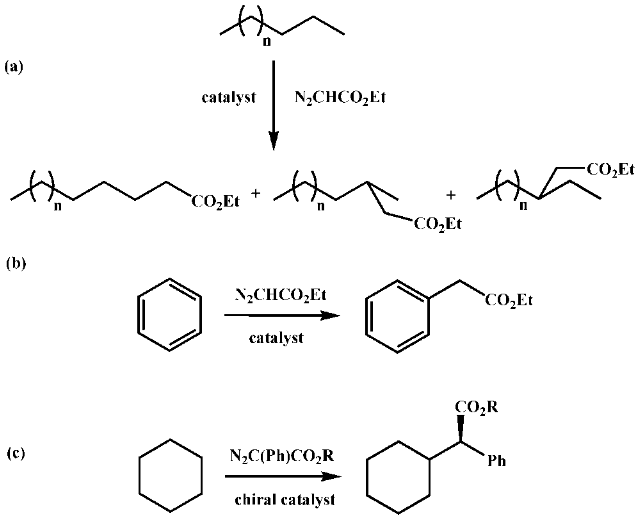
1. Introduction

The catalytic decomposition of diazo compounds and the subsequent insertion of a carbene group into a C−H bond constitute one of the very few examples of effective catalytic functionalization of hydrocarbons (eq 1).[1,2] With alkanes as the substrate, such a transformation has been achieved with rhodium-,[3–5] copper-,[6,7] silver-,[8,9] and gold-based[10] catalysts under mild conditions. For instance, this methodology has allowed the direct conversion of *n*-alkanes such as pentane or hexane into mixtures of esters (Scheme 1a) or benzene into ethyl phenylacetate (Scheme 1b). The asymmetric reaction has also been reported by Davies and co-workers (Scheme 1c), with chiral rhodium catalysts. These systems work under homogeneous conditions; therefore, product separation and catalyst recovery and recycling are not an easy operation. Immobilization of catalysts for carbene transfer from diazo compounds has been reported in a few cases, mainly for the olefin cyclopropanation reaction, using inorganic solids,[11] fluorous solvents,[12] polymeric materials,[13,14] or ionic liquids.[15] In a recent report from this laboratory, we have described[16] a catalytic system for the transfer of :$CHCO_2Et$ units from ethyl diazoacetate (EDA) to saturated and unsaturated substrates with the complex $[Tpm^*Cu(NCMe)]PF_6$ (**1**; Tpm* = $HC(3,5\text{-}Me_2pz)_3$) as the



(1)

Scheme 1. Examples of the Catalytic Functionalization of Hydrocarbons by Carbene Insertion from Diazo Compounds



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* To whom correspondence should be addressed. E-mail: perez@dqcm.uhu.es, mcnica@dqcm.uhu.es.

† Universidad de Huelva.

‡ CSIC-Universidad de Sevilla.

(1) Doyle, M. P.; McKervey, M. A.; Ye, T. *Modern Catalytic Methods for Organic Synthesis with Diazo Compounds*; John Wiley & Sons: New York, 1998.

(2) Díaz-Requejo, M. M.; Belderraín, T. R.; Nicasio, M. C.; Pérez, P. J. *Dalton Trans.* **2006**, 5559.

(3) (a) Demonceau, A.; Noels, A. F.; Hubert, A. J.; Teyssié, P. *J. Chem. Soc., Chem. Commun.* **1981**, 688. (b) Demonceau, A.; Noels, A. F.; Hubert, A. J.; Teyssié, P. *Bull. Soc. Chim. Belg.* **1984**, *93*, 945. (c) Demonceau, A.; Noels, A. F.; Teyssié, P.; Hubert, A. J. *J. Mol. Catal.* **1988**, *49*, L13. (d) Demonceau, A.; Noels, A. F.; Hubert, A. J. *J. Mol. Catal.* **1989**, *57*, 149. (e) Demonceau, A.; Noels, A. F.; Costa, J. L.; Hubert, A. J. *J. Mol. Catal.* **1990**, *58*, 21.

(4) (a) Callot, H. J.; Metz, F. *Tetrahedron Lett.* **1982**, *23*, 4321. (b) Callot, H. J.; Metz, F. *Nouv. J. Chim.* **1985**, *9*, 167.

(5) (a) Davies, H. M. L.; Hansen, T. *J. Am. Chem. Soc.* **1997**, *119*, 9075. (b) Davies, H. M. L.; Hansen, T.; Churchill, M. R. *J. Am. Chem. Soc.* **2000**, *122*, 3063.

(6) (a) Scott, L. T.; DeCicco, G. J. *J. Am. Chem. Soc.* **1974**, *96*, 322. (b) Wulfman, D. S., Jr.; Peace, B. W. *Tetrahedron* **1976**, *32*, 1241.

(7) (a) Díaz-Requejo, M. M.; Belderrain, T. R.; Nicasio, M. C.; Trofimenko, S.; Pérez, P. J. *J. Am. Chem. Soc.* **2002**, *124*, 896. (b) Caballero, A.; Díaz-Requejo, M. M.; Belderrain, T. R.; Nicasio, M. C.; Trofimenko, S.; Pérez, P. J. *J. Am. Chem. Soc.* **2003**, *125*, 1446. (c) Caballero, A.; Díaz-Requejo, M. M.; Belderrain, T. R.; Nicasio, M. C.; Trofimenko, S.; Pérez, P. J. *Organometallics* **2003**, *22*, 4145. (d) Fructos, M. R.; de Frémont, P.; Nolan, S. P.; Díaz-Requejo, M. M.; Pérez, P. J. *Organometallics* **2006**, *25*, 2237.

(8) Urbano, J.; Belderrain, T. R.; Nicasio, M. C.; Trofimenko, S.; Díaz-Requejo, M. M.; Pérez, P. J. *Organometallics* **2005**, *24*, 1528.

(9) (a) Dias, H. V. R.; Browning, R. G.; Richey, S. A.; Lovely, C. J. *Organometallics* **2004**, *23*, 1200. (b) Dias, H. V. R.; Browning, R. G.; Richey, S. A.; Lovely, C. J. *Organometallics* **2005**, *24*, 5784.

(10) Fructos, M. R.; Belderrain, T. R.; de Frémont, P.; Scott, N. M.; Nolan, S. P.; Díaz-Requejo, M. M.; Pérez, P. J. *Angew. Chem., Int. Ed.* **2005**, *44*, 5284.

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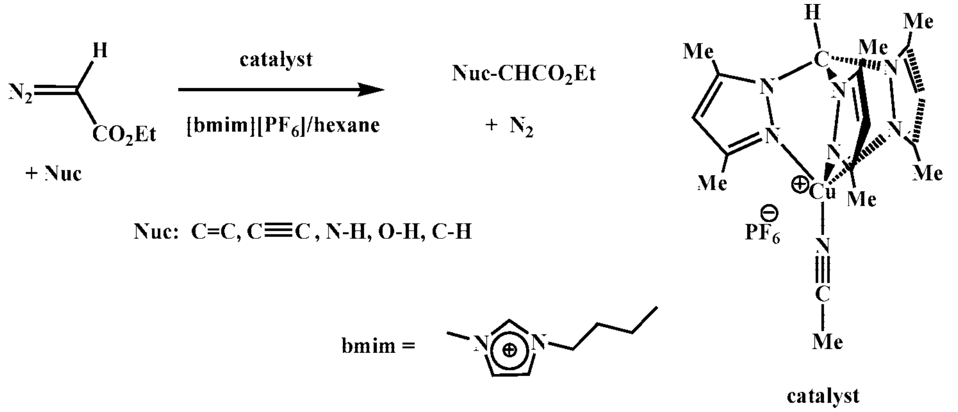
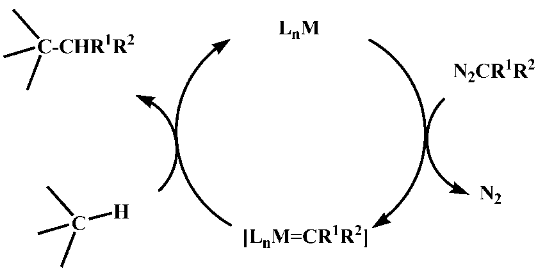
Scheme 2. Catalytic Transfer of :$CHCO_2Et$ from EDA under Biphasic Conditions Using [bmim][PF_6]



catalyst and using the ionic liquid [bmim][PF_6] (bmim = 1-*n*-butyl-3-methylimidazolium hexafluorophosphate) and hexane as the biphasic reaction mixture. The insertion reactions into N−H and O−H bonds were quantitative, and the catalyst was recovered and recycled five times. However, when cyclohexane was used as the substrate, only 35% conversions were observed (Scheme 2). It is worth mentioning that, in spite of this low yield, this is the unique example, to the best of our knowledge, of the intermolecular catalytic functionalization of a C−H bond by this methodology using an ionic liquid as a reaction medium. Actually, under biphasic conditions, we are only aware of two examples, described by Maas et al.[12a–c] and Biffis et al.[12d] in which rhodium(II) complexes containing perfluoro chains were employed as the catalyst for the carbene transfer from methyl diazoacetate to the C−H bonds of hexane.

On the basis of our preliminary results[16] and of our experience in the design of copper-based catalysts for C−H bond functionalization with EDA,[7] we decided to focus on the synthesis of new catalysts capable of inducing such a transformation with low reactive, unmodified alkanes and using an ionic liquid as the reaction medium to favor catalyst separation and recycling. In this paper, we report the synthesis and structural characterization of two copper complexes that encompass that goal and that can be recovered and reused several times without loss of activity.

Scheme 3. Catalytic Cycle for C−H Bond Functionalization by Carbene Insertion from Diazo Compounds



2. Results and Discussion

Synthesis and Characterization of Tris(3-mesitylpyrazol-1-yl)methane (Tpm^{Ms}) and Bis(3-mesitylpyrazol-1-yl)(5-mesityl-pyrazol-1-yl)methane (Tpm^{Ms*}) and Their Copper(I) [$Tpm^xCu(NCMe)$]PF_6 Complexes. As mentioned above, the complex [$Tpm^*Cu(NCMe)$]PF_6 induced decomposition of EDA and the subsequent transfer of the :$CHCO_2Et$ unit to several substrates using an ionic liquid as the reaction medium. However, cyclohexane was converted into ethyl cyclohexylacetate in low yield (35 %), with diethyl fumarate (DEF) and maleate (DEM) being the major products in this case. This result is due to the low nucleophilicity of the C−H bond of cyclohexane; therefore, the electrophilic metallocarbene intermediate presumably formed during this transformation,[1] being not reactive enough toward the hydrocarbon (Scheme 3). Two factors affect the interaction of such an intermediate and the C−H bond: the electrophilicity of the metallocarbene species and the steric protection of the metal center. The low electronic density at the metal center favors not only its reaction with the diazo compound but also further interaction with the C−H bond. In addition, the steric protection of the $M=CR^1R^2$ unit seems

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(11) (a) For example, see: Lemaire, M. *Pure Appl. Chem.* **2004**, *76*, 679. (b) Lancaster, T. M.; Lee, S. S.; Ying, J. Y. *Chem. Commun.* **2005**, 3577. (c) Sacco, L.; Lambert, S.; Pirard, J. P.; Noels, A. F. *J. Catal.* **2005**, *232*, 51. (d) Kantam, M. L.; Haritha, Y.; Reddy, N. M.; Choudary, B. M.; Figuers, F. *Catal. Lett.* **2002**, *83*, 187. (e) Fraile, J. M.; Garcia, J. I.; Herrerias, C. I; Mayoral, J. A.; Reiser, O; Socuellamos, A.; Werner, H. *Chem.—Eur. J.* **2004**, *10*, 2997. (f) Cornejo, A.; Fraile, J. M.; García, J. I.; Gil, M. J.; Herrerías, C. I.; Legarreta, G.; Martínez-Merino, V.; Mayoral, J. A. *J. Mol. Catal. A* **2003**, *196*, 101. (g) Zhang, J.-L.; Liu, Y.-L.; Che, C.-M. *Chem. Commun.* **2002**, 2906. (h) Fraile, J. M.; García, J. I.; Mayoral, J. A.; Tarnai, T. *Tetrahedron: Asymmetry* **1998**, *9*, 3997. (i) Fraile, J. M.; García, J. I.; Mayoral, J. A.; Roldán, M. *Org. Lett.* **2007**, *9*, 731.

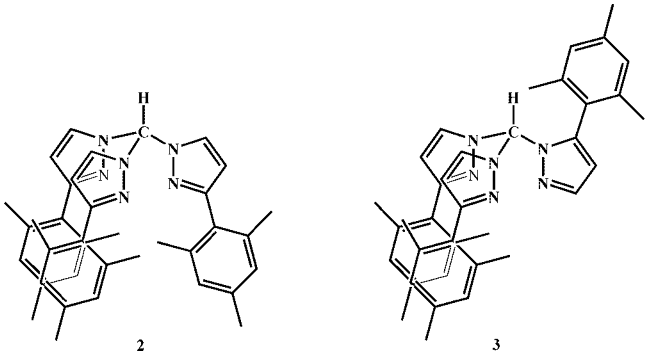
(12) (a) Endres, A.; Maas, G. *Tetrahedron* **2002**, *58*, 3999. (b) Endres, A.; Maas, G. *J. Organomet. Chem.* **2002**, *643*, 174–644. (c) Endres, A.; Maas, G. *Tetrahedron Lett.* **1999**, *40*, 6365. (d) Biffis, A.; Braga, M.; Cadamuro, S.; Tubaro, C.; Basato, M. *Org. Lett.* **2005**, *7*, 1841. (e) Urbano, J.; Izarra, R.; Gómez-Ariza, J. L.; Trofimenko, S.; Díaz-Requejo, M. M.; Pérez, P. J. *Chem. Commun.* **2006**, 1000.

(13) (a) Doyle, M. P.; Yan, M.; Gau, H.-M.; Blossey, E. C. *Org. Lett.* **2003**, *5*, 561. (b) Doyle, M. P.; Timmons, D. J.; Tumonis, J. S.; Gau, H.-M.; Blossey, E. C. *Organometallics* **2002**, *21*, 1747. (c) Burguete, M. I.; Fraile, J. M.; García, J. I.; García-Verdugo, E.; Luis, S. V.; Mayoral, J. A. *Org. Lett.* **2000**, *2*, 3905.

(14) (a) Davies, H. M. L.; Walji, A. M. *Org. Lett.* **2005**, *7*, 2941. (b) Davies, H. M. L.; Walji, A. M.; Nagashima, T. *J. Am. Chem. Soc.* **2004**, *126*, 4271. (c) Davies, H. M. L.; Walji, A. M. *Org. Lett.* **2003**, *5*, 479. (d) Nagashima, T.; Davies, H. M. L. *Org. Lett.* **2002**, *4*, 1989.

(15) (a) Forbes, D. C.; Patrawala, S. A.; Tran, K. L. T. *Organometallics* **2006**, *25*, 2693. (b) Kantam, M. L.; Neelima, B.; Reddy, C. V. *J. Mol. Catal. A* **2006**, *256*, 269. (c) Davies, D. L.; Kandola, S. K.; Patel, R. K. *Tetrahedron: Asymmetry* **2004**, *15*, 77. (d) Fraile, J. M.; García, J. I.; Herrerías, C. I.; Mayoral, J. A.; Reiser, O.; Vaultier, M. *Tetrahedron Lett.* **2004**, *45*, 6765. (e) Fraile, J. M.; García, J. I.; Herrerías, C. I.; Mayoral, J. A.; Gmough, S.; Vaultier, M. *Green Chem.* **2004**, *6*, 93. (f) Yadav, J. S.; Reddy, B. V. S.; Reddy, P. N. *Adv. Synth. Catal.* **2004**, *346*, 53. (g) Chandrasekhar, S.; Narasihmulu, Ch.; Jagadeshwar, V.; Reddy, K. V. *Tetrahedron Lett.* **2003**, *44*, 3629. (h) Iwasa, S.; Tsushima, S.; Nishiyama, K.; Tsuchiya, Y.; Takezawa, F.; Nishiyama, H. *Tetrahedron: Asymmetry* **2003**, *14*, 855. (i) Yang, F.; Zhang, Y.-M.; Qiu, W.-W.; Tang, J.; He, M.-Y. *Chin. J. Chem.* **2002**, *20*, 114. (j) Fraile, J. M.; García, J. I.; Herrerías, C. I.; Mayoral, J. A.; Carrié, D.; Vaultier, M. *Tetrahedron: Asymmetry* **2001**, *12*, 1891.

(16) Rodríguez, P.; Caballero, A.; Díaz-Requejo, M. M.; Nicasio, M. C.; Pérez, P. J. *Org. Lett.* **2006**, *8*, 557.



2 **3**

Figure 1. Proposed geometries for the molecules of **2** and **3**.

to disfavor the formation of the coupling products DEF and DEM. A few years ago, we applied this strategy with the complex Tp^{Ms}Cu,[7a] which catalyzed the insertion of :CHCO$_2$Et (from EDA) into the C−H bonds of cycloalkanes or cyclic ethers. With the idea of preparing a similar catalyst that could operate under biphasic conditions in a manner similar to that found with [Tpm*Cu(NCMe)]PF$_6$, we decided to synthesize the related Tpm^{Ms} ligand HC(3-Ms-pz)$_3$, which could later be employed for the preparation of the complex analogue to **1**.

The synthesis of the Tpm^{Ms} ligand was performed following the method described by Reger and co-workers[18] for related ligands. 3-Mesitylpyrazole was deprotonated and further reacted with chloroform at 70 °C for 24 h. After workup, NMR studies carried out with the reaction crude revealed the existence of two compounds. One of them showed a set of signals for three equivalent pyrazolyl rings, whereas a second, major species showed all of the pyrazolyl resonances split into a 2:1 ratio. Separation of both compounds was achieved by column chromatography, affording the new compounds with analytical purity. On the basis of the previous literature,[18,19] it is reasonable to assume that the compound with the three equivalent pyrazolyl groups corresponds to the targeted Tpm^{Ms} (**2**), with the other having a less symmetric structure with two pyrazolyl rings oriented in the opposite direction from the third one (Figure 1). By analogy with the trispyrazolylborate case, the latter has been named as Tpm^{Ms*} (**3**). The proposal of the bulkier groups pointing away from the methinic C−H bond is also a resemblance of the Tp^{x} ligands. However, very recently we have described a series of typical Tp^{x} ligands[20] in which the bulkier groups were located in the vicinity of the B−H bond. Thus, to unambiguously establish the structure of **2** and **3**, X-ray diffraction studies have been performed with single crystals of both, leading to the establishment of the actual orientation of the pyrazolyl rings. Figure 2 displays the structures of **2** and **3**, where the actual orientation of the pyrazolyl rings is demonstrated. In the case of Tpm^{Ms}, the three 3-mesitylpyrazolyl groups are oriented with the mesityl group in the opposite direction of the unique C−H bond, whereas for Tpm^{Ms*} one of the pyrazolyl rings displays a reverse direction. It is worth mentioning that although these compounds are similar to their related trispyrazolylborate ligands Tp^{Ms} and Tp^{Ms*} (Table 1), there is a significant difference in both systems. When synthesized, the Tp^{Ms*} ligand is the only compound formed.[21] It requires heating at high temperature to induce isomerization to Tp^{Ms}. In our case, the formation of both compounds **2** and **3** occurs under the reaction conditions (70 °C, 24 h). However, prolonged heating of solutions of pure samples of **2** and **3** at 100 °C did not show any conversion of one into the other.

The structural data in **2** and **3** are quite similar to those of the 3-phenyl derivative, already reported by Reger and co-workers.[22] The structure of **2** consists of discrete molecules with aromatic−aromatic intermolecular associations, π stacking, and edge-to-face interactions. The orientation of the three pyrazolyl rings is a propeller arrangement with only one of the donor N atoms oriented toward the potential bonding “pocket” of the ligand. This arrangement is in good agreement with published results for comparable molecules.[18] Therefore, the molecule does not have threefold symmetry. In the case of **3**, a similar structure with aromatic−aromatic intermolecular associations, π stacking, and edge-to-face interactions, as well as with the orientation of the three pyrazolyl rings in a propeller arrangement, has been determined.

The above ligands have been employed to prepare new copper(I) complexes by their direct reaction with Cu^{I} in acetonitrile as the solvent, at room temperature, followed by the addition of AgPF$_6$ to promote chloride extrusion and acetonitrile coordination (eq 2). Crystalline materials of composition [Tpm^{x}Cu(NCMe)]PF$_6$ (Tpm^{x} = Tpm^{Ms}, **4**; Tpm^{Ms*}, **5**) have been isolated in 65–70% yield. NMR data is in accordance with the existence of a Tpm^{x} ligand coordinated to the copper center, with patterns of signals similar to those of the free ligands, as well as those of a coordinated acetonitrile molecule. These data are in accordance with a structure in which the Cu ion is bonded to the three N donors of the Tpm^{x} ligand and to the N donor of the acetonitrile ligand, in a tetrahedral environment, similarly to other related cationic complexes.[18,23] Figure 3 shows the structure of the molecules of **4** obtained by X-ray diffraction studies, which corroborates this proposal. The Cu^{I} ion is tetrahedrally coordinated by three N atoms of Tpm^{Ms} and one N atom of acetonitrile. The Cu−NCMe unit is slightly deviated from linearity, as is inferred from the value of the Cu1−N7−C38 angle of 165.5°, in contrast with other analogous complexes that show an almost linear Cu−N−C unit (176–179°).[23a] The Cu−N distance to the N atom of acetonitrile 1.877(2) Å is almost identical with that of analogously described complexes.[18,23] The pyrazolyl and mesityl rings are not in the same plane, with the torsion angles between the rings being 122.5°, 113.8°, and 110.4°. This implies that the steric hindrance at the position of the pyrazolyl ring located in the vicinity of the metal center (Ms, ^{t}Bu, ^{i}Pr) does not significantly affect the structures of the acetonitrile complexes.

$$\mathbf{Tpm^{x} + CuI \xrightarrow[\text{2) AgPF}_6]{\text{1) MeCN, r. t.}} [Tpm^{x}Cu(NCMe)]PF_6 + AgI} \qquad (2)$$

Catalytic Functionalization of Alkane C−H Bonds. As mentioned above, previous work[16] from this laboratory has

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(17) Davies, H. M. L.; Beckwith, R. E. J. *Chem. Rev.* **2003**, *103*, 2861.

(18) Reger, D. L.; Collins, J. E.; Rheingold, A. L.; Liable-Sands, L. M. *Organometallics* **1996**, *15*, 2029.

(19) (a) Trofimenko, S. *J. Am. Chem. Soc.* **1970**, *92*, 5118. (b) Julia, S.; del Mazo, J. M.; Ávila, L.; Elguero, J. *Org. Prep. Proced. Int.* **1984**, *16*, 299.

(20) Yap, G. P. A.; Jove, F.; Urbano, J.; Álvarez, E.; Trofimenko, S.; Díaz-Requejo, M. M.; Pérez, P. J. *Inorg. Chem.* **2007**, *46*, 780.

(21) Trofimenko, S. *Scorpionates, The Coordination Chemistry of Polypyrazolylborate Ligands*; Imperial College Press: London, 1999.

(22) Reger, D. L.; Grattan, T. C.; Brown, K. J.; Little, C. A.; Lamba, J. J. S.; Rheingold, A. L.; Sommer, R. D. *J. Organomet. Chem.* **2000**, *607*, 120.

(23) (a) Fujisawa, K.; Ono, T.; Ishikawa, Y.; Amir, N.; Miyashita, Y.; Okamoto, K.; Lehnert, N. *Inorg. Chem.* **2006**, *45*, 1698. (b) Cvetkovic, M.; Batten, S. R.; Moubaraki, B.; Murray, K. S.; Spiccia, L. *Inorg. Chim. Acta* **2001**, *324*, 131.

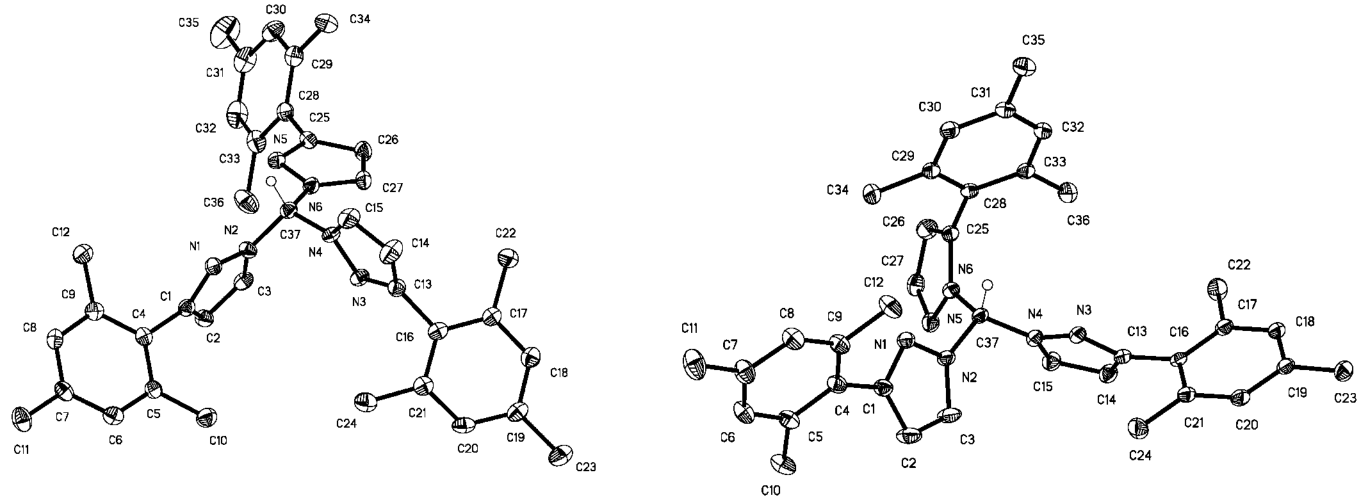
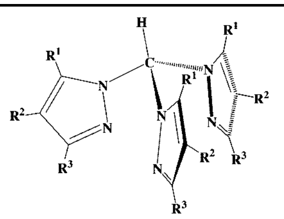
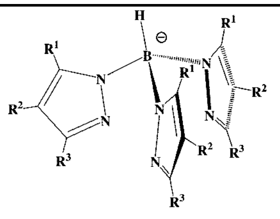


Figure 2. Molecular structures of (left) tris(3-mesitylpyrazol-1-yl)methane (Tpm^{Ms}, **2**) and (right) bis(3-mesitylpyrazol-1-yl)(5-mesityl-1pyrazol-1-yl)methane (Tpm^{Ms*}, **3**). Thermal ellipsoids are drawn at the 50% probability level. H atoms have been omitted for clarity.

Table 1. Trispyrazolylmethane and Trispyrazolylborate Ligands Relevant to This Work

							
Tpm^x	**R^1**	**R^2**	**R^3**	**Tp^x**	**R^1**	**R^2**	**R^3**
Tpm*	CH_3	H	CH_3	Tp*	CH_3	H	CH_3
Tpm^{Ms}	H	H	Ms^a	Tp^{Ms}	H	H	Ms
Tpm^{Ms*}	H (2 pyr) Ms (1 pyr)	H	Ms (2 pyr) H (1 pyr)	Tp^{Ms*}	H (2 pyr) Ms (1 pyr)	H	Ms (2 pyr) H (1 pyr)

[a] Ms = 2,4,6-$Me_3C_6H_2$.

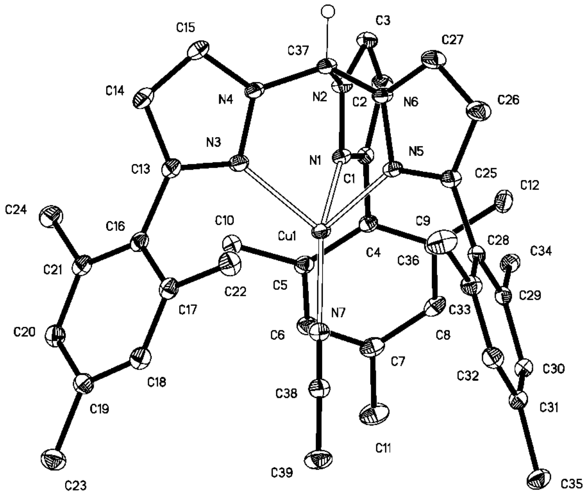
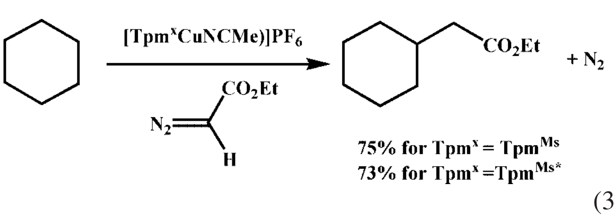


Figure 3. Molecular structure of **4**. Thermal ellipsoids are drawn at the 30% probability level. The H atoms, the PF_6 anion, and the three MeCN solvation molecules have been omitted for clarity.

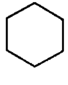
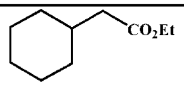
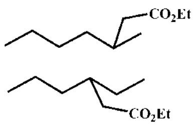
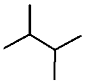
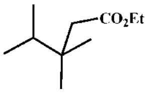
shown that the complex **1** catalyzed the decomposition of EDA and the transfer of the :$CHCO_2Et$ unit to several unsaturated and saturated substrates under biphasic conditions in ionic liquids. Only in the case of its insertion into the C−H bonds of cyclohexane were the conversions low (35%), whereas nearly no insertion was observed in the case of other alkanes such as *n*-hexane or 2,3-dimethylbutane. Once the complexes **4** and **5** were prepared, we screened their catalytic potential toward this transformation using cyclohexane as a model substrate (eq 3). The results were quite stimulating because conversions of ca. 75% were observed in both cases under homogeneous conditions (a cyclohexane/dichloromethane mixture as the solvent) using 0.05 mmol as the catalyst loading and 1 mmol of EDA (see the Experimental Section). These conversions were quite higher compared with those obtained with **1**, and the cationic nature of **4** and **5** allowed the extension of the study to the ionic liquid [bmim]PF_6 as the reaction medium.



(3)

As a general procedure, a solution of the copper catalyst in the ionic liquid was prepared and the hydrocarbon (cyclohexane,

Table 2. Carbene Transfer from EDA to Alkane C−H Bonds Using 4 and 5 as Catalysts, under Homogeneous or Biphasic (Ionic Liquid) Conditions[a]

		4		5	
Substrate	Products	Homog[b]	Biphasic[b]	Homog[b]	Biphashic[b]
		77	75	73	75
		24 (80:20)[c]	21 (75:25)[c]	23 (75:25)[c]	21 (70:30)[c]
		10	13	40	45

[a] Reactions performed at room temperature with 0.05 mmol of the catalyst, 5% with respect to EDA. [b] Percentage of products, based on EDA (average of two runs), determined by ^{1}H NMR with trimethylvinylsilane as the internal standard. DEF and DEM accounted for the remaining EDA. [c] C2:C3 regioselectivity, determined by gas chromatography.

n-hexane, or 2,3-dimethylbutane) was added as a second layer. The diazo compound dissolved in the hydrocarbon was added with the aid of a syringe pump. After the addition, the organic layer was investigated by NMR using an internal standard. The results are shown in Table 2. It is clearly observable that the catalytic activity shown in the homogeneous phase (the hydrocarbon as the sole solvent) was nearly identical with that under biphasic conditions. It is well-known that one of the main drawbacks of homogenous catalysis is the problem of catalyst and product separation, and immobilization of homogeneous catalysts is a common strategy to surpass such a problem. However, in many cases, such immobilization supposes a certain loss of the degree of the activity and/or selectivity of the catalyst. In our case, the transition from homogeneous to biphasic conditions does not alter either the activity or the selectivity. Data in Table 2 indicate that, as is usually observed in these types of transformations, cyclohexane C−H bonds are readily functionalized in comparison with those of other less constrained alkanes. The low reactivity of *n*-hexane precluded higher conversions, although only very few examples in the literature have reported moderate to high yields with this substrate. No discrimination about the use of **4** or **5** for the functionalization of cyclohexane or *n*-hexane seems to exists, but when 2,3-dimethylbutane was employed, a substantial difference was observed. This alkane was modified in 40−45% yield (homogeneous and biphasic, respectively) with **5** as the catalyst, whereas the use of **4** only provided ca. 10%. Because the only reactive site is the tertiary C−H bond, i.e., the most sterically hindered, a perceptible effect of the size of the catalytic pocket must exist to account for this behavior. The existence of one "inverted" pyrazolyl ring in the molecules of **5**, with one of the mesityl groups in the methine side and far away from the metal, should enlarge the catalytic pocket, facilitating the functionalization of the tertiary sites of this substrate. This could also explain the regioselectivity observed in the case of *n*-hexane, where the C2:C3 functionalization ratio is slightly higher with **4** as the catalyst.

Once the catalytic capabilities of these complexes for the functionalization of C−H bonds of unreactive alkanes were demonstrated, the separation and recycling of the catalyst was tested for five cycles. Thus, once the reaction was finished, the organic layer was separated, the ionic liquid was washed twice with the same hydrocarbon before the next loading of alkane was added, and EDA was introduced in the reaction mixture. After five cycles, the conversions of 75, 72, 71, 73, and 68% could be considered to be constant, within experimental error. It is worth mentioning that after each cycle the mass balance was verified by NMR in the organic layer; therefore, all of the initial EDA was converted into the functionalized alkane and a mixture of DEF and DEM. In addition, in order to verify a potential leaching of the copper complex into the organic layer, we charged the latter with more EDA. After 24 h, all of the added EDA remained unreacted, indicating the inexistence of appreciable amounts of active copper species in the extract. We can conclude at this stage that these compounds operate under biphasic conditions in a manner similar to that under homogeneous conditions and with the advantage of being separated and recycled several times with no loss of activity. To the best of our knowledge, these results find no precedent in the catalytic functionalization of C−H bonds by carbenoid insertion. This is the first example of efficient catalyst recovery and recycle in an ionic liquid. The already mentioned work by Endres and Maas,[12a−c] the unique reported example of this transformation under biphasic conditions (a fluorous medium), gave a ca. 40% conversion with *n*-hexane in the first cycle and 10% in the second, with no more consecutive runs being described.

IR and Kinetic Studies: Insights for Further Catalyst Development. As shown in Scheme 3, the main requirement for a transition metal to catalyze these transformations is to display a certain electrophilic character at the metal center.[1,2,17] Such nature would enhance its interaction with the diazo compound and, once the metallocarbene intermediate is formed, also would enhance the electrophilia at the carbene C atom, therefore favoring the reaction with the nucleophile, the C−H bond. Because the latter is a poor nucleophile, increasing the electrophilia at the metal center is the main strategy to improve catalytic activities. Only a few systems have been reported to induce these transformations, some of them being based in copper or silver complexes of type Tp^xM containing trispyrazolylborate ligands (Tp^x).[7a−c,8,9] In this case, a useful tool to estimate the electron density at the metal center is to evaluate the ν(CO) of the carbonyl adducts Tp^xCu(CO). A correlation between ν(CO) and the catalytic activity is usually observed, in such a way that the higher the ν(CO) values, the higher the catalytic activity. Therefore, we have applied this methodology to complexes **4** and **5**, upon bubbling CO throughout

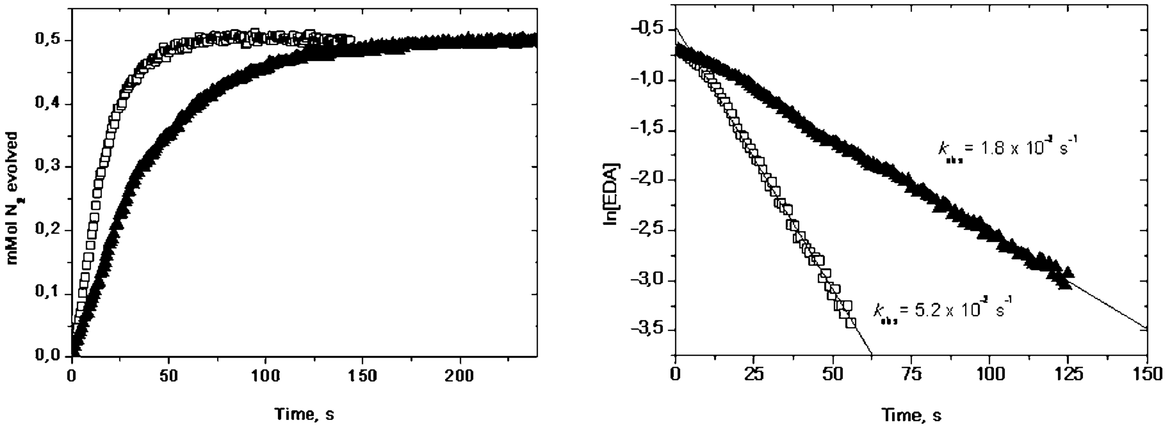
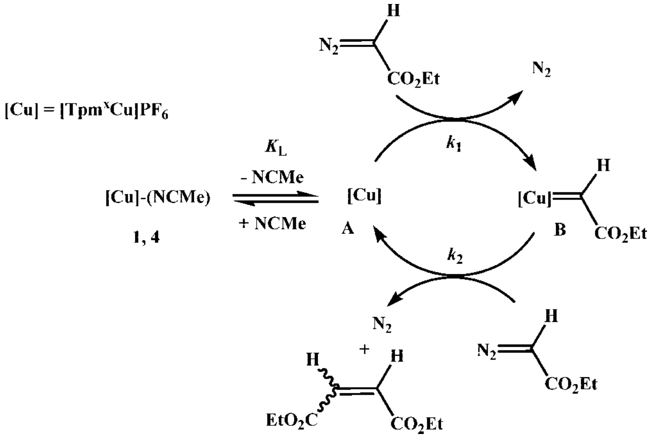


Figure 4. Plots of the evolution of N_2 and of ln [EDA] vs time for the EDA decomposition using **1** (▲) and **4** (□) as the catalysts.

their solutions in CH_2Cl_2 and registering their IR spectra in solution. A sharp absorption was observed in both cases centered at 2100 and 2113 cm^{-1} for $[Tpm^{Ms}Cu(CO)]PF_6$ and $[Tpm^{Ms*}Cu(CO)]PF_6$, respectively. Interestingly, the carbonyl adduct of Tpm*, already reported by Reger and co-workers,[18] also displayed ν(CO) at 2113 cm^{-1}. This behavior is in contrast with the aforementioned trispyrazolylborate-related complexes. Thus, the values of ν(CO) for Tp*Cu(CO) and $Tp^{Ms}Cu(CO)$ are respectively 2056 and 2079 cm^{-1}, which correlate with a moderate activity of the latter and a nearly nonactivity of the former toward the functionalization of C−H bonds by this methodology. Back to the trispyrazolylmethane systems, both Tpm^{Ms}- and Tpm^{Ms*}-containing complexes **4** and **5** display higher activities than **1**, the Tpm*-based catalyst. A very recent, elegant work[23a] by Fujisawa and co-workers has demonstrated, on the basis of experimental and theoretical calculations, that Tpm^x ligands are weaker donors than Tp^x ligands when bonded to Cu^I. They also propose that ν(CO) values can be employed as a probe for the measurement of the electron density at the metal center. We believe that this can be applied with the exception of aryl substituents in the C3 position of the pyrazolyl ring. Dias and Kim described the $[Tpm^{Ph}Cu(CO)]^+$ complex[24] to show a 2104 cm^{-1} band, and our mesityl-containing ligands have provided cationic copper(I) complexes with absorptions similar or lower than that with Tpm*. In no case did these complexes provide ν(CO) absorptions higher than 2113 cm^{-1}. The question that arises from these results is about the electron density at the metal center with these ligands and whether or not the replacement of Tpm* by Tpm^{Ms} or Tpm^{Ms*} provides the expected decrease in the electron density, a crucial feature for the improvement of the catalytic activity.

Scheme 4. Catalytic Cycle for the EDA Decomposition Reaction in the Presence of 1 or 4 as the Catalyst



To validate the proposal of the electron density at the metal center, we have performed kinetic studies using the complexes **1** and **4** as the catalyst for the sole decomposition of EDA into DEF and DEM. Figure 4 shows the evolution of N_2 with time as well as the plot of ln [EDA] vs time. It is clearly observable that the complex with the Tpm^{Ms} ligand decomposes EDA faster than that with Tpm*; i.e., **4** is more active for the diazo compound decomposition. The observation of first-order kinetics is in accordance with the formation of the metallocarbene intermediate as the rate-determining step,[25] in a fashion similar to that of previous studies, including the related trispyrazolylborate copper catalysts, for which we have already reported kinetic data. On the basis of this previous work, we propose a pathway similar to that depicted in Scheme 4. Starting from the acetonitrile adducts **1** or **4**, the first step would involve the dissociation of the acetonitrile ligand to give an unsaturated species **A**, which would react with EDA to afford the copper−carbene intermediate (**B**), similar to those already independently reported by Straub and Hofman[26] and Dai and Warren.[27] Further reaction with a second molecule of EDA would lead to the formation of the alkenes and the release of **A** to restart the catalytic cycle. The aforementioned observation of first-order kinetics supports this proposal. Assuming that **B** is under steady-state conditions, the following rate law for this transformation can be deduced:[28]

$$\frac{-\mathrm{d[EDA]}}{\mathrm{d}t} = \frac{2k_1K_\mathrm{L}[\mathrm{Cu}]_\mathrm{T}}{K_\mathrm{L} + [\mathrm{MeCN}]}[\mathrm{EDA}] = k_\mathrm{obs}[\mathrm{EDA}]$$

$$k_\mathrm{obs} = \frac{2k_1K_\mathrm{L}[\mathrm{Cu}]_\mathrm{T}}{K_\mathrm{L} + [\mathrm{MeCN}]}$$

where $[Cu]_T$ is the total amount of the copper catalyst added initially. Data from kinetic studies show k_{obs} values of 5.2 × 10^{-2} and 1.8 × 10^{-2} s^{-1} and $[Cu]_T$ values of 3.12 × 10^{-5} and 6.25 × 10^{-5} M for **4** and **1** as the catalysts, respectively. On

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(24) Dias, H. V. R.; Kim, H.-J. *Organometallics* **1996**, *15*, 5374.

(25) (a) Díaz-Requejo, M. M.; Caballero, A.; Belderrain, T. R.; Nicasio, M. C.; Trofimenko, S.; Pérez, P. J. *J. Am. Chem. Soc.* **2002**, *124*, 978. (b) Díaz-Requejo, M. M.; Belderrain, T. R.; Nicasio, M. C.; Prieto, F.; Pérez, P. J. *Organometallics* **1999**, *18*, 2601.

(26) Straub, B. F.; Hofmann, P. *Angew. Chem., Int. Ed.* **2001**, *40*, 1288.

(27) Dai, X. L.; Warren, T. H. *J. Am. Chem. Soc.* **2004**, *126*, 10085.

(28) Derivation of kinetic equations is provided in the Supporting Information.

the basis of X-ray data that show nearly identical Cu−NCMe distances for both complexes **1** and **4**, we can assume that the coordination−decoordination equilibria would not differ much from one to another, with the values of K_L also being similar. Thus, we can write the previous equation as follows:

$$k_{obs} = k'k_1[Cu]_T \quad \text{where } k' = \frac{2K_L}{K_L + [MeCN]}$$

Under the previous assumption and from data in Figure 4, we can calculate the ratio $k_1(\mathbf{4})/k_1(\mathbf{1})$ as 5.7, demonstrating that the incorporation of the mesityl group into the pyrazolyl rings induced a considerable enhancement of the catalytic activity of the corresponding copper complex. It is worth returning to the already mentioned ν(CO) values for these complexes: in spite of the frequency trend observed for $[Tpm^xCu(CO)]PF_6$, Tpm* = Tpm^{Ms*} > Tpm^{Ms}, the Tpm*-based catalyst is less active than **4** (or **5**). Therefore, the use of IR data in this family of complexes, when including aromatic substituents in the pyrazolyl rings, as an estimation of the electron density at the metal center should be taken with precautions.

Therefore, the above results indicate that the replacement of 3,5-dimethylpyrazole by mesitylpyrazole in the Tpm^x ligands exerts a decrease in the electron density at the metal center, which cannot be envisaged using the traditional method based in IR studies of carbonyl adducts. Such a decrease affects the catalytic activity of those complexes toward the decomposition of EDA and the subsequent insertion of the :$CHCO_2Et$ unit into the C−H bonds of alkanes. On the basis of this knowledge, the design of more electrophilic copper complexes containing novel Tpm^x ligands that could promote higher degrees of activation of C−H bonds of alkanes is currently underway in our laboratory.

3. Conclusion

The functionalization of unreactive C−H bonds of several hydrocarbons has been achieved at room temperature by the formal insertion of carbene/$CHCO_2Et$ units, from EDA, into such bonds, using cationic copper-based catalysts in a biphasic reaction medium of an ionic liquid and hydrocarbon. Separation of products is readily performed, and the recycle of the catalyst for five cycles has been achieved without any loss of the catalytic activity. These novel results serve as a starting point for the development of more active and selective catalysts for this transformation, with the goal of its application to a larger array of alkanes.

4. Experimental Section

General Methods. All reactions and manipulations were carried out under an oxygen-free nitrogen atmosphere with standard Schlenk techniques or in a glovebox. All substrates were purchased from Aldrich. Substrates and solvents were dried and degassed before use. The complex $[Tpm^*Cu(NCMe)]BF_4$,[18] the ionic liquid $[bmim]PF_6$,[29] and 3-mesitylpyrazole[21] were prepared according to literature procedures. NMR spectra were recorded on a Varian Mercury 400 MHz spectrometer. ^1H NMR chemical shifts were measured relative to deuterated solvent peaks but are reported relative to tetramethylsilane. IR data were collected in a Varian Scimitar 1000 Fourier transform IR spectrophotometer. Gas chromatography (GC) data were collected with a Varian GC-3900 chromatograph with a flame ionization detector. Elemental analyses were performed in the Microanalytical Laboratory of the Instituto de Investigaciones Químicas Isla de la Cartuja.

Tris(3-mesitylpyrazol-1-yl)methane and Bis(3-mesitylpyrazol-1-yl)(5-mesityl1pyrazol-1-yl)methane. To a mixture of 3-mesitylpyrazole (2 g, 0.011 mol) and tetra-*n*-butylammonium bromide (0.21 g, 0.67 mmol) was added distilled water (20 mL). With vigorous stirring, sodium carbonate (7.2 g, 0.07 mol) was added slowly to the reaction mixture. After the mixture was cooled to room temperature, chloroform (10 mL) was added, and the reaction mixture was heated at 70 °C for 24 h. A dark-orange suspension was obtained, which was allowed to cool to room temperature and filtered to remove the excess of base. The organic layer was separated from the aqueous layer. The aqueous layer was extracted with diethyl ether (3 × 10 mL), the combined organic fractions were washed with distilled water (20 mL) and dried ($MgSO_4$), and the solvent was evaporated under vacuum, yielding a yellow solid. ^1H NMR analysis of the reaction crude in $CDCl_3$ showed the presence of the desired isomer and the isomer with two pyrazole rings with the mesityl group at the 3 position and the third ring with the mesityl group at the 5 position in a 1:2 ratio. The isomers could be separated by flash chromatography on silica gel (3 × 15 cm; petroleum ether/ether diethyl 4:1; 10 mL fractions). The major isomer was eluted first, and evaporation of the solvent gave 0.62 g of $HC(3\text{-}Ms\text{-}pz)_2(5\text{-}Ms\text{-}pz)$ as a pale-yellow solid. The desired compound was eluted next, and evaporation of the solvent afforded 0.33 g of $HC(3\text{-}Ms\text{-}pz)_3$ as a cream-colored solid. Yield: 0.95 g, 45% (based on 3-mesitylpyrazole).

$HC(3\text{-}Ms\text{-}pz)_3$ (Tpm^{Ms}, 2). ^1H NMR (400 MHz, $CDCl_3$): δ 8.47 (s, 1H, *H*C), 7.69 (d, 3H, C*H*(pz), J_{HH} = 2.4 Hz), 6.91 (s, 6H, CH(Ar)), 6.28 (d, 3H, C*H*(pz), J_{HH} = 2.4 Hz), 2.30 (s, 9H, CH_3(Ar)), 2.08 (s, 18H, CH_3(Ar)). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 153.4 (C(pz)), 138.1 (C(Ar)), 137.6 (*C*H(pz)), 130.4, 130.3 (C(Ar)), 128.4 (*C*H(Ar)), 108.3 (*C*H(pz)), 83.7 (H*C*), 21.4, 20.7 (Me(Ar)). Anal. Calcd for $C_{37}H_{40}N_6$: C, 78.17; H, 7.04; N, 14.79. Found: C, 77.90; H, 7.32; N, 14.65.

$HC(3\text{-}Ms\text{-}pz)_2(5\text{-}Ms\text{-}pz)$ (Tpm^{Ms*}, 3). ^1H NMR (400 MHz, $CDCl_3$): δ 7.97 (s, 1H, *H*C), 7.83 (d, 1H, C*H*(pz), J_{HH} = 1.8 Hz), 7.79 (d, 2H, C*H*(pz), J_{HH} = 2.6 Hz), 6.92 (s, 2H, C*H*(Ar)), 6.90 (s, 4H, C*H*(Ar)), 6.29 (d, 1H, C*H*(pz), J_{HH} = 1.8 Hz), 6.27 (d, 2H, C*H*(pz), J_{HH} = 2.6 Hz), 2.31 (s, 9H, CH_3(Ar)), 2.06 (s, 12H, CH_3(Ar)), 1.94 (s, 6H, CH_3(Ar)). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 152.4, 143.3 (C(pz)), 142.0 (*C*H(pz)), 140.1, 138.9, 137.8, 137.7, 130.6 (C(Ar)), 129.6 (*C*H(pz)), 128.8, 128.4 (*C*H(Ar)), 125.1 (C(Ar)), 108.5 (C*H*(pz)), 107.4 (C*H*(pz)), 80.4 (H*C*), 21.5, 21.4, 20.5, 20.2 (Me(Ar)). Anal. Calcd for $C_{37}H_{40}N_6$: C, 78.17; H, 7.04; N, 14.79. Found: C, 77.86; H, 7.08; N, 14.70.

Synthesis of $[Tpm^{Ms}Cu(NCMe)]PF_6$ (4). To a stirred solution of CuI (0.1g, 0.53 mmol) in acetonitrile (20 mL) was added a suspension of the ligand $HC(3\text{-}Ms\text{-}pz)_3$ (0.30 g, 0.53 mmol) in acetonitrile (10 mL). A pale-yellow solution was obtained. The reaction mixture was stirred for 2 h, $AgPF_6$ (0.13 g, 0.53 mmol) was added to the mixture, and precipitation of AgI was observed. The resulting suspension was filtered, and the solvent was removed under vacuum. The crude product was recrystallized from acetonitrile to give 0.28 g (65% yield) of **4** as white crystals. ^1H NMR (400 MHz, $CDCl_3$): δ 8.99 (s, 1 H, *H*C), 8.34 (d, 3H, C*H*(pz), J_{HH} = 2.5 Hz), 6.84 (s, 6H, C*H*(Ar)), 6.26 (d, 3H, C*H*(pz), J_{HH} = 2.5 Hz), 2.27 (s, 9H, CH_3(Ar)), 1.91 (s, 18H, CH_3(Ar)), 1.49 (s, 3H, CH_3CN). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 153.3 (C(pz)), 138.4 (C(Ar)), 137.6 (*C*H(pz)), 132.8, 128.8 (C(Ar)), 128.1 (*C*H(Ar)), 108.0 (*C*H(pz)), 76.6 (H*C*), 21.3, 20.4 (Me(Ar)), 1.8 (*Me*CN). $^{31}P\{^1H\}$ NMR (161 MHz, $CDCl_3$): δ −142.5 (sept, PF_6, J_{PF} = 713 Hz). Anal. Calcd for $C_{39}H_{43}N_7CuPF_6\cdot NCMe$: C, 57.31; H, 5.36; N, 13.05. Found: C, 57.48; H, 5.43; N, 13.42.

Synthesis of $[Tpm^{Ms*}Cu(NCMe)]PF_6$ (5). The procedure above using $HC(3\text{-}Ms\text{-}pz)_2(5\text{-}Ms\text{-}pz)$ as the ligand afforded white crystals

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(29) (a) Wilkes, J. S.; Levisky, J. A.; Wilson, R. A.; Hussey, C. L. *Inorg. Chem.* **1982**, *21*, 1263. (b) Suarez, P. A. Z.; Dullius, J. E. L.; Einloft, S.; de Souza, R. F.; Dupont, J. *Polyhedron* **1996**, *15*, 1217.

of **5** (yield: 0.30 g, 69%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.06 (br s, 2H, C*H*(pz)), 7.97 (s, 1H, *H*C), 7.71 (br s, 1H, C*H*(pz)), 7.12 (s, 2H, C*H*(Ar)), 6.89 (s, 4H, C*H*(Ar)), 6.26 (br s, 1H, C*H*(pz)), 6.22 (br s, 2H, C*H*(pz)), 2.43 (s, 3H, C*H*$_3$(Ar)), 2.29 (s, 6H, C*H*$_3$(Ar)), 1.94 (s, 12H, C*H*$_3$(Ar)), 1.87 (s, 3H, C*H*$_3$CN), 1.85 (s, 6H, C*H*$_3$(Ar)). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 153.4, 143.9 (C(pz)), 142.0 (C(Ar)), 141.7 (*C*H(pz)), 138.5, 137.7, 137.6 (C(pz)), 132.9 (*C*H(pz)), 129.7 (*C*H(Ar)), 128.8 (C(Ar)), 128.2 (*C*H(Ar)), 122.5 (C(Ar)), 108.0, 107.6 (*C*H(pz)), 74.5 (H*C*), 21.5, 21.3, 20.4, 19.8 (Me(Ar)), 2.2 (*Me*CN). ^{31}P{^{1}H} NMR (161 MHz, $CDCl_3$): δ −143.4 (sept, PF_6, $J_{PF} = 712$ Hz). Anal. Calcd for $C_{39}H_{43}N_7CuBF_4$: C, 61.63; H, 5.75; N, 13.11. Found: C, 62.04; H, 5.93; N, 13.19.

General Catalytic Procedure for Homogeneous Reactions. The catalyst (0.05 mmol) was dissolved in a mixture of CH_2Cl_2 (2 mL) and the alkane (2 mL). Molecular sieves were added to absorb the adventitious water (if any). A solution of EDA (1 mmol) in a mixture of CH_2Cl_2 (1.5 mL) and the alkane (1.5 mL) was slowly added (6 h) with the aid of a syringe pump; no remaining EDA was detected by GC at the end of the addition time. The solution was investigated by and the conversion determined by ^{1}H NMR of the reaction crude using trimethylvinylsilane (1 mmol) as the internal standard.

General Catalytic Procedure for Biphasic Reactions. The amount of catalyst and substrates as well as reaction procedures and conditions are similar to those in the homogeneous reactions. The catalyst and the alkane (2 mL) were added to [bmim]PF_6 (2 mL). A solution of EDA (1 mmol) in the alkane (3 mL) was added with the aid of a syringe pump for 6 h. No EDA was detected by GC at the end of the addition time. The organic phase was separated, and the ionic liquid was washed three times with the solvent (2 mL) that was employed during the reaction. The organic solution was investigated by and the conversion determined by ^{1}H NMR of the reaction crude using trimethylvinylsilane (1 mmol) as the internal standard.

Kinetic Studies. A solution of the catalyst (3.12×10^{-5} M for **4** and 6.25×10^{-5} M for **1**) in methylene chloride (5 mL) was placed into a 25 mL round-bottomed flask connected to a computer-connected pressure gauge. EDA was added in one portion (0.5 mmol), and the evolution of nitrogen was monitored until the pressure was maintained constant; i.e., all of the EDA was consumed.

Crystal Structure Analyses. Crystal data for **4**: $C_{45}H_{52}CuF_6N_{10}P$ ($C_{39}H_{43}CuN_7$, F_6P, and $3C_2H_3N$), $M_w = 941.48$; a single crystal of suitable size, yellow prism ($0.26 \times 0.26 \times 0.15$ mm^3) crystallized from acetonitrile, coated with dry perfluoropolyether was mounted on a glass fiber and fixed in a cold nitrogen stream, 100(2) K, to the goniometer head; monoclinic, space group $P2_1/c$ (No. 14), $a = 17.6524(8)$ Å, $b = 19.7974(7)$ Å, $c = 14.4264(6)$ Å, $\beta = 112.1990(10)°$, $V = 4667.9(3)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.340$ g cm^{-3}, λ(Mo Kα_1) = 0.710 73 Å, $F(000) = 1960$, $\mu = 0.569$ mm^{-1}; 62 780 reflections were collected from a Bruker-Nonius X8 Apex-II CCD diffractometer in the range of $5.66 < 2\theta < 59.44°$, and 13 136 independent reflections [R(int) = 0.0559] were used in the structural analysis. The data were reduced (BR SINT) and corrected for Lorentz and polarization effects and absorption by a multiscan method applied by *SADABS*.[30,31] The structure was solved by direct methods (*SIR-2002*)[32] and refined against all F^2 data by full-matrix least-squares techniques (*SHELXL97*)[33] converged to final R1 = 0.0532 [$I > 2\sigma(I)$] and wR2 = 0.1481 for all data, with a GOF on F^2, and $S = 1.023$ and 568 parameters. Crystal data for **2**: $C_{37}H_{40}N_6$, $M_w = 568.75$; a single crystal of suitable size, colorless needle ($0.51 \times 0.15 \times 0.14$ mm^3) crystallized from dichloromethane/diethyl ether, coated with dry perfluoropolyether was mounted on a glass fiber and fixed in a cold nitrogen stream, 100(2) K, to the goniometer head; orthorhombic, space group $Pca2_1$ (No. 29), $a = 17.5980(9)$ Å, $b = 17.1666(8)$ Å, $c = 10.4896(5)$ Å, $V = 3168.9(3)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.192$ g cm^{-3}, λ(Mo Kα_1) = 0.710 73 Å, $F(000) = 1216$, $\mu = 0.072$ mm^{-1}; 25 489 reflections were collected from a Bruker-Nonius X8 Apex-II CCD diffractometer in the range of $6.64 < 2\theta < 52.78°$, and 3403 independent reflections [R(int) = 0.0557] were used in the structural analysis. Data reduction, solution, and refinement were performed likewise for **4** converged to final R1 = 0.0369 [$I > 2\sigma(I)$] and to wR2 = 0.0881 for all data, with a GOF on F^2, and $S = 1.067$ and 398 parameters. Crystal data for **3**: $C_{37}H_{40}N_6$, $M_w = 568.75$; a single crystal of suitable size, colorless prism ($0.53 \times 0.50 \times 0.40$ mm^3) crystallized from light petroleum containing diethyl ether, coated with dry perfluoropolyether was mounted on a glass fiber and fixed in a cold nitrogen stream, 100(2) K, to the goniometer head; triclinic, space group $P\bar{1}$ (No. 2), $a = 8.2398(9)$ Å, $b = 11.7664(14)$ Å, $c = 17.0887(18)$ Å, $\alpha = 75.768(3)°$, $\beta = 79.294(3)°$, $\gamma = 85.418(3)°$, $V = 1577.0(3)$ Å^3, $Z = 2$, $\rho_{calcd} = 1.198$ g cm^{-3}, λ(Mo Kα_1) = 0.710 73 Å, $F(000) = 608$, $\mu = 0.072$ mm^{-1}; 44 957 reflections were collected from a Bruker-Nonius X8 Apex-II CCD diffractometer in the range of $5.88 < 2\theta < 59.66°$, and 8770 independent reflections [R(int) = 0.0372] were used in the structural analysis. Data reduction, solution, and refinement were performed likewise for **4** converged to final R1 = 0.0525 [$I > 2\sigma(I)$] and to wR2 = 0.1574 for all data, with a GOF on F^2, and $S = 1.022$ and 397 parameters.

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Supporting Information Available: Derivation of kinetic equations and crystallographic files in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org.

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(30) Bruker. *Apex 2*, version 2.1; Bruker AXS Inc.: Madison, WI, 2004.

(31) Bruker. SAINT and SADABS; Bruker AXS Inc.: Madison, WI, 2001.

(32) Burla, C.; Camalli, M.; Carrozzini, B.; Cascarano, G. L.; Giacovazzo, C.; Polidori, G.; Spagna, R. SIR2002: the program. *J. Appl. Crystallogr.* **2003**, *36*, 1103.

(33) Sheldrick, G. M. *SHELXL97*; University of Gottingen: Gottingen, Germany, 1997.